



Understanding Himalayan erosion and the significance of the Nicobar Fan



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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.

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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; France-Lanord et al., 2016; Schwenk and Spiess, 2009; Moore et al., 1974). 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 m below seafloor (mbsf), and from 1150 mbsf to within 10s 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 quartzofeldspathic 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 quartzofeldspathic (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 dramati-

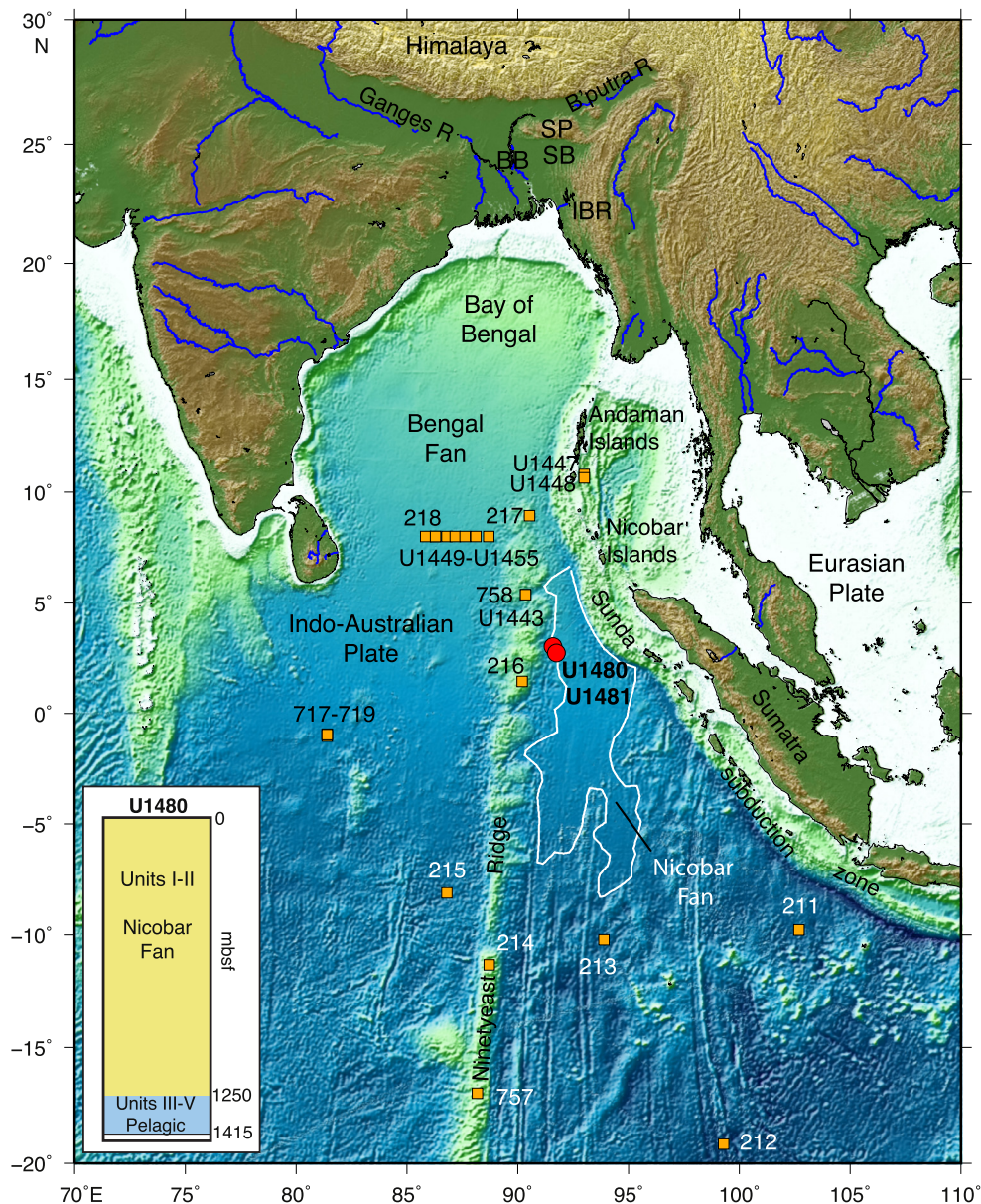


Fig. 1. Regional map of study area. Map includes Bengal–Nicobar Fan system, river systems, eastern Himalayan provinces, and relevant DSDP/ODP/IODP sites. BB = Bengal Basin; SP = Shillong Plateau; SB = Surma Basin; IBR = Indo–Burman Ranges. Inset summarizes Site U1480 lithostratigraphy.

cally 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 in-

creased 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](#)).

