Understanding Himalayan Erosion and the Significance of the Nicobar Fan

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Highlights:

- Sediment accumulation rates in Nicobar Fan abruptly increase 9.5 Ma
- Increased sediment flux to eastern Indian Ocean and restructuring of sediment routing
- Nicobar Fan holds significant record of Indian Ocean sedimentation in late Neogene
- Shillong Plateau and Indo-Burmese wedge uplift drive sediment south in late Miocene

Abstract

A holistic view of the Bengal-Nicobar Fan system requires sampling the full sedimentary section of the Nicobar Fan, which was achieved for the first time by International Ocean Discovery Program (IODP) Expedition 362 west of North Sumatra. We identified a distinct rise in sediment accumulation rate (SAR) beginning ~9.5 Ma and reaching 250-350 m/Myr in the 9.5-2 Ma interval, which equal or far exceed rates on the Bengal Fan at similar latitudes. This marked rise in SAR and a constant Himalayan-derived provenance necessitates a major restructuring of sediment routing in the Bengal-Nicobar submarine fan. This coincides with the inversion of the Eastern Himalayan Shillong Plateau and encroachment of the west-propagating Indo-Burmese wedge, which reduced continental accommodation space and increased sediment supply directly to the fan. Our results challenge a commonly held view that changes in sediment flux seen in the Bengal-Nicobar submarine fan were caused by discrete tectonic or climatic events acting on the Himalayan-Tibetan Plateau. Instead, an interplay of tectonic and climatic processes caused the fan system to develop by punctuated changes rather than gradual progradation.

Key Words: Bengal-Nicobar Fan, submarine fan, Himalayan tectonics, Asian monsoon, Indian Ocean

1. Introduction

The Bengal-Nicobar Fan, Indian Ocean (Fig. 1), has the greatest area and length of any submarine fan, and has long been studied to investigate possible links between Himalayan tectonics and the Asian monsoon (e.g., An et al., 2001; Bowles et al., 1978; Clift et al., 2008; Curray, 2014; Curray and Moore, 1974; Curray et al., 1982; France-Lanord et al., 2016; Schwenk and Spiess, 2009). To date, a holistic synthesis of the Indian Ocean fan system history and related processes of tectonics, climate and erosion has been hampered by a lack of data from the Nicobar Fan. The importance of sampling widely across a sedimentary system to avoid biases due to major temporal changes in channel and lobe activity was noted (Stow et al., 1990), and highlighted that the under-sampled Nicobar Fan may hold a key component of the eastern Indian Ocean sedimentation record.

International Ocean Discovery Program (IODP) Expedition 362 sampled and logged the Nicobar Fan offshore North Sumatra in 2016 (Fig. 1). The stratigraphic results from this expedition (Dugan et al., 2017) are integrated here with results from previous sites on the Bengal-Nicobar Fan and Ninetyeast Ridge (NER) of the Deep Sea Drilling Program (DSDP Leg 22, von der Borch, et al., 1974), Ocean Drilling Program (ODP Leg 116, Cochran et al., 1989; Leg 121, Peirce et al., 1989) and IODP (Expedition 353, Clemens et al., 2016; Expedition 354, France-Lanord et al., 2016). We present the first stratigraphic data from the Nicobar Fan and reappraise published chronostratigraphic data from Bengal Fan and NER drillsites into a unified modern timescale to facilitate accurate comparison of depositional records across the whole system. Comparing sediment accumulation rates (SARs) between these sites gives a new and integrative understanding of the timing of fan growth and distribution of fan deposits.

2. Nicobar Fan stratigraphy and sediment source

Expedition 362 drilled two sites on the northern Nicobar Fan east of the NER (Fig. 1), sampling the complete sedimentary section at Site U1480 to a basement depth of 1415 meters below seafloor (mbsf), and from 1150 mbsf to within 10's m of basement at Site U1481 at 1500 mbsf. At both sites

Units I and II represent the Nicobar Fan, with Units III-V representing intervals dominated by pelagic sedimentation with significantly reduced SARs (Fig. 1).

Bengal Fan sediments are predominantly micaceous quartzo-feldspathic sands of the Ganges and Brahmaputra that drain the Himalaya and southern Tibet plus contributions from the Meghna river that drains northeastern India and Bangladesh (France-Lanord et al., 2016). Despite proximity to the Sunda forearc, the Nicobar Fan sediments at Sites U1480 and U1481 (Fig. S1) contain a similar range of siliciclastic sediment gravity-flow (SGF) deposits (mostly turbidites) as Bengal Fan sites. The sand- and silt-size grain assemblage in the Nicobar Fan is relatively uniform downhole as quartzo-feldspathic (arkosic) sands, with pelitic metamorphic lithic grains, mica, minor detrital carbonate (<5%), minor woody debris, and an abundant and diverse assemblage of mostly high-grade metamorphic heavy minerals (including kyanite and sillimanite). Candidate sources for the Nicobar Fan include the Himalayan-derived Ganges-Brahmaputra, Indo-Burman Ranges/West Burma, Sunda forearc and arc, and NER. Detrital zircon age spectra of samples from the Nicobar Fan sand-silt SGF deposits are dominantly sourced from the Greater and Tethyan Himalaya mixed with sediment from the Burmese arc-derived Paleogene Indo-Burman Ranges, similar to the provenance of Neogene sands deposited in the eastern Bengal and Surma basins (Najman et al., 2008, 2012) (Figs. 1-3). The limited arc-derived ash content in sediments at Sites U1480-1481 suggests that the Sunda forearc makes only a minor contribution. Significant input from the Irrawaddy drainage is unlikely as it would require transfer of material across the forearc and possibly the trench. Cenozoic sediment isopachs of the Martaban back arc basin, the main north–south-oriented depocentre in the Andaman Sea related to the development of the Thanlwin-Irrawaddy delta system, show no obvious evidence for major routing to the west where carbonate-capped volcanic highs (e.g. Yadana High) served as a barrier for most of the Neogene (Racey and Ridd, 2015). Nevertheless we consider Irrawaddy sources in our provenance interpretations.

