IODP Expedition 353: Indian Monsoon Rainfall
Site U1443 Summary

Background and Objectives

Ninetyeast Ridge represents the trace of the Kerguelen/Ninetyeast hotspot prior to the middle Eocene rifting [Peirce, Weissel et al., 1989]. As a result of northward movement, Site U1443 moved from temperate southern latitudes during the Campanian, to ~5° south near the Oligocene/Miocene boundary and to its 5°N present location in the southernmost Bay of Bengal. The site has been within 10° of the equator for the past 35 Ma [Peirce, Weissel, et al., 1989]. The ridge-top location has prevented the deposition of sedimentary sequences typically associated with fan transport processes and is thus a useful location for recovery of open-ocean pelagic sediments.

Site U1443 is located ~100 m southeast of Ocean Drilling Program (ODP) Site 758, on the crest of the Ninetyeast Ridge and is a re-drill of ODP Site 758. Previous drilling at this site included overlapping holes (ODP 758A and 758B) only for the uppermost 92 m of the total 527 m of sediments drilled. This limited the resulting composite record to the past 7.3 Ma [Farrell and Janecek, 1991].

In spite of these limitations, the IODP sample database shows that over 16,000 sediment samples have been taken from ODP Site 758 cores in the last 10 years. Parts of the upper-most sections are almost entirely depleted and sampling has move to the archive half. Recent research using ODP Site 758 sediments include high resolution (sub-orbital) late Pleistocene reconstruction of changes in upper water-column structure based on multi-species planktonic foraminifera records [Bolton et al., 2013], reconstruction of the Li isotope composition of seawater over the past 70 Ma [Misra et al., 2012], Late Cretaceous to early Eocene reconstruction of seawater Neodymium [Le Houedec, 2011] and glacial-interglacial scale reconstruction of Os isotopic composition of seawater [Burton, 2010]. The re-drilling of ODP Site 758 had the following main objectives:

- Establish a composite section for the entire Miocene–Oligocene sedimentary succession at the Ninetyeast Ridge, which would be the base for establishing a first orbitally tuned Indian Ocean isotope stratigraphy for this time interval.

- Recover a more complete record of the Cretaceous–Paleogene boundary interval, which was only incompletely retrieved at the base of the core catcher of Core 121-758A-31X.
- Correlate the onset of increased terrigenous clay component and sedimentation rates in the late Miocene to orbitally tuned isotope and magnetic reversal stratigraphy.
- Precisely determine the timing of intensifications of the Indian monsoon, as evident from increased freshwater input to the Bay of Bengal and northern end of the Ninteyast Ridge using salinity proxies based on Mg/Ca-temperature estimates and $\delta^{18}O$ of surface dwelling planktonic foraminifers.
- Investigate variability and possible influence of orbital forcing on fluxes of terrigenous material to the northern Ninetyeast Ridge since the middle Miocene. In particular, relate terrigenous pulses at ~7.0 to 5.6 Ma and ~3.9 to 2.0 Ma, which were interpreted to represent variations in the fluvial flux resulting from the uplift and erosion of the Himalaya [Hovan & Rea, 1992], to the variability of the Indian Monsoon.
- Extend the Plio–Pleistocene stable isotope record for ODP Site 758, which is the only "high resolution" record across the initiation of the northern hemisphere glaciation in the Indian Ocean [Hoogakker et al., 2006; Mudelsee and Raymo, 2005], into the Miocene and Oligocene.
- Use the Nd isotope composition of Ninetyeast Ridge sediments to extend reconstructions of the relative contribution of discharge from the Ganges-Bramaputra, Irrawaddy and Arkan Rivers as indicators of glacial-interglacial variability in monsoon strength into the Miocene [Burton and Vance, 2000; Stoll et al., 2007; Gourlan et al., 2008, 2010]. A complete Neogene sediment archive at Site U1443 opens the possibility to obtain proxy records for river discharge in sufficient time resolution to document the relation between global climate and the Indian monsoon throughout the Neogene.

Operations

At Site U1443, Holes U1443A, U1443B, U1443C, and U1443D were drilled to total depths of 344.0, 326.4, 209.4, and 8.2 m DSF, respectively. In Holes U1443A and U1443B, the full-length (9.7 m long) APC system, the half-length (4.7 m long) APC (HLAPC) system, and the XCB systems were used. In Hole U1443C the APC and

HLAPC systems were deployed and in Hole U1443D only the HLAPC system was used. For Holes U1443A and U1443B, the APC and HLAPC systems were used to refusal. Following refusal of the APC and HLAPC systems, the XCB was deployed to total depth. A total of 118 cores were recovered for the site. A total of 444.06 m of core over a 471.7 m interval were recovered using the APC system (94% recovery). The cored interval with the HLAPC system was 156.4 m with a recovery of 161.25 m of core (103%). The cored interval with the XCB system was 258.4 m with a recovery of 220.35 m of core (85%). The overall recovery percentage for Site U1443 was 93%.