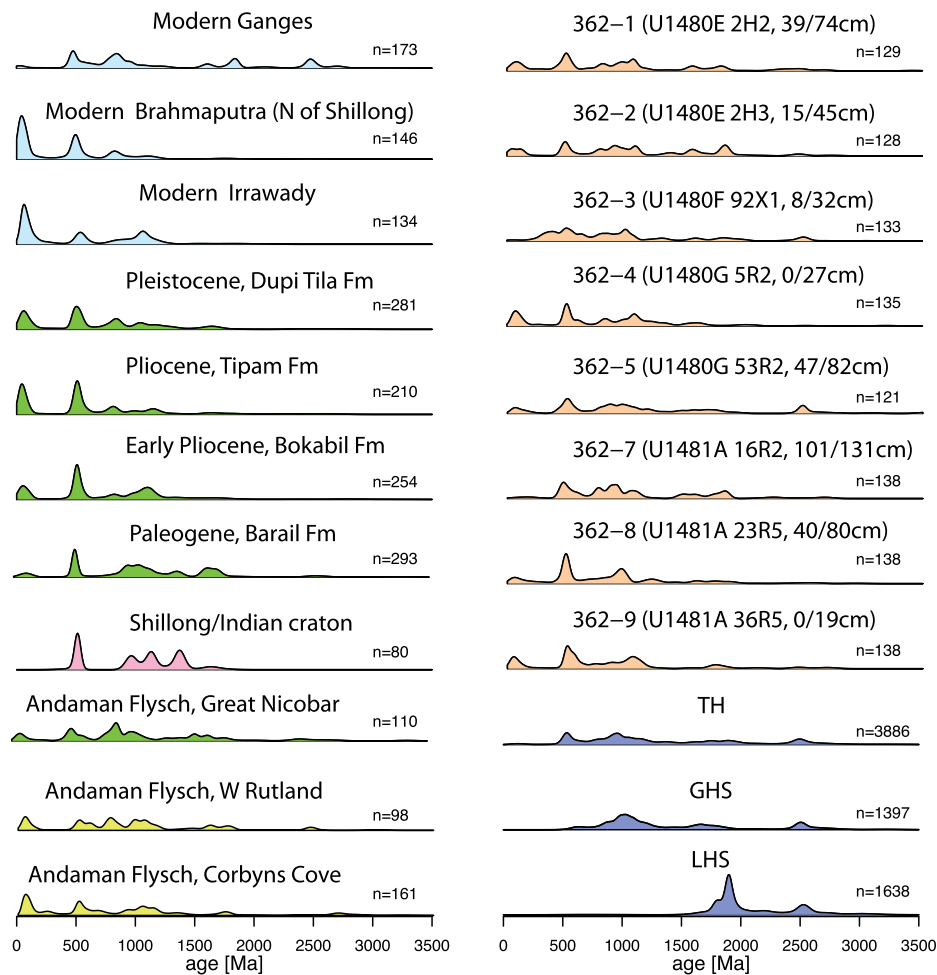


Fig. 2. Detrital zircon age plots for samples and equivalent plots of regional rivers and formations. TH = Tethyan Himalaya; GHS = Greater Himalaya Series; LHS = Lesser Himalaya Series. Details of Expedition 362 samples are given in Table S1.

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-levee 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; Bouquillon 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 and 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.