3. Bengal-Nicobar Fan Sediment Accumulation Patterns

Age-depth distributions of calcareous nannofossils, planktonic foraminifers, diatoms, silicoflagellates, and radiolarians were used to create tie points for SARs for Expedition 362 sites (Dugan et al., 2017) (Fig. 4A; Supplementary Material). Also, published latest Eocene-Recent biomagnetostratigraphic data from six representative DSDP, ODP and IODP Bengal Fan and NER sites were reassessed and placed on a common time scale (Hilgen et al., 2012; Pälike et al., 2006) (Fig. 4; Supplementary Material). The reassessment of previous biostratigraphic data and the choice of age model tie points considered recent developments in understanding the consistency and reliability of biohorizons in lower latitude environments. At all sites, the age-depth relationship is non-linear. At Sites U1480 and U1481 on the Nicobar Fan, the SAR increases dramatically at 9.5-9 Ma, from <15 m/Myr to >200 m/Myr, which corresponds to the onset of significant fan deposition at the Unit III-II boundary. Specifically, at Site U1480 rates increase from 2-15 to 223 m/Myr, and at Site U1481 from 11-27 to 207 m/Myr (Figs. 4, S2). At Site U1480, high rates persist and in the earliest Pleistocene (~2-2.5 Ma), they increase further to 360 m/Myr (Fig. S2). In the Bengal Fan, such high rates, of the order of 250-300 m/Myr or greater, are only found within the more proximal fan (e.g., Weber et al., 1997, although greater spatial and temporal variability in rates might be expected here due to high impact of sea level fluctuation coupled with shifting channel/levée systems) or in the latest Pleistocene (e.g., Expedition 354 results of France-Lanord et al., 2016). These results emphasize the significance of the Nicobar Fan within the wider Bengal-Nicobar Fan system from the late Miocene to early Pleistocene (~9-2 Ma).

The NER (separating the Bengal and Nicobar fans) is thought to capture an elevated expression of fan deposition despite its predominantly pelagic composition (Peirce et al., 1989), due to increased flow lofting (cf., Stow et al., 1990) and nepheloid layer flux. Remarkably, at all northern NER sites (216, 217 and 758/1443; Fig. 2B) SARs increase by a factor of 2-3 at ~10-8 Ma, coeval with the Nicobar Fan site increases. Decreasing carbonate content values at Sites 217, 758, 1443, support that the increase in SAR resulted from the effect of increased input of clay.

When SARs increase on the Nicobar Fan and NER (at 2-9°N), rates on the Bengal Fan at related mid-fan positions (Fig. 4A) show either a marked decrease (e.g., Site 718, at 1°S) or minimal change (e.g., Site 1451, at 8°N), and all rates are lower than on the Nicobar Fan immediately after 9-9.5 Ma. At Site 718, rates decrease from 275 to 12-13 m/Myr at 9.5 Ma and only exceed 100 m/Myr in the late Pleistocene (Fig. S2). At Site 1451, rates from 9.5 Ma do not exceed 150 m/Myr (range: 70-150 m/Myr; Fig. S4). Local variations in deposition between Leg 116 sites (717, 718, 719) can be explained by late Miocene folding on the Indian plate controlling accommodation and potential submarine-channel routing (Stow et al., 1990).

Depositional history at a single site is inevitably affected by individual channel and lobe positions and there will be variability across the fan in terms of sediment accumulation due to depositional environment, e.g., channel-axis, channel-margin, levee-overbank, lobe and lobe fringe etc. (e.g., Stow et al., 1990; Schwenk and Spiess, 2009). However, on the Nicobar Fan seismic horizons and packages can be traced over large distances with confidence in unit correlation and with minimal evidence of unit thickness variation across and along the oceanic plate. No onlap in the vicinity of the drillsites is observed, and channel-levée complexes that might correlate with enhanced deposition are evenly distributed spatially and temporally (Dugan et al., 2017). In addition, our analysis of data from other Expedition 354 Bengal Fan transect sites where SARs may be greater than at Site U1451 (e.g., U1450, France-Lanord et al., 2016) continues to support that during the late Miocene and Pliocene, Nicobar Fan rates either exceeded or were broadly comparable with those on the Bengal Fan. This interpretation is further supported because the Expedition 354 sites on the Bengal Fan are located 5°N of the Expedition 362 sites on the Nicobar Fan (and therefore probably in a more proximal position).

Preliminary benthic foraminiferal data from the Site U1480 pre-fan and lowermost Nicobar Fan deposits indicate that this part of the Indian plate was at upper abyssal depths (2500-3000 m; Supplementary Material), not isolated at a higher elevation which could delay arrival of fan sediments. Combining these facts, we have confidence that the drillsite stratigraphic record is representative of the wider Nicobar Fan.

Compilation of age-depth plots and SARs from across the fan system enables us to examine earlier sedimentation patterns. These indicate that by at least 15 Ma, SARs on the Bengal Fan were high with sediment directed west of the NER (Fig. 5C). The oldest recovered sediments in the central part of the Bengal Fan are Oligocene (25-28 Ma) thin-bedded silts, and the first significant sands are late Miocene, although this may be related to changes in coring technique and recovery (9-10 Ma: Site U1451, France-Lanord et al., 2016). At other Expedition 354 sites, the apparent earliest onset of substantial sand was <8 Ma (Sites U1450 and U1455), although we note that low recovery in parts of the deeper section at these sites may allow for the presence of additional earlier thick sand layers. In the distal Bengal Fan (Leg 116 Sites 717–719), early Miocene (back to 17 Ma) silts came from the Himalaya and minor components from the Indian subcontinent (Cochran et al., 1989; Bouqillon et al., 1990; Copeland et al., 1990). At Nicobar Fan Site U1481, a 20-m interval within the period 19-9 Ma (sample 362-9 in Figs. 2&3) includes minor very fine-grained sandstones and siltstones, with the same zircon assemblage as other Expedition 362 sand/silt samples (Fig. 2), supporting an eastern Himalayan source. These predate the dramatic increase in sediment flux to the Nicobar Fan sites.

In summary, although the Bengal-Nicobar Fan was clearly developing prior to the late Miocene, the SARs at a range of sites support a marked increase in sediment flux at around 9.5 Ma, in particular to the eastern part of the system, the Nicobar Fan (Fig. 5B; an idea postulated by Bowels et al. (1978), confirmed here with detailed and integrated drilling and seismic data). A major conclusion from our appraisal of SARs is that when high SARs are recorded on the Bengal Fan, they are significantly lower on the Nicobar Fan, and that between ~9.5–2 Ma this switches abruptly (Fig. 3), with highest sediment flux deflected to the east.

