IODP Expedition 354: Bengal Fan

Site U1451 Summary

Background and Objectives

Site U1451 is the easternmost of the seven-site Bengal fan transect and was the only one aimed to core the older portions of the fan. The site is located above the western flank of the Ninetyeast Ridge at 8°0.42′N and 88°44.50′E, in 3607.3 m water depth. Seismic data shows that the overall fan section is condensed at Site U1451 compared to the axial part of the fan due to ongoing deformation along the Ninetyeast Ridge since the Miocene (Schwenk and Spiess, 2009). The drilling objective was to recover the complete fan section down to a seismic unconformity, which is believed to indicate the onset of fan deposition at this location. Site U1451 also contributes to the Miocene–Pliocene transect of three ~900 m deep holes to document Himalayan erosion and paleoenvironment. Finally the upper section of the site is part of the seven-site transect to investigate Late Pliocene to Recent depocenter migration and overall fan sedimentation.

Two holes were drilled at Site U1451 to 582.1 and to 1181 m DSF (Holes U1451A and U1451B, respectively). Hole U1451A was advanced by APC, half-length APC (HLAPC), and XCB. From 200 to 582.1 m, 4.8 m intervals were drilled without coring between HLAPC cores to allow overall coring depths to be achieved. At Hole U1451B, a reentry cone with 400 m casing was drilled into the seafloor. Below 400 m, Hole U1451B was cored with XCB from 542.0 to 640.8 m and then by RCB to 1181 m DSF. Wireline logging failed due to unstable hole conditions. Core recovery was 86% in Hole U1451A and 29% in Hole U1451B.

Principal Results

Coring at Site U1451 returned a complete sedimentary record of the Bengal fan construction to the Paleogene. It constrained the fan turbiditic onlap to the Late Oligocene (around 26–28 Ma) and provides the longest continuous record of Himalayan erosion throughout the Neogene. The upper section, as part of the seven-site transect at 8°N, documents a change since the Miocene towards a higher proportion of hemipelagic clay-rich deposition, consistent with a position less exposed to fan deposition due to Ninetyeast Ridge deformation.

The recovered turbiditic record extends to the Late Oligocene, which is marked by a transition from Paleogene pelagic limestones toward Early Neogene claystones and siltstones, intercalated into pelagic intervals. While this old turbiditic record carries all characteristics of Himalayan erosion across the full grain size spectrum including sands, the growth rate of the fan deposits remained overall relatively low, on the order of a few cm/k.y. A distinct change is observed in the Middle Miocene, when fan growth intensified by almost an order of magnitude (>10 cm/k.y.). In the Pliocene, coarser material is absent, and the time interval between Early Pliocene and Early Pleistocene is characterized by accumulation of carbonate-rich hemipelagic units. In the Pleistocene, a higher fine-grained detrital input is observed, but only since ~0.4 Ma ago, fan deposits dominate lithology again. As at the other Expedition 354 sites, hemipelagic sediments dominate the surficial deposition.

The Site U1451 record, combined with that of Site U1450, reflects steady conditions of Himalayan erosion as well as for Himalaya geological and structural evolution as documented by the recovered sediments relatively uniform chemical composition and clay mineral assemblages. This will be further constrained and refined with post-expedition studies, which will reveal information about sources, erosion rates, and evolution of weathering.

At first glance, the Neogene record appears remarkably stable through time. One notable exception to this is the detrital carbonate content of the turbidites that are markedly higher before 6–7 Ma. This reflects either a long-term change in the geological sources or difference in the weathering regime. The petrology of the sand reveals that high-grade metamorphic rocks fragments and minerals that are characteristic in the modern river sediments are present since the Middle Miocene and were less abundant during the Early Miocene and Late Oligocene. Such trends are consistent with an increasing exhumation of high metamorphic grade rocks through time, but confirmation by post-expedition studies is required. Turbiditic sediments that are deposited at Site U1451 since 28 Ma reflect detrital archives similar in many aspects to those of recent fan deposits or to modern river sediments. Nonetheless, fan clastic deposition is not only restricted to turbidites, but deposition of detrital clays is prevalent in hemipelagic intervals during the Neogene and likely represents deposition associated to fan activity. Similar conditions of distal fan activity may also have been involved in the formation of the Early Miocene and

Oligocene claystones recovered, which have similar accumulation rates as Pleistocene hemipelagic units.