Principal Results

Lithostratigraphy

The sediments recovered from Site U1443 reveal a range of pelagic and hemipelagic sediments of Late Pleistocene to Campanian age, comprising four distinct lithologic units (I–IV). Unit I is 108 m thick and composed of Late Pleistocene–late Miocene light–dark gray nannofossil oozes with varying proportions of foraminifers, clay, and volcanic ash. Unit II is 135 m thick and composed of pale yellow to white nannofossil oozes and chalks with varying amounts of authigenic carbonate and foraminifera that are late Miocene to early Oligocene in age. Unit III is late Paleocene to late Campanian in age and comprises a 66 m thick package of pale yellow and brown nannofossil chalks with varying proportions of authigenic carbonate and occasional chert and porcellanite nodules and thin beds. Thirty-one meters of Unit IV, comprised of a succession of greenish gray marlstones with glauconite of late Campanian age, was recovered before Hole U1443A was terminated at 344 m DSF. Lithostratigraphic units are defined by changes in lithology (as identified by visual core description and smear slide observations), physical properties, and color reflectance (L*, a*, and b*). The observed lithologic differences between the units are primarily the result of varying abundances of nannofossils, clay, and authigenic carbonate, with glauconite influencing the color and magnetic susceptibility (MS) properties in Unit IV. Lithologic descriptions are based primarily on sediments recovered from Hole U1443A, supplemented with observations from Holes U1443B, U1443C, and U1443D.

Biostratigraphy

Calcareous nannofossils are abundant throughout the section in Hole U1443A, which is Late Pleistocene (<0.29 Ma) to Campanian (>72.1 Ma) in age, with a large unconformity

that spans most of the Eocene and the latest Paleocene. Nannofossil assemblages are typically tropical to subtropical and are well preserved in the Pleistocene to the upper Miocene sections (~110 m CSF-A, Lithologic Unit I). Below this interval, evidence of diagenetic overgrowth becomes apparent. SEM analyses revealed that *Emiliania huxleyi* (<0.29 Ma) is present in Intervals U1443A-1H, 0–50 cm and U1443B-1H, 0–10 cm. Cretaceous sediments contain abundant moderately to poorly preserved calcareous nannofossils. The Cretaceous–Paleocene boundary was identified in Core U1443A-39X, but is highly bioturbated and appears to be incomplete.

At Site U1443, diatoms are most abundant from 0–28 m CSF-A, while their occurrence becomes sporadic down section until 192 m CSF-A. The diatom community in the uppermost 28 m CSF-A of Site U1443 is diverse and mainly consists of Pleistocene to Holocene species, mostly typical of warm to temperate, low-latitude ocean waters and includes species indicating transport of coastal waters to Site U1443.

Planktonic foraminifers are dominant to abundant in Samples U1443A-1H-CC through 43X-CC, which are Pleistocene to Late Cretaceous in age. Abundance decreases from common to few in Samples U1443A-44X-CC through 48X-CC. Preservation is good to moderate throughout the Cenozoic with a few exceptions in the late Miocene (Sample U1443A-13H-CC) and the Oligocene to Paleocene (Samples U1443A-33X-CC and U1443A-34X-CC), where preservation is poor. Preservation in the Cretaceous (Samples U1443A-39X-CC to 48X-CC) is moderate to poor.

The age-depth relationship for Hole U1443A is based on the biostratigraphy of the three fossil groups studied (diatoms, planktonic foraminifers, and calcareous nannofossils) as well as paleomagnetic stratigraphy. Age datums of the fossil groups and paleomagnetics show good agreement for the Pleistocene. Calcareous nannofossils and planktonic foraminifers show consistent age-depth relationships throughout the Cenozoic and Late Cretaceous, with no major outliers. The combined biostratigraphic and paleomagnetic age model indicates a mean sedimentation rate of 1.20 cm/k.y. in the upper part of Lithologic Unit I (0–80 m CSF-A, Pleistocene to late Miocene). Mean sedimentation rate decreases to 0.41 cm/k.y. between 100–130 m CSF-A (the upper part of Lithologic Unit IIa, late Miocene to middle Miocene). Sedimentation rates between 135–200 m CSF-A, the lower half of Lithologic Unit IIa, average 0.81 cm/k.y. (early Miocene to Oligocene). Finally, following a hiatus that spans the latest Oligocene to late Paleocene, mean sedimentation

rate in the late Paleocene and Late Cretaceous (Lithologic Units III and IV) is 0.36 cm/k.y. These sedimentation rate and age estimates broadly agree with those published for ODP Site 758.