4. Nicobar Fan volumetrics and late Miocene-Recent growth of the Sunda forearc

Using sediment thickness from seismic profiles and ocean drilling boreholes, we have made a new estimate of the late Miocene-Recent Nicobar Fan volume, incorporating the component of fan now accreted into the Sunda subduction margin (see Supplementary Material). Estimates of the present day Nicobar Fan volume are ~$0.5x10^6$ km^3 (Figs. 1, S4; Supplementary Material), without decompaction. An additional $0.4x10^6$ km^3 is estimated to have been added to the accretionary prism between the Nicobar Islands and Southern Sumatra, using present day sediment thicknesses and plate convergence rates back to 9 Ma (Fig. S5). This generates a minimum late Miocene-Recent (i.e. from ~9.5 Ma to present) Nicobar Fan volume of ~$1x10^6$ km^3. This volume is significant compared with the estimated Bengal Fan volume of $7.2x10^6$ km^3 for the entire Neogene, a period of ~20 Myr (Clift, 2002).

The increase in thickness of the Indian plate sediment section at ~9.5 Ma would have corresponded to a marked and abrupt change in sediment volume input to the north Sunda margin. Offshore North Sumatra and the Nicobar Islands, the forearc prism is markedly wide (150-180 km) and thick relative to the rest of the margin and to other accretionary prisms (McNeill and Henstock, 2014), and the northern Sumatran prism forms an unusual plateau inferred to be a consequence of internal and basal material properties and/or prism growth history (e.g., Fisher et al., 2007). The large additional sediment input volume from 9.5 Ma to present in the easternmost Indian Ocean is a significant proportion of the prism volume and can explain the anomalously large northern Sunda prism (supporting hypotheses by Hamilton, 1973; Karig et al., 1979).

5. Discussion

Our new integrated Nicobar-Bengal Fan sediment records show a net increase in flux to the eastern Indian Ocean at 9.5-9 Ma, representing the onset of a new sedimentary regime in the east Indian Ocean. Detrital zircon ages (Fig. 2) and petrology from the Nicobar Fan sediments show the sand provenance remained unchanged throughout the middle Miocene to present. To constrain sources we compared these results with detrital zircon ages from potential source regions in the Himalayas as well as the Burmese arc and Irrawady drainage due to the presence of Cenozoic age zircons (mainly between 60-20 Ma). Comparison of the zircon age distributions (Fig. 3) show SGF deposits exposed on the Andaman-Nicobar Islands are closely similar to Nicobar Fan sediments and that both have affinities with Himalayan-derived units, the Trans-Himalaya and arc-derived input from erosion of the Indo-Burman Ranges that were expanding westwards during the Pliocene. These are the same sources as Neogene sands deposited in the northeast Bengal and Surma basins via the paleo-Brahmaputra River (Najman et al., 2012) (Fig. 1). Between 15-9 Ma the northeast Bengal Basin underwent inversion related to tectonic shortening and exhumation of the Shillong Basin Plateau which accommodates up to 1/3 of the present-day convergence across the Eastern Himalaya (Bilham and England, 2001; Biswas et al., 2007; Clark and Bilham, 2008) (Fig. 1). Exhumation and erosion of the Himalayan-derived Surma Group atop the Shillong Plateau began at this time followed by the main phase of surface uplift < 3.5 Ma (Najman et al., 2016) - these timings provide an excellent fit with the high SARs on the Nicobar Fan (from 9.5, and 2.5-2 Ma). We propose that this inversion of the Shillong region and westward migration of the Indo-Burmese wedge reduced accommodation and diverted sediments south to the shelf and Nicobar Fan. The most significant sediment pulse to the Nicobar Fan, at 2.5-2 Ma, may also record erosion of the exhumed eastern Himalayan syntaxis and resulting erosion, with at least 12 km of material since 3 Ma - a signal recorded in the Surma Basin from the latest Pliocene (Bracciali et al., 2016) but not previously identified in the Indian Ocean. From ~2 Ma, a SAR reduction on the Nicobar Fan supports the hypothesis that impingement of the NER on the Sunda Trench diverted the primary flux west of the ridge with concomitant high mid-late Pleistocene SARs on the Bengal Fan (e.g., France-Lanord et al., 2016) (Fig. 5A), although westward re-routing of the Brahmaputra River may also have played a role (Najman et al., 2016).

The Nicobar Fan is volumetrically significant within the Bengal-Nicobar Fan system, and at certain times during the late Miocene-early Pleistocene, such as the near 400 m/Myr SARs of the earliest Pleistocene, it may have been a dominant sediment sink. Since 10 Ma, sea level has generally fallen (Miller et al., 2005), decreasing accommodation on the shelf, thus amplifying the processes driving sediment southward to the fan. Erosion was probably aided by South Asian monsoon strengthening in the mid to late Miocene (e.g., An et al., 2001; Betzler et al., 2016; Kroon et al., 1991; Peterson and Backman, 1990; Prell and Kutzbach, 1992) combined with the orographic forcing that caused the locus of monsoon precipitation to shift south onto the newly uplifted Shillong Plateau (Biswas et al., 2007). Enhanced erosion rates (Duvall et al., 2012) and/or uplift in the eastern Tibetan plateau (e.g., An et al., 2001) in the late Miocene would also contribute to the volume of sediment available.

Avulsion of large-scale channel-levée complexes is common to many submarine fans (e.g., Amazon Fan; Flood et al., 1991). We propose that the eastward deflection of sediment towards the Nicobar Fan at 9.5 Ma was the result of channel avulsion in response to increased sediment flux. Consequently, the proportion of sediment routed from the northeastern Bengal Basin to the Bengal Fan was significantly reduced. Any differential seafloor topography on the shelf and the subsiding NER could have assisted this eastward diversion process. Similar processes have been observed in physical flume experiments, for example, lobe switching observed with change in sedimentation supply/rate, accommodation, and depositional slope (Fernandez et al., 2014; Parsons et al., 2002).