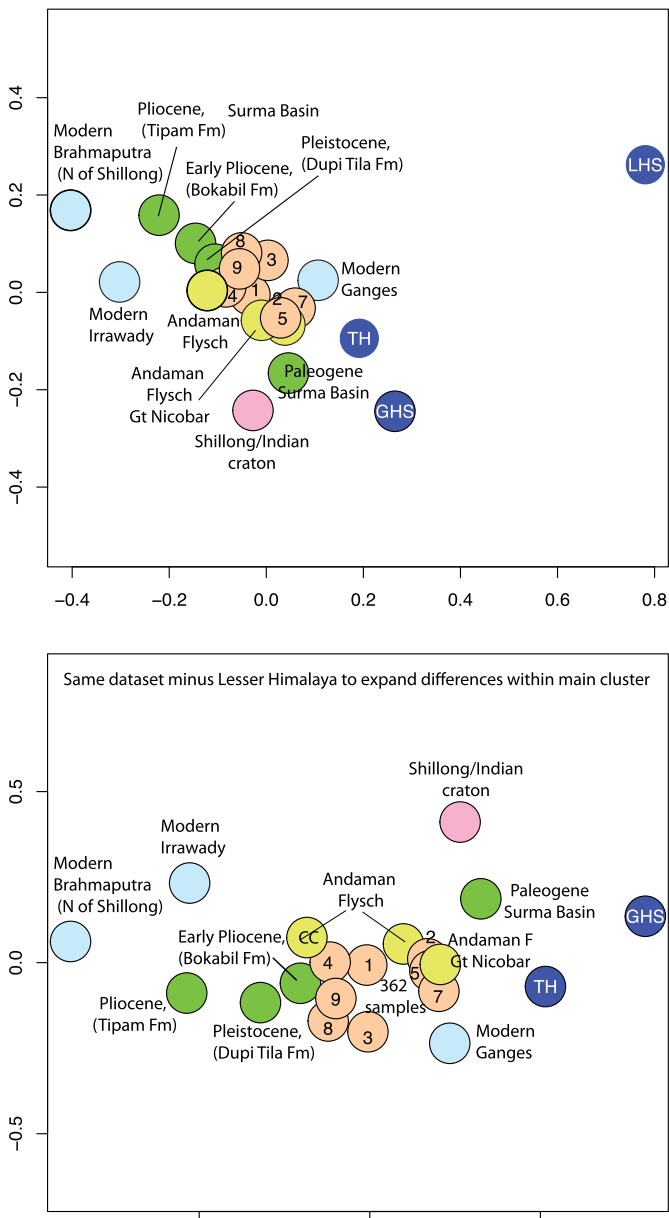


Fig. 3. Detrital zircon age comparison plots of samples from this study and regional rivers and formations. Multidimensional scaling maps (Vermeech, 2013) based on calculated K-S distances between U–Pb age spectra, comparing Nicobar Fan sand samples from this study with possible source areas compiled 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 Fig. 2 for acronyms.

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 $\sim 0.5 \times 10^6 \text{ km}^3$ (Figs. 1, S4; Supplementary Material), without decompaction. An additional $0.4 \times 10^6 \text{ km}^3$ 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 $\sim 1 \times 10^6 \text{ km}^3$. This volume is significant compared with the estimated Bengal Fan volume of $7.2 \times 10^6 \text{ km}^3$ for the entire Neogene, a period of ~ 20 Myr (Cliff, 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. Off-shore 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 Irrawaddy 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,