Geochemistry

The composition of the interstitial water (IW) and bulk sediment samples reflects the variation in sediment composition and reactions that occurred since deposition. Overall, the sediments have a high carbonate content (>80% throughout most of the section) and low total organic carbon (TOC; <0.3%). IW major and minor element concentrations vary downhole. The depositional environment changed as the site migrated from the Southern hemisphere to the current location as the collision of India with Asia delivered more and more terrigenous material to the location. In the upper sediments, ash deposition from the nearby Indonesian Arc plays an important role. In general the data from Site U1443 agrees well with that from ODP Site 758 but the new data provides a better resolution in the sections recovered by APC/HLAPC coring compared to the XCB coring at Site 758.

Paleomagnetism

Paleomagnetic measurements were conducted on all of the archive half sections and 127 discrete samples taken from Holes U1443A, U1443B, and U1443C. Some of the discrete samples were also subjected to rock magnetic analyses. Magnetic polarity patterns were recovered for most of the APC and HLAPC cores, but not for the XCB cores. The resulting magnetostratigraphy was produced for two time periods: 0–6 Ma (Holes U1443A and U1443C) and 18–25 Ma (Hole U1443A). The age-depth model from paleomagnetic measurements agrees well with the biostratigraphic ages. Between these age intervals, patterns based on pass-through magnetic measurements were inconclusive due to a decrease in NRM intensity. A lithologic change to higher carbonate and a decrease in the concentration of fine-grained ferrimagnetic minerals explains the poor signal. Preliminary rock magnetic experiments suggest changes in bulk magnetic properties are primarily controlled by variations in the concentration of fine-grained magnetite/maghemite.

Physical Properties

Physical property measurements at Site U1443 show downhole variations reflecting changes in lithology, condensed sections associated with depositional hiatuses, and

diagenetic processes. The overall suite of physical property data is divided into three broad units with two subunits occurring within Lithologic Unit II. These subunits mark important anomalous events in the depositional history of this site. The general porosity trend decreases with depth with a few excursions correlating with the three subunits. In Lithologic Unit I, high variability in magnetic susceptibility (MS), natural gamma radiation (NGR), *P*-wave velocity, and color reflectance reflect numerous ash layers intercalated within clayey, nannofossil ooze. The MS peaks are likely the result of higher iron content in the ash layers with the color reflectance data displaying changes between darker ash and lighter nannofossil ooze, and changes in the clay content of the nannofossil ooze. Unit II is defined by shift to an overall lighter color relative to Unit I, with a relatively uniform, low NGR and low *P*-wave velocity trend. The sedimentologists identified this unit to be comprised of chalk. From the physical property data, two anomalous intervals were identified within Unit II. These intervals show a marked change to increased density, *P*-wave velocity, and natural gamma radiation with no corresponding change in color reflectance. Thus, these changes in physical properties were undetectable by visual analysis of the core alone. The physical property anomalies were used to assist in directing sampling for smear slide and SEM analysis, which together provided evidence that the anomalous intervals were reflecting high authentic overgrowth and carbonate cementation correlating with strong, positive, seismic reflections and biostratigrahic defined depositional hiatuses. Lithologic Unit III data display an abrupt change to a darker color unit with higher NGR, MS, and *P*-wave values suggesting a transition to a stronger, more lithified material with an increase of magnetic minerals and clays that are likely the result of an increase in terrigenous sediments. Overall, our physical properties results were generally found to be in good agreement with the lithostratigraphy at this site.

Stratigraphic Correlation

A composite section and splice to establish a continuous sediment sequence was created using Holes U1443A, U1443B, U1443C, U1443D. Correlation and splicing was based on magnetic susceptibility (MS), natural gamma radiation (NGR), and Reflectance Spectroscopy b* data. MS data proved particularly useful for correlation in the upper ~63 m CCSF-A, due to the occurrence of several tephra layers coinciding with positive MS peaks. NGR and Reflectance Spectroscopy b* data were used throughout the rest of the records. A continuous splice was created spanning the upper 180 m, approximately

tripling the length of time over which a continuous record was achieved for Site 758. This is mostly due to the use of the HLAPC tool, which greatly extended the penetration depth of the piston-cored section.