An early, lower-volume phase of fan deposition is recorded in the accreted sediments of the Sunda forearc (to ~40-50 Ma; Curray and Moore, 1974; Curray et al., 1979; Karig et al., 1980). A model of trench-axial supply, with sediment now almost entirely accreted, can explain this earlier phase (nascent Nicobar Fan), with trench overspill delivering minor sands/silts recorded at Site U1481 by the middle Miocene.

An accurate history of siliciclastic deposition on the Bengal-Nicobar Fan system necessitates knowledge of both fans. Using estimates of fan volume, we demonstrate that the Nicobar Fan is significant within the overall sediment budget of the Bengal-Nicobar Fan, particularly from 9.5-2 Ma. An interplay of tectonic, climatic and sedimentological processes, rather than a discrete tectonic or climatic event or mechanism such as monsoon onset, as often invoked (e.g., Betzler et al., 2016; Clift et al., 2008), moved sediment through a series of staging areas and controlled SARs in the various sediment sinks of the Indo-Asian system. Our reappraisal of integrated drilled fan data is inconsistent with the long-held notion of gradual fan progradation (Curray et al., 2003) but rather suggests a more dynamic system of punctuated and abrupt changes (Fig. 5D). Our work highlights the importance of sediment routing from the uplifting Eastern Himalaya along the eastern Indian Ocean to the Nicobar Fan during the late Neogene, a region whose role has been significantly underappreciated.

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Figure Captions

Figure 1. Regional map of study area. Map includes Bengal-Nicobar Fan system, river systems, eastern Himalayan provinces, and relevant DSDP/ODP/IODP sites. BB= Bengal Basin; SP=Shillong Plateau; SB=Surma Basin; IBR=Indo-Burman Ranges. Inset summarizes Site U1480 lithostratigraphy.

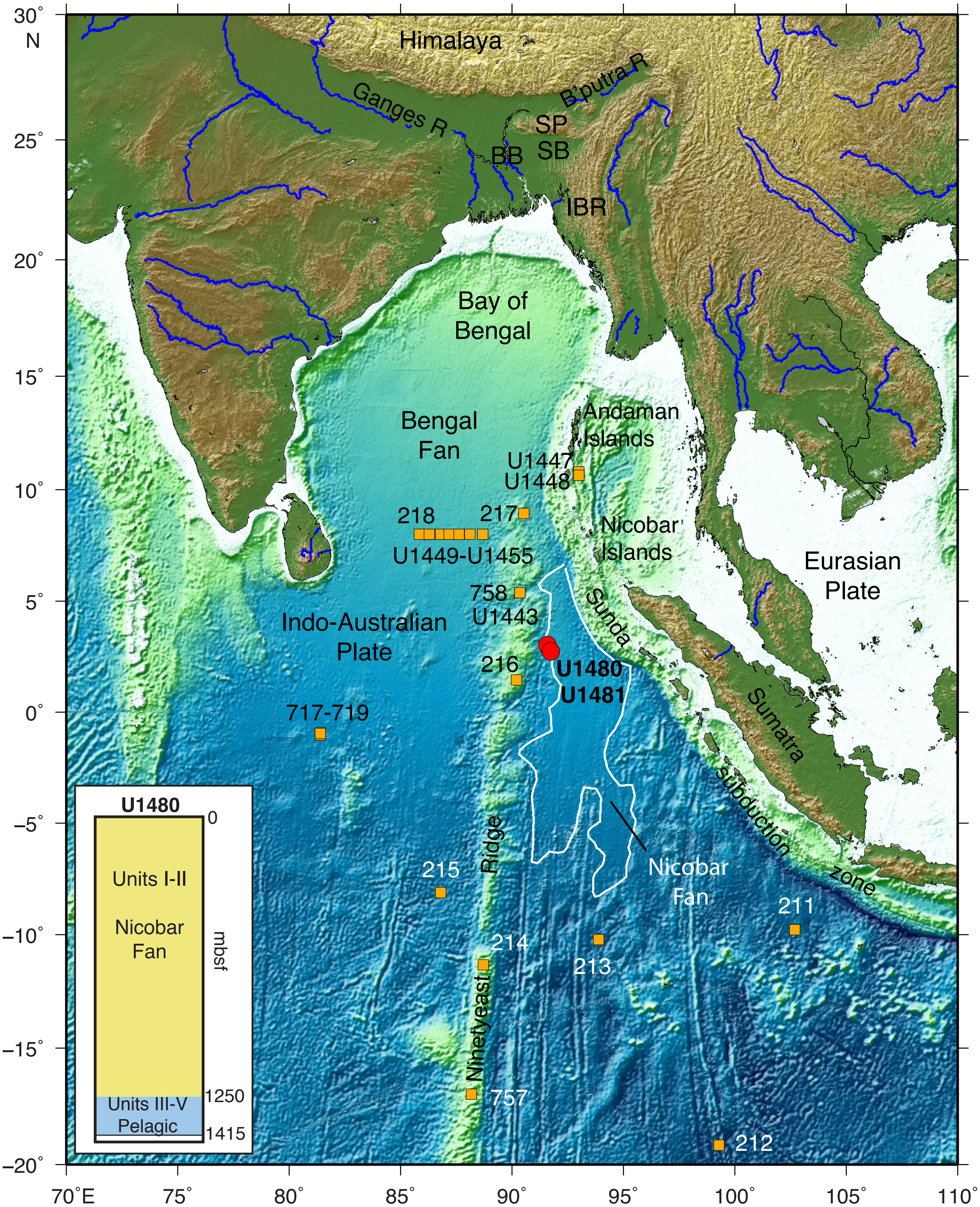
Figure 2. Detrital zircon age plots for samples and equivalent plots of regional rivers and formations. TH= Tethyan Himalaya; GHS=Greater Himalaya Series; LHS=Lesser Himalaya Series. Details of Expedition 362 samples are given in Table S1.