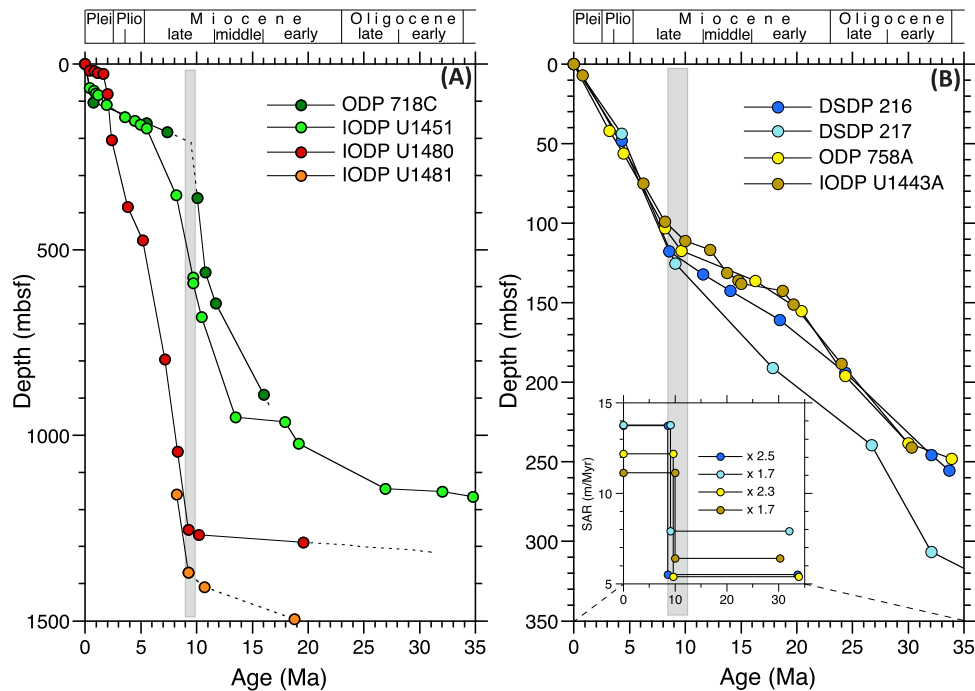


Fig. 4. Age-depth relationships at ocean drilling sites. Panel (A) shows tie points of biomagnetostratigraphic age-depth relationships for Bengal Fan sites (718C, U1451) and Nicobar Fan sites (U1480, U1481). Panel (B) shows biomagnetostratigraphic tie points of age-depth relationships for sites from 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 Figs. S2 and S3, and Tables S2 and S3.

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 ob-

served 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. This previously unquantified sediment sink likely also contributes to organic carbon burial budgets (cf. Galy et al., 2007). 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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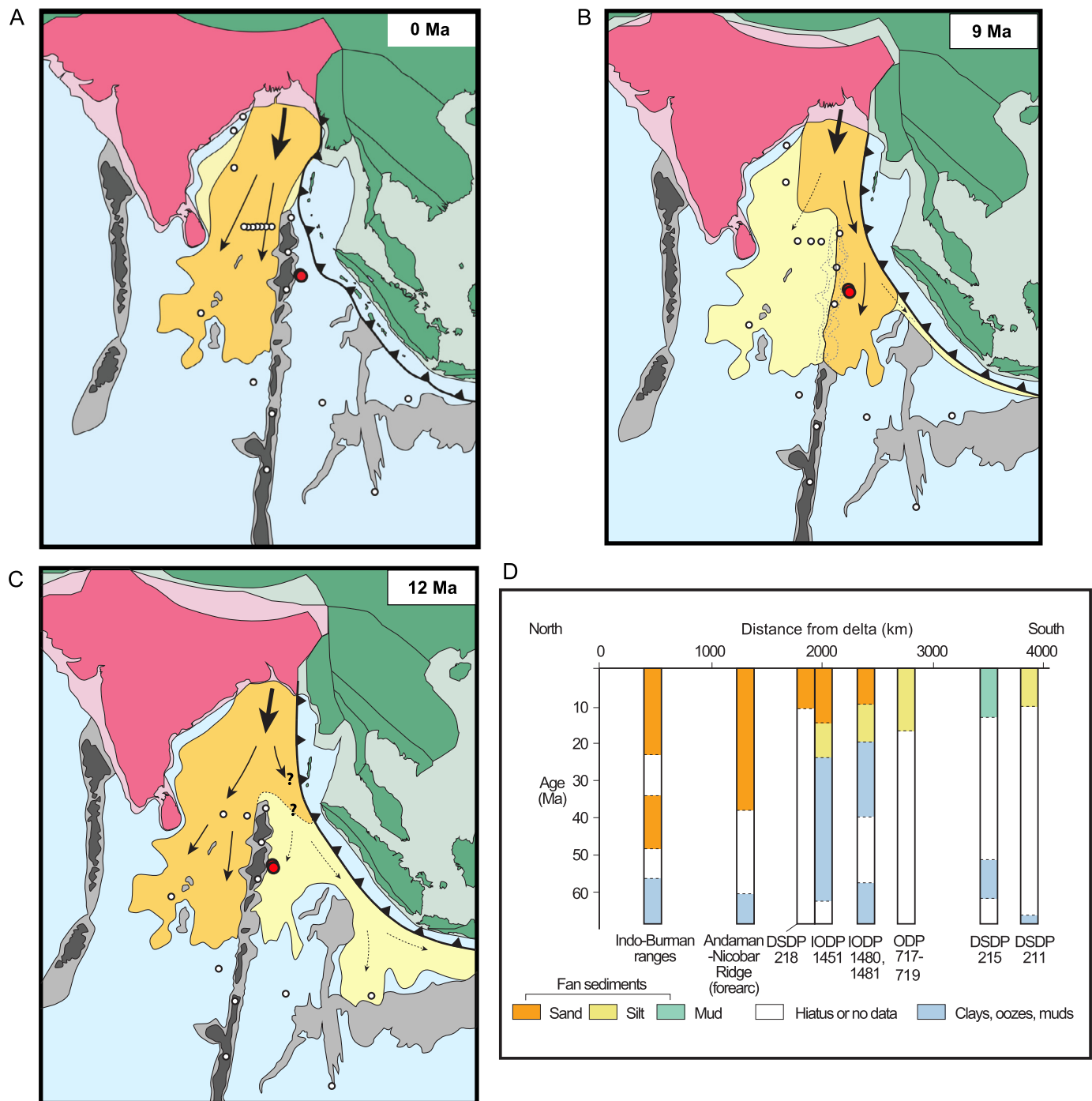