From seismic data, the early history of fan deposition at Site U1451 is associated with a change in depositional style above a seismic unconformity. This unconformity was likely cored at the bottom of the hole, recovering Eocene and Paleocene limestones, and containing a 16–18 m.y. hiatus. The structurally disturbed unit immediately overlying the unconformity is an Oligocene–Eocene limestone and claystone unit, injected by sand and silt (injectites). On top parallel strata are onlapping, which clearly indicates turbiditic sedimentation. Tilting of these Miocene strata with respect to the modern stratification, however, indicates tectonic deformation associated to the Ninetyeast Ridge, which has affected fan deposition to a minor degree at Site U1451 since the Miocene.

The well-represented hemipelagic deposition at Site U1451 during the last 6 Ma provides an excellent opportunity to develop a stratigraphic framework for the whole transect based on high-resolution biostratigraphy, oxygen isotopes, and perhaps cyclostratigraphy. This chronology can be tied into the seismic stratigraphy and will provide ages throughout the Pliocene–Pleistocene part of the transect, as hemipelagic units were confirmed to be prominent and easy traceable horizons.

The Miocene section reveals a pronounced parallel stratification in seismic data, which seems to be related to the different consolidation behavior of sands, silts, clays, and hemipelagic unit. Carbonate-bearing and clay units show a much more rapid lithification, while sand remains unconsolidated. This might explain why sand was not well represented in rotary cores. The stratification of the Miocene section, which is similar across the 8°N drill site transect, may in turn indicate a different mode of deposition, with less channelized transport and more widespread distribution of turbiditic deposits. Whether this is linked to an overall change in sediment transport or grain size has to await further detailed analysis, carefully considering the potential sampling bias.

Operations

Hole U1451A extended from the seafloor to 582.1 m DSF and was advanced by the APC, HLAPC, and XCB systems. Below 200 m, 4.8 m intervals were drilled without coring after most HLAPC cores in order to fit in the operational time frame. Formation temperature measurements (APCT-3) were made down to 406.4 m and are the deepest piston core formation temperature measurements ever obtained. Hole U1451A cored 394.9 m and recovered 337.80 m of core (86%).

In Hole U1451B, a reentry cone with 400 m of casing was drilled into the seafloor. This assembly was intended to stabilize the hole for deep coring and logging operations. XCB coring in the upper 600 m was stopped due to failures of XCB cutting shoes. Hole U1451B was reentered a second time and RCB coring penetrated to 1181 m. RCB coring penetrated 627.6 m and recovered 180.86 m (29%). Wireline logging failed due to unstable hole conditions, probably due to collapse of the sand formation around 500 m.

Lithostratigraphy

Recovered sediments from Site U1451 were subdivided into 23 lithostratigraphic units based on lithological and microfossil characteristics, obtained through macroscopic and smear slide analyses and physical property measurements. The overall lithology of the expedition's deepest hole is comparable to that described at other sites, with the exception of the Oligocene–Eocene section, which is lithified and was not penetrated at the other sites. The dominant lithology at Site U1451 is mica- and quartz-rich sand, silt and clay turbidites, carrying high-grade metamorphic minerals in some intervals. Units of turbidites are separated by bioturbated nannofossil-rich calcareous clays and, occasionally, calcareous ooze. Five volcanic ash layers with fresh glass shards have been identified in non-turbiditic intervals above 154 m (CSF-A), including the Toba ash layer that is present at 2.6 mbsf of Hole U1451A.

Hemipelagic calcareous clay intervals of variable carbonate content, observed between 50 and 190 m CSF, are common throughout the Pleistocene and Pliocene. These intervals are intercalated with intermittent sand and mud turbidites, representing intervals of rapid deposition during the Late Pleistocene. During the Miocene and Late Oligocene, calcareous clay deposition is reduced and the record is dominated by turbiditic sediments. The latter contains numerous sand-rich layers down to 520 m (about 9 Ma). Downhole, the proportion of sand decreases. This observation is likely biased by the change in coring technique from HLAPC in Hole U1451A to RCB in Hole U1451B, as RCB was believed to be unable to recover loose sand. The turbidite units from 190 m downward mark an extended period of proximal channel or turbidite activity at this site from Late Oligocene to Late Miocene (~6 to 28 Ma). Below this interval, calcareous and clastic sediments become increasingly lithified. Green to brown claystones are interbedded with light green and yellow calcareous claystones and limestones. Within the calcareous claystone sequences, there are breccias of calcareous claystone clasts in a siltstone and sandstone matrix, interpreted to be post-depositional intrusions or injectites. The bottom ~100 m of Hole U1451B contains foraminiferal limestones, mottled calcareous claystones, and claystones reflecting the pre-fan paleoceanographic environment and much reduced influence of fan sedimentation. The transition from turbidites to limestone around 1100 m marks the last occurrence of any significant fan deposition at this site. The present lithostratigraphic section therefore captures the complete sedimentary record of fan deposition down to the onlap of the fan onto late Oligocene limestones. This sedimentary record extends existing oceanic archives of the Himalayan erosion by about 10 Ma.