Figure 3. Detrital zircon age comparison plots of samples from this study and regional rivers and formations. Multidimensional scaling maps (Vermeesch, 2013) based on calculated K–S distances between U–Pb age spectra, comparing Nicobar Fan sand samples from this study with possible

source areas compiled from the literature (Allen et al., 2008; Bracciali et al., 2015; 2016; Campbell et al., 2005; Gehrels et al., 2011; Limonta et al., 2017; Najman et al., 2008). The maps show 362 samples share the same sources as the SGF deposits exposed on the Andaman-Nicobar Islands and Neogene sediments deposited in northeast Bengal that were originally sourced from erosion of the Indo-Burma Ranges. The IODP sands are not directly comparable to sands from the modern Brahmaputra or Irrawaddy. See Figure 2 for acronyms.

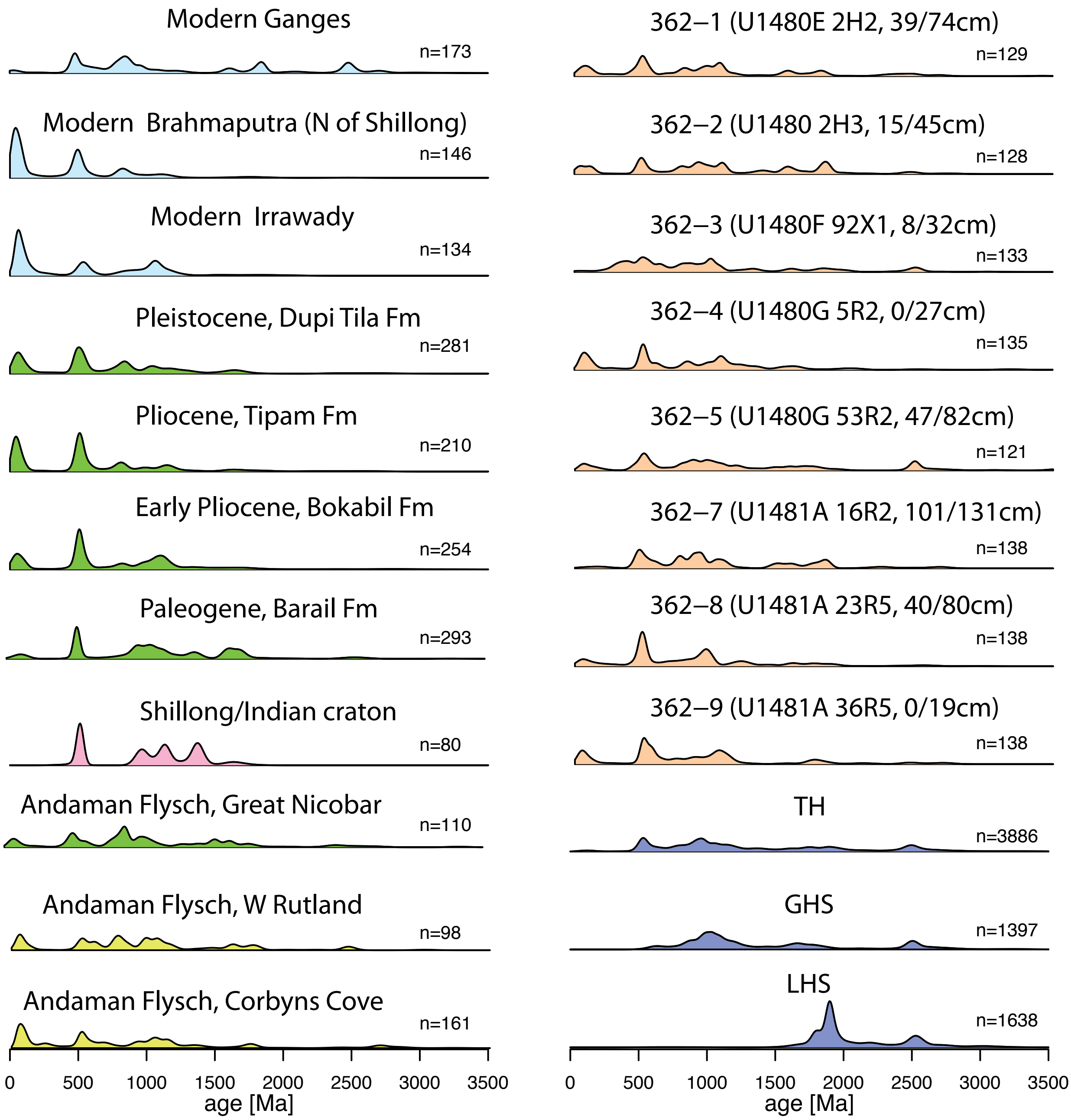
Figure 4. Age-depth relationships at ocean drilling sites. Panel (A) shows tie points of biomagnetostratigraphic age-depth relationships for Bengal Fan sites (718C, U1451) and Nicobar Fan sites (U1480, U1481). Panel (B) shows biomagnetostratigraphic tie points of age-depth relationships for sites from the Ninetyeast Ridge crest (216, 217, 758A, 1443A). Inset shows sediment accumulation rate (SAR) increase between 9 and 10 Ma. Data are presented in detail in Figures S2 and S3, and Tables S2 and S3.