Fig. 5. Conceptual model of Bengal–Nicobar Fan system history (tectonics from Hall (2012); fan morphology from Bowles et al. (1978) and Curray (2014); fan data from DSDP/ODP/IODP sites (white dots; red dots = Expedition 362 sites). A) Late Pleistocene to Recent, sedimentation primarily on Bengal Fan, 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.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.epsl.2017.07.019>.

References

- Allen, R., Najman, Y., Carter, A., Barfod, D., Bickle, M.J., Chapman, H.J., Garzanti, E., Vezzoli, G., Andò, S., Parrish, R., 2008. Provenance of the Tertiary sedimentary rocks of the Indo–Burman Ranges, Burma (Myanmar): Burman arc or Himalayan-derived? *J. Geol. Soc. (Lond.)* 165 (6), 1045–1057.
- An, Z., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. *Nature* 411, 62–66. <http://dx.doi.org/10.1038/35075035>.
- Bandopadhyay, P.C., Ghosh, B., 2015. Provenance analysis of the Oligocene turbidites (Andaman Flysch), South Andaman Island: a geochemical approach. *J. Earth Syst. Sci.* 124, 1019–1037. <http://dx.doi.org/10.1007/s12040-015-0586-5>.
- Betzler, C., et al., 2016. The abrupt onset of the modern South Asian Monsoon winds. *Sci. Rep.* 6, 29838. <http://dx.doi.org/10.1038/srep29838>.
- Bilham, R., England, P., 2001. Plateau “pop-up” in the great 1897 Assam earthquake. *Nature* 410, 806–809. <http://dx.doi.org/10.1038/35071057>.
- Biswas, S., Coutand, I., Grujic, D., Hager, C., Stockli, D., Grasemann, B., 2007. Exhumation and uplift of the Shillong plateau and its influence on the eastern Himalayas: new constraints from apatite and zircon (U–Th–[Sm])/He and apatite fission track analyses. *Tectonics* 26, TC6013. <http://dx.doi.org/10.1029/2007TC002125>.
- Bouquillon, A., France-Lanord, C., Michard, A., Tiercelin, J.-J., 1990. Sedimentology and isotopic chemistry of the Bengal Fan sediments: the denudation of the Himalaya. In: Cochran, J.R., Stow, D.A.V., et al. (Eds.), *Leg 116 Distal Bengal Fan*. In: Proc. ODP Sci. Res., vol. 116. Ocean Drilling Program, College Station, TX. <http://dx.doi.org/10.2973/odp.proc.sr.116.1990>.
- Bowles, F.A., Ruddiman, W.F., Jahn, W.H., 1978. Acoustic stratigraphy, structure, and depositional history of the Nicobar Fan, eastern Indian Ocean. *Mar. Geol.* 26, 269–288. [http://dx.doi.org/10.1016/0025-3227\(78\)90063-4](http://dx.doi.org/10.1016/0025-3227(78)90063-4).
- Bracciali, L., Najman, Y., Parrish, R.R., Akhter, S.H., Millar, I., 2015. The Brahmaputra tale of tectonics and erosion: Early Miocene river capture in the Eastern Himalaya. *Earth Planet. Sci. Lett.* 415, 25–37.
- Bracciali, L., Parrish, R., Najman, Y., Smye, A., Carter, A., Wijbrans, J.R., 2016. Plio–Pleistocene exhumation of the eastern Himalayan syntaxis and its domal “pop-up”. *Earth-Sci. Rev.* 160, 350–385. <http://dx.doi.org/10.1016/j.earscirev.2016.07.010>.