Highlights

Plio–Pleistocene Tephrochronology

The Pliocene to Holocene tephra layers of the northern Ninetyeast Ridge provide a unique record of explosive volcanism derived from the Indonesian island of Sumatra, the northernmost part of the Sunda Arc and the nearest volcanically active region (Dehn et al., 1991). Recovery of a complete succession of tephra layers within a complete splice with a high-resolution orbitally tuned isotope stratigraphy and the possibility of correlation of individual tephra layers between three holes make Site U1443 a unique observatory of volcanic activity in this region over the last 5 m.y. The volcanic tephra layers form excellent tools for lithostratigraphic correlation of the marine sediment successions within the five different holes on the northern Ninetyeast Ridge. Detailed studies of the tephra layers will contribute to the understanding of the magmatic evolution in the source region and allow determination and precise dating of eruptive cycles. In particular the eruption history of the Toba caldera in northern Sumatra is well documented on the northern Ninetyeast Ridge (Ninkovich et al., 1978; Ninkovich, 1979; Dehn et al., 1991) and individual tephra layers at Site U1443 can be tentatively correlated to the main eruptions of the Toba caldera complex at 75, ~450, ~840, and ~1200 ka (Chesner and Rose, 1991; Dehn et al., 1991; Farrell & Janecek, 1991). The possibility of $^{40}Ar/^{39}Ar$ dating of these ash layers and correlation to a robust paleomagnetic reversal scheme in Site U1443 in combination with high resolution stable isotope records will further contribute to intercalibrate the Plio–Pleistocene geomagnetic reversal and $\delta^{18}O$ chronostratigraphy (Hall & Farrell, 1993, 1995).

Transitional Cretaceous–Paleocene Boundary

The sedimentary record of the Cretaceous–Paleogene (K/Pg) boundary transition was difficult to assess in ODP Site 758. In Hole 758A, it occurs at the base of the core catcher of Core 758A-31X (295.6 mbsf) and may be incomplete due to the coring gap between Cores 758A-31X and 32X. At Site U1443, the K/Pg transition was recovered in a complete sedimentary sequence between Samples U1443A-39X-4, 40 cm and U1443A-39X-5, 60 cm. The sediments in this interval are heavily bioturbated (containing burrows,

blebs, patches, color banding, and mottles) and most samples studied within this interval contain a mixture of Cretaceous and Paleocene nannoplankton species. In particular, *Zoophycos* spreite-burrows are common in the K/Pg boundary succession and are a prominent feature in upper Maastrichtian sediments of Holes U1443A and U1443B.

First complete spliced record of Neogene deepwater sediments in the Indian Ocean
The continuous pelagic sediment record of Site U1443 with well-preserved benthic and planktonic foraminifers will allow for the extension of existing Plio–Pleistocene isotope records from ODP Site 758 to the base of the Neogene and the tracking of deepwater and surface water isotopic signals in the eastern equatorial Indian Ocean over the last 25 million years. Sedimentation rates of >0.41 cm/k.y. will still allow for analyses of stable isotopes and geochemical records in a resolution sufficient to resolve orbital-scale climate variability and to correlate these records to existing in Atlantic and Pacific orbitally tuned isotope curves.

Late Oligocene to middle Miocene paleomagnetic record
The high quality paleomagnetic record of Site 758 was limited to the uppermost 100 m, which were retrieved by APC coring. Below this level, biscuiting of the cored sediment by the XCB coring prohibited high quality magnetic measurements. At Site U1443, APC/HLAPC coring extended to over 200 m CSF-A, which opened up a new window for obtaining paleomagnetic records for the lower part of the Miocene and upper Oligocene. In particular the record at Site U1443 between 130–200 m CSF-A is characterized by high quality paleomagnetic data that allow the establishment of a complete paleomagnetic reversal scale that covers the entire lower Miocene and upper Oligocene, including the Oligocene–Miocene stage boundary.

Recovery of expanded Campanian-Maastrichtian sediment succession
The Campanian to Maastrichtian part of the succession at Site U1443 is characterized by moderate to high recovery of indurated yellowish brown nannoplankton chalk, which grades downcore into greenish, glauconite-rich chalk with intervals of abundant *Inoceramus* shell fragments. The lower part of this interval includes several centimeter-thick indurated chert nodules and nodular layers, which caused significant decrease in drilling progress and recovery in the lowermost two cores of Hole 1443A (Cores U1443A-47X and 48X). The recovery of Upper Cretaceous sediments above these Campanian siliceous layers was good in both Holes U1443A and U1443B resulting in a

complete stratigraphic record of this interval, which was characterized by only fragments recovered in ODP Site 758. The low degree of diagenesis and the complete recovery may allow the construction of a spliced bulk carbonate carbon isotope record that covers the entire Maastrichtian to middle/late Campanian including the Campanian–Maastrichtian boundary.

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