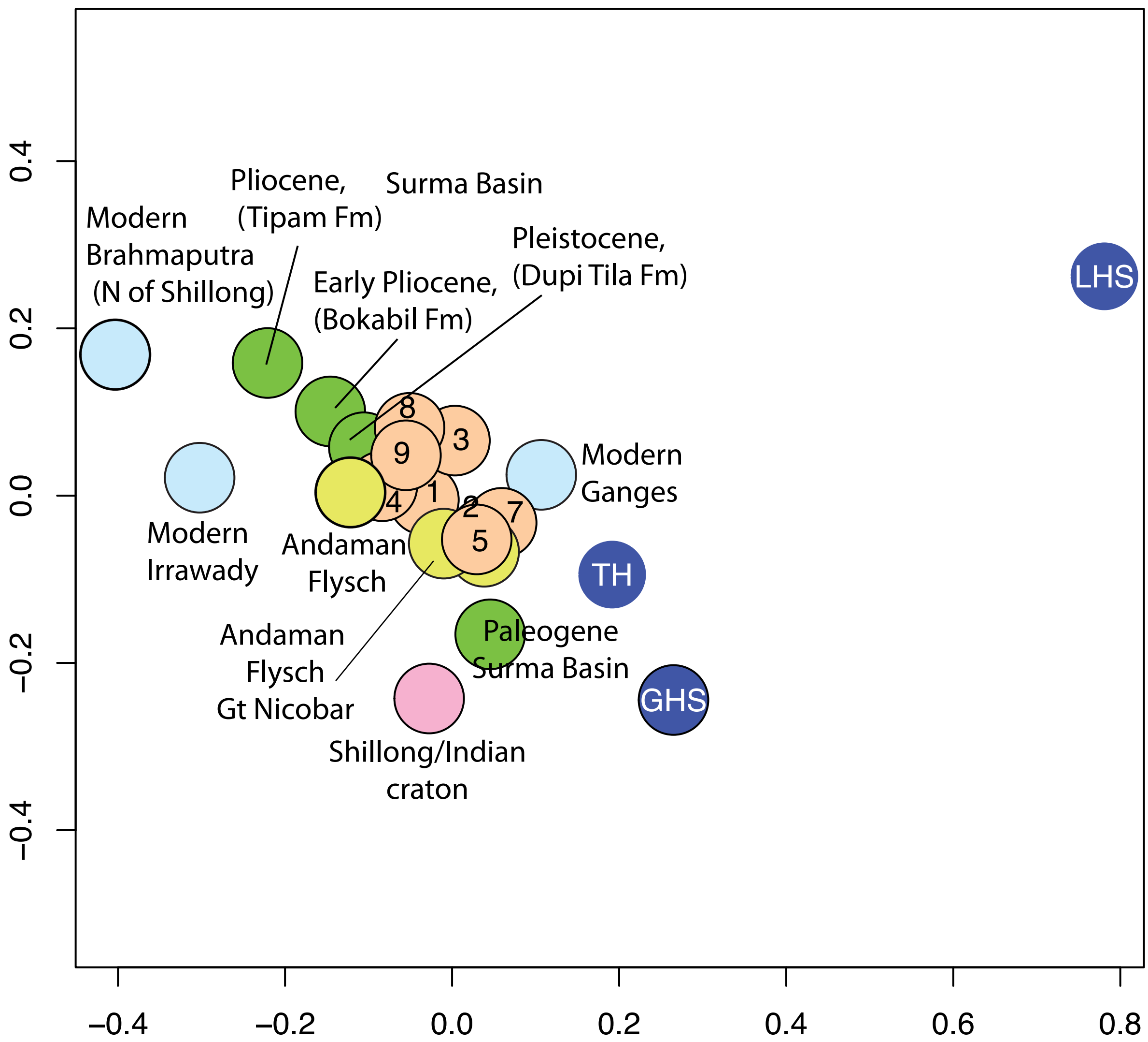
Figure 5. Conceptual model of Bengal-Nicobar Fan system history (tectonics from Hall (2012); fan morphology from Bowles et al. (1978) and Curray (2014); fan data from DSDP/ODP/IODP sites (white dots; red dots=Expedition 362 sites). A) Late Pleistocene to Recent, sedimentation primarily on Bengal Fan, B) late Miocene-Pliocene, Nicobar Fan dominates, C) pre-late Miocene, Bengal Fan dominates, minor trench-axial supply to Sunda margin/Nicobar Fan. D) Pattern of sedimentation along the Bengal Fan system from proximal (left) to distal (right) indicating absence of simple fan progradational pattern (updated from Curray et al., 2003). Data sources: Indo-Burman Ranges and Andaman-Nicobar forearc data (Bandopadhyay and Ghosh, 2015; Curray et al., 2003 and references therein); ocean drilling site data (Cochran et al., 1989, 1990; France-Lanord et al., 2016; von der Borch et al., 1974; this study). All sites converted to modern timescale (Supplementary Material). Note that 9.5-18 Ma silts for Nicobar Fan sites are only present at Site U1481.