- Campbell, I.H., Reiners, P.W., Allen, C.M., Nicolescu, S., Upadhyay, R., 2005. He–Pb double dating of detrital zircons from the Ganges and Indus Rivers: implication for quantifying sediment recycling and provenance studies. *Earth Planet. Sci. Lett.* 237, 402–432. <http://dx.doi.org/10.1016/j.epsl.2005.06.043>.
- Clark, M., Bilham, R., 2008. Miocene rise of the Shillong Plateau and the beginning of the end for the Eastern Himalaya. *Earth Planet. Sci. Lett.* 269, 337–351. <http://dx.doi.org/10.1016/j.epsl.2008.01.045>.
- Clemens, S.C., Kuhnt, W., LeVay, L.J., et al., 2016. Indian Monsoon Rainfall. Proc. IODP, vol. 353. International Ocean Discovery Program, College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.353.2016>.
- Clift, P., 2002. A brief history of the Indus River. In: Clift, P., Kroon, D., Gaedicke, C., Craig, J. (Eds.), *Tectonic and Climatic Evolution of the Arabian Sea Region*. In: *Geol. Soc. London, Spec. Publ.*, vol. 195, pp. 97–116.
- Clift, P.D., Hodges, K.V., Heslop, D., Hannigan, R., van Long, H., Calves, G., 2008. Correlation of Himalayan exhumation rates and Asian monsoon intensity. *Nat. Geosci.* 1, 875–880. <http://dx.doi.org/10.1038/ngeo351>.
- Cochran, J.R., Stow, D.A.V., et al., 1989. Leg 116 Distal Bengal Fan. Proc. ODP Init. Rep., vol. 116. Ocean Drilling Program, College Station, TX. <http://dx.doi.org/10.2973/odp.proc.ir.116.1989>.
- Cochran, J.R., Stow, D.A.V., et al., 1990. Leg 116 Distal Bengal Fan. Proc. ODP Sci. Res., vol. 116. Ocean Drilling Program, College Station, TX. <http://dx.doi.org/10.2973/odp.proc.sr.116.1990>.
- Copeland, P., Harrison, T.M., Heizler, M.T., 1990. ⁴⁰Ar/³⁹Ar single-crystal dating of detrital muscovite and K-feldspar from Leg 116, southern Bengal Fan: implications for the uplift and erosion of the Himalayas. In: Cochran, J.R., Stow, D.A.V., et al. (Eds.), *Leg 116 Distal Bengal Fan*. In: Proc. ODP Sci. Res., vol. 116. Ocean Drilling Program, College Station, TX.
- Curry, J.R., 2014. The Bengal depositional system: from rift to orogeny. *Mar. Geol.* 352, 59–69. <http://dx.doi.org/10.1016/j.margeo.2014.02.001>.
- Curry, J.R., Moore, D.G., 1974. Sedimentary and tectonic processes in the Bengal deep-sea fan and geosyncline. In: Burk, C.A., Drake, C.L. (Eds.), *Continental Margins*. Springer, New York, pp. 617–627.
- Curry, J.R., Moore, D.G., Lawver, L.A., Emmel, F.J., Raitt, R.W., Henry, M., Kiekheffer, R., 1979. Tectonics of the Andaman Sea and Burma. In: Watkins, J., Montadert, L., Dickerson, P.W. (Eds.), *Tectonics of the Andaman Sea and Burma*. In: *AAPG Mem.*, vol. 29, pp. 189–198.
- Curry, J.R., Emmel, F.J., Moore, D.G., 2003. The Bengal Fan: morphology, geometry, stratigraphy, history and processes. *Mar. Pet. Geol.* 19, 1191–1223. [http://dx.doi.org/10.1016/S0264-8172\(03\)00035-7](http://dx.doi.org/10.1016/S0264-8172(03)00035-7).
- Dugan, B., McNeill, L.C., Petronotis, K.E., the Expedition 362 Scientists, 2017. Expedition 362 Preliminary Report: Sumatra Subduction Zone. Intern. Ocean Discovery Program. <http://dx.doi.org/10.14379/iodp.pr.362.2017>.