Biostratigraphy

Calcareous nannofossils and foraminferal biostratigraphic analyses at Site U1451 resulted in the identification of 39 biomarkers and the construction of 31 biozones, providing a comprehensive and detailed age model for the long-term development of the middle Bengal Fan, from the Paleogene to Recent. Furthermore, the transition from probably Himalayan-derived turbiditic sediments to pelagic-dominated sedimentation has been constrained to the Late Oligocene.

The top 120 m of Hole U1451A (Lithostratigraphic Units I–III) are a sequence of turbiditic sands and muds, with minor intercalated hemipelagic layers. Six biomarkers were identified within this sequence, providing good age control for Pleistocene fan development at this site. A thick (66 m) pelagic sequence was recovered in Cores U1451A-23F to 29F (Lithostratigraphic Unit IV) and contains eight biomarkers. This sequence represents over 3 m.y. of pelagic sedimentation with little turbiditic influence. Directly below Lithostratigraphic Unit IV, 450 m of turbidite-dominated sedimentation, present from Core 30F to the base of U1451A, was deposited in approximately 3.5 m.y., based on four biomarkers observed in this sequence. The accumulation rates between ~1 and >10 cm/k.y. in the pelagic sequence and the turbidite-dominated sequence, respectively, suggest that the majority of fan development occurred in the Miocene and Pleistocene and is more restricted in the Pliocene. The FO of *Catinaster coalitus* was observed at the base of Hole U1451A (midpoint of 575.60 m CSF-A) and the top of Hole

U1451B (590.06 m CSF-A) and provides tight age control for the overlap succession of the two holes.

The Oligocene/Miocene (OM) boundary was recovered and lies between Samples U1451B-54R-CC and 55R-CC. This boundary is identified by the LO of *Reticulofenestra bisectus* and *Zygrhablithus bijugatus* (NP25). A major change from turbidite-dominated to pelagic-dominated sedimentation occurs between Cores U1451B-62R and 63R during nannofossil biozone (NP24).

Due to the intense recrystallization and preservation issues, the depositional age of the limestones are difficult to constrain. Samples 1451B-71R-CC and 1451B-72R-CC contained *Morozobella aragonensi*s, which is a marker species for foraminifer zone E9 (43.6 to 52.3 Ma). The radiolarian species *Thyrsocritic rhizodon* was observed in U1451B-69R-CC, confirming an Eocene age for these sediments.

There appears to be a significant hiatus of 16–18 Ma between Samples U1451B-71R-CC and 72R-CC. Sample U1451B-72R-1-W 0/1 contains *Discoaster multiradiatus* and *Fasciculithus* spp., which are biomarkers for nannofossil zone NP10. Sample U1451B-73R-CC represents a gap zone marked by the absence of *Discoaster multiradiatus* and places the base of Site U1451 in the Paleocene (Thanetian). Confirming the presence and extent of this hiatus will be the subject of postcruise research.

Paleomagnetics

Paleomagnetism of 269 archive section halves and 93 discrete samples from Site U1451 allowed us to identify 12 polarity reversals in Hole U1451A, mostly in calcareous clay deposits. We place the Brunhes/Matuyama boundary between 41.9 m and 79.4 m depth (CSF-A; likely between 68.31 m and 75.78 m) in Hole U1451A. A calcareous ooze deposit in Hole U1451A contains polarity zones corresponding to the Jaramillo and Cobb Mountain subchrons (80.40–81.85 m and 83.15–83.44 m CSF-A, respectively), allowing us to correlate the interval with similar lithostratigraphic units at Sites U1449 and U1450. Several reversals between 140 and 160 m CSF-A in Hole U1451A are interpreted as the Gauss and Gilbert chrons and their subchrons. Reversals at 108.10 m and 218.70 m CSF-A in Hole U1451A have not yet been linked to the geomagnetic polarity time scale. Multiple declination changes have been observed in Hole U1451B, most related to within rotation during the coring process. None have yet been identified unambiguously as polarity reversals.

Physical Properties

Physical property data were acquired at Site U1451 for all Hole U1451A and Hole U1451B cores, including density, magnetic susceptibility, *P*-wave velocity, natural gamma radiation, and thermal conductivity. The data from APC cores are mostly of good quality. However, the whole-round track data from cores obtained through RCB drilling—the majority of Hole U1451B—underestimate density, magnetic susceptibility, and natural gamma radiation because they typically do not completely fill the liner cross section and therefore underestimate in situ values.