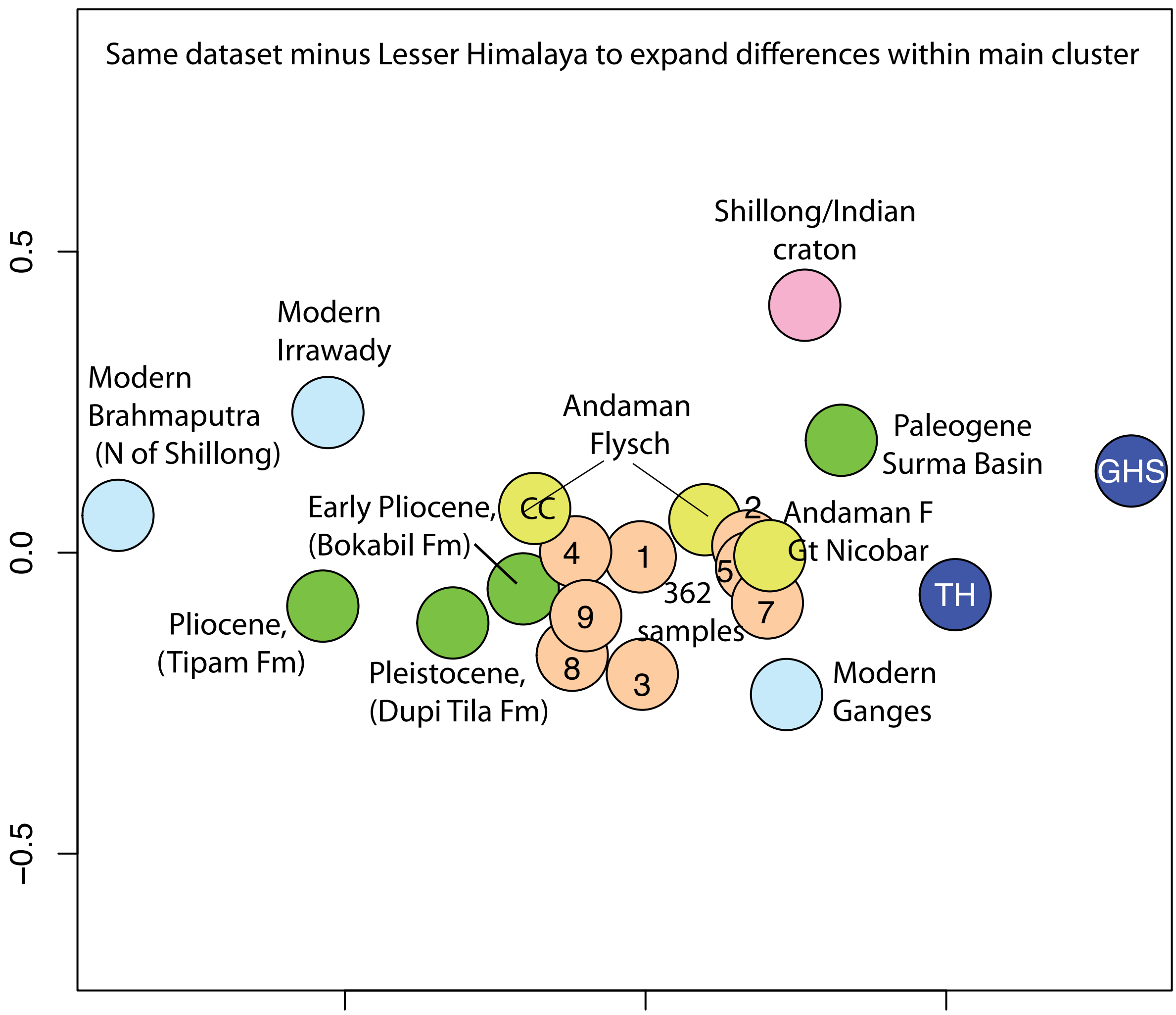


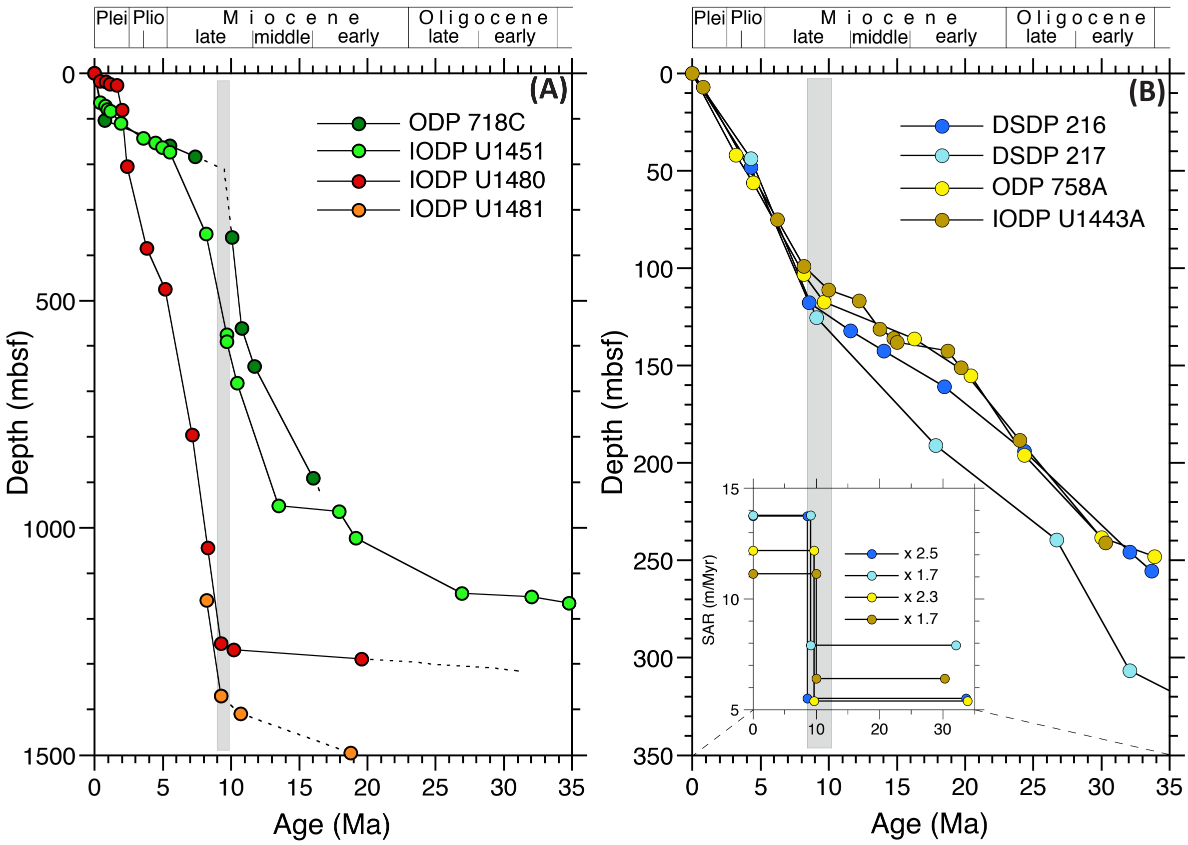
Himalaya
Ganges R
B'putra R
SP
SB
BB
IBR
Bay of Bengal
Bengal Fan
Andaman Islands
U1447
U1448
218
217
U1449-U1455
Nicobar Islands
Eurasian Plate
758
U1443
Sunda
Indo-Australian Plate
216
U1480
U1481
Sumatra
717-719
subduction
zone
Nicobar Fan
215
Ridge
211
214
213
Ninetyeast
757
212
U1480
0
Units I-II
Nicobar Fan
mbsf
1250
Units III-V
Pelagic
1415
30° N
25°
20°
15°
10°
5°
0°
−5°
−10°
−15°
−20°
70°E
75°
80°
85°
90°
95°
100°
105°
110°

Figure 1.