- Duvall, A.R., Clark, M.K., Avdeev, B., Farley, K.A., Chen, Z., 2012. Widespread late Cenozoic increase in erosion rates across the interior of eastern Tibet constrained by detrital low-temperature thermochronometry. *Tectonics* 31, TC3014. <http://dx.doi.org/10.1029/2011TC002969>.
- Fernandez, R.L., Cantelli, A., Pirmez, C., Sequeiros, O., Parker, G., 2014. Growth patterns of subaqueous depositional channel lobe systems developed over a basement with a downdip break in slope: laboratory experiments. *J. Sediment. Res.* 84, 168–182. <http://dx.doi.org/10.2110/jsr.2014.10>.
- Flood, R.D., Manley, P.C., Kowmsan, R.O., Appi, C.J., Pirmez, C., 1991. Seismic facies and late Quaternary growth of Amazon Submarine Fan. In: Weimer, P., Link, M.H. (Eds.), *Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems*. Springer-Verlag, New York, pp. 415–433.
- France-Lanord, C., Spiess, V., Klaus, A., Schwenk, T., et al., 2016. Bengal Fan. Proc. IODP, vol. 354. International Ocean Discovery Program, College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.354.2016>.
- Fisher, D., Mosher, D., Austin, J.A., Gulick, S.P., Masterlark, T., Moran, K., 2007. Active deformation across the Sumatran forearc over the December 2004 Mw 9.2 rupture. *Geology* 35, 99–102. <http://dx.doi.org/10.1130/G22993A.1>.
- Galy, V., France-Lanord, C., Beyssac, O., Faure, P., Kudrass, H., Palhol, F., 2007. Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system. *Nature* 450, 407–410. <http://dx.doi.org/10.1038/nature06273>.
- Gehrels, G., Kapp, P., DeCelles, P., Pullen, A., Blakey, R., Weislogel, A., Ding, L., Guynn, J., Martin, A., McQuarrie, N., Yin, A., 2011. Detrital zircon geochronology of pre-Tertiary strata in the Tibetan–Himalayan orogen. *Tectonics* 30, 1944–1994. <http://dx.doi.org/10.1029/2011TC002868>.
- Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics* 570–571, 1–41. <http://dx.doi.org/10.1016/j.tecto.2012.04.021>.
- Hamilton, W., 1973. Tectonics of the Indonesia region. *Geol. Soc. Malaysia Bull.* 6, 3–10.
- Hilgen, F.J., Lourens, L.J., Van Dam, J.A., 2012. The Neogene period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), *The Geological Time Scale 2012*, vol. 2. Elsevier, Amsterdam, pp. 923–978.
- Karig, D.E., Suparka, S., Moore, G.F., Hehanussa, P.E., 1979. Structure and Cenozoic evolution of the Sunda arc in the Central Sumatra region. In: Watkins, J., Montadert, L., Dickerson, P. (Eds.), *Geological and Geophysical Investigations of Continental Slopes and Rises*. In: *AAPG Mem.*, vol. 29, pp. 223–237.
- Karig, D.E., Lawrence, M.B., Moore, G.E., Curry, J.R., 1980. Structural framework of the forearc basin, NW Sumatra. *J. Geol. Soc. (Lond.)* 137, 77–91.
- Kroon, D., Steens, T., Troelstra, S.T., 1991. Onset of monsoonal related upwelling in the western Arabian sea as revealed by planktonic foraminifers. In: Proc. ODP Sci. Res., vol. 117. Ocean Drilling