Hole U1451A recovered core material from 0 to 579 m CSF-A and Hole U1451B cores recovered core material from 542 to 1175 m CSF-A. The total core recovery at Site U1451 was 518.66 m (51%). Physical properties at Site U1451 primarily reflect lithological variations, but also show downcore compaction and lithification documented by decreasing porosities, and increasing densities and *P*-wave velocities, specifically in the lowermost Cores U1451B-65R to 73R. Based on the principal lithological name from the core description, average physical properties were determined for ten lithologies. The most common principal lithology is calcareous ooze (~120 m), followed by clay (~96 m), sand (~84 m), and silt (~74 m). Claystone (~65 m) and limestone (~41 m) and siltstone (~21 m) make up the lower part of Hole U1451B. Volcanic ash occurs only in limited intervals (totaling 0.57 m) and siliceous ooze is absent. The physical property measurements follow the following general trends: limestones have the highest average density and *P*-wave velocity; sands have the highest magnetic susceptibility; volcanic ashes, clays, and claystones have the highest natural gamma radiation; and calcareous oozes generally have the lowest values in all of the measurements. Some of the sand-rich intervals were difficult to recover and were often fluidized, which sometimes resulted in incompletely filled core liners; this had the effect of giving anomalously low whole-round measurements (GRA density, magnetic susceptibility, and NGR values). The same is true for most of the lithified intervals drilled by RCB, where GRA values significantly underestimate MAD values.

Geochemistry

Detailed pore water measurements show that five hydrological units can be distinguished based on sulfate, phosphate, silica, magnesium, potassium, calcium, and alkalinity content. The deepest unit bears distinct characteristics due to the strong influence of the limestones. It is characterized by a strong rise in calcium content while the alkalinity remains low and constant, buffered by pressure-dissolution and recrystallization of the carbonate-rich lithology and an upward diffusion/advection of interstitial water.

Throughout Site U1451, the carbonate content of bulk sediments varies widely from 0.2 to 96.6 wt% $CaCO_3$, reflecting contrasted depositional environments including significant contributions from detrital carbonates. Turbiditic sediments have low carbonate content in the upper section (Pleistocene) with values roughly doubling around 150 m CSF-A. This sharp transition occurs during the early Pliocene and is followed by gradually increasing carbonate content until 700 m CSF-A. These trends in carbonate content of the turbiditic sediments most likely reflect a change in detrital carbonate supply, which correlates with observations at Site U1450. Turbiditic sediments are absent below 1097 m CSF-A (mid-Oligocene) and limestone—at times almost pure ($CaCO_3$ > 97 wt%)—becomes the dominant lithology. Hemipelagic clays are present throughout the entire record and are characterized by highly variable carbonate content, often indistinguishable from that of turbiditic sediments. Major and trace element concentrations (e.g. CaO and Sr) measured via hand-held XRF suggest that turbiditic and hemipelagic sediments consist of distinct binary mixings between carbonate and silicate end-members. The contrasted composition of the silicate fraction of hemipelagic clays is further supported by their frequent depletion in K and enriched Fe compared to turbiditic clays. In turbiditic sediments, the major element composition (e.g. Fe/Si and Al/Si) closely matches the chemical composition observed in sediments from the actual Ganges–Brahmaputra river system.

Overall, total organic carbon content (TOC) is low with an average value of 0.3%. Within turbidites, TOC broadly co-varies with Al/Si ratios—a proxy for sediment grain size and mineral composition—reflecting preferential association of organic matter with clays previously documented in both the modern Ganges–Brahmaputra river system, and in active channel-levee sediments in the Bay of Bengal deposited over the past 18 k.y. (e.g. Galy et al., 2007). Clay-rich turbiditic sediments are often characterized by significant organic carbon depletion compared with sediments from the modern Ganges–Brahmaputra river system and the active channel-levee system at 17°N. However, the TOC budget is likely to be also affected by the frequent presence of woody debris concentrated in the lower part of turbiditic sequences.

Microbiological subsampling of sediments and pore waters at Site U1451 included establishing a microbial cell counting method, with further processing of the samples to be performed following the expedition.

References

Galy, V., France-Lanord, C., Beyssac, O., Faure, P., Kudrass, H. and Palhol, F., 2007. Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system. Nature, 450, 407–410.

Schwenk, T., and Spiess, V. (2009). Architecture and stratigraphy of the Bengal Fan as response to tectonic and climate revealed from high-resolution seismic data. In SEPM Special Publication (Vol. 92, pp. 107–131).