Modern Ganges
n=173
Modern Brahmaputra (N of Shillong)
n=146
Modern Irrawady
n=134
Pleistocene, Dupi Tila Fm
n=281
Pliocene, Tipam Fm
n=210
Early Pliocene, Bokabil Fm
n=254
Paleogene, Barail Fm
n=293
Shillong/Indian craton
n=80
Andaman Flysch, Great Nicobar
n=110
Andaman Flysch, W Rutland
n=98
Andaman Flysch, Corbyns Cove
n=161
0 500 1000 1500 2000 2500 3000 3500
age [Ma]
362–1 (U1480E 2H2, 39/74cm)
n=129
362–2 (U1480 2H3, 15/45cm)
n=128
362–3 (U1480F 92X1, 8/32cm)
n=133
362–4 (U1480G 5R2, 0/27cm)
n=135
362–5 (U1480G 53R2, 47/82cm)
n=121
362–7 (U1481A 16R2, 101/131cm)
n=138
362–8 (U1481A 23R5, 40/80cm)
n=138
362–9 (U1481A 36R5, 0/19cm)
n=138
TH
n=3886
GHS
n=1397
LHS
n=1638
0 500 1000 1500 2000 2500 3000 3500
age [Ma]


0.4
0.2
0.0
−0.2
−0.4
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
Modern
Brahmaputra
(N of Shillong)
Pliocene,
(Tipam Fm)
Surma Basin
Pleistocene,
(Dupi Tila Fm)
Early Pliocene,
(Bokabil Fm)
LHS
Modern
Ganges
Modern
Irrawady
Andaman
Flysch
TH
Andaman
Flysch
Gt Nicobar
Paleogene
Surma Basin
GHS
Shillong/Indian
craton


Same dataset minus Lesser Himalaya to expand differences within main cluster
0.5
0.0
−0.5
Shillong/Indian
craton
Modern
Irrawady
Modern
Brahmaputra
(N of Shillong)
Andaman
Flysch
Paleogene
Surma Basin
GHS
Early Pliocene,
(Bokabil Fm)
CC
Andaman F
Gt Nicobar
TH
362
samples
Pliocene,
(Tipam Fm)
Pleistocene,
(Dupi Tila Fm)
Modern
Ganges



Plei
Plio
M i o c e n e
late
middle
early
O l i g o c e n e
late
early
(A)
ODP 718C
IODP U1451
IODP U1480
IODP U1481
Depth (mbsf)
Age (Ma)
(B)
DSDP 216
DSDP 217
ODP 758A
IODP U1443A
SAR (m/Myr)
x 2.5
x 1.7
x 2.3
x 1.7

Figure 4.

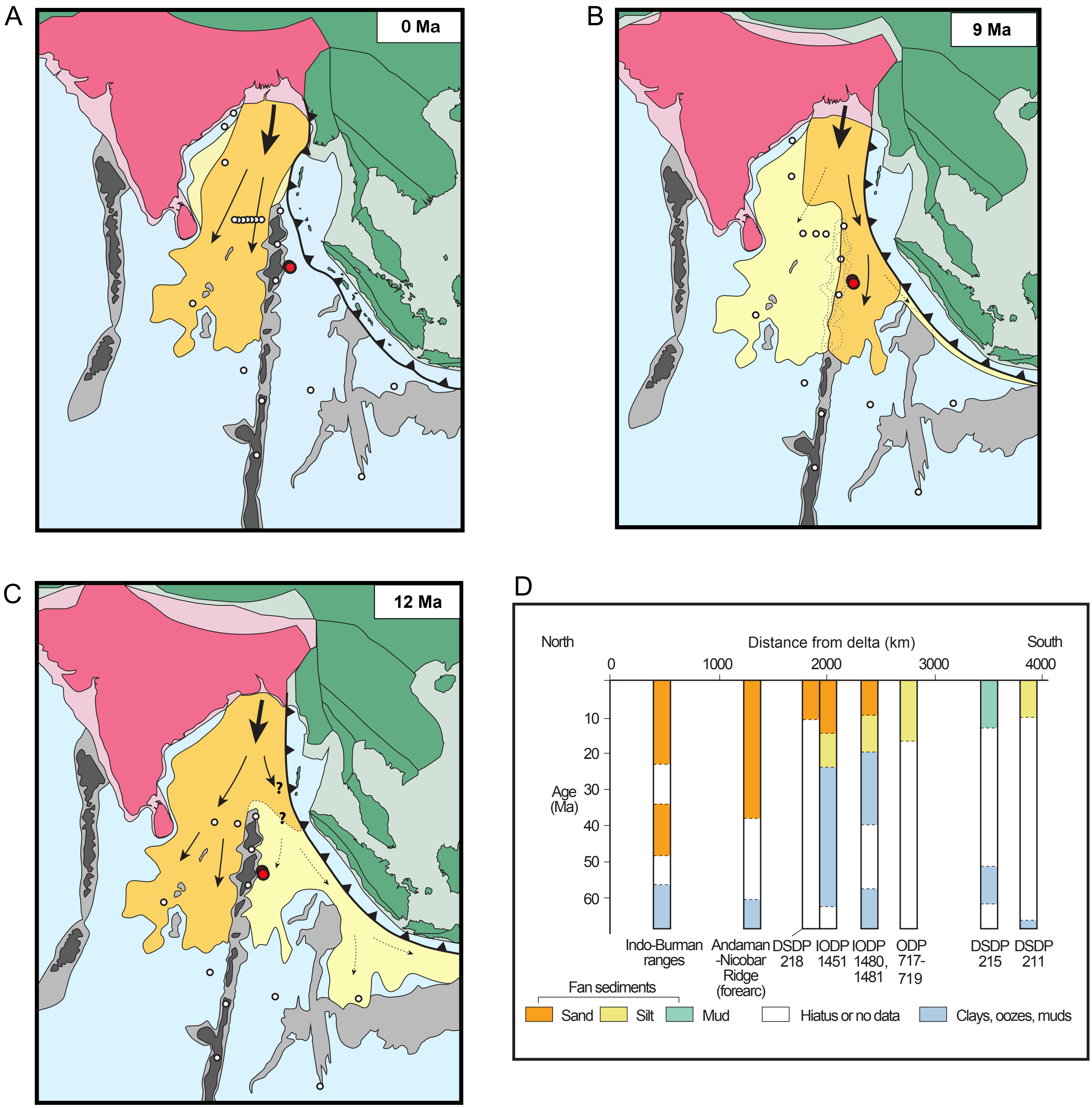

A
0 Ma
B
9 Ma
C
12 Ma
?
?
D
North
Distance from delta (km)
South
0
1000
2000
3000
4000
Age (Ma)
10
20
30
40
50
60
Indo-Burman ranges
Andaman -Nicobar Ridge (forearc)
DSDP 218
IODP 1451
IODP 1480, 1481
ODP 717-719
DSDP 215
DSDP 211
Fan sediments
Sand
Silt
Mud
Hiatus or no data
Clays, oozes, muds

Figure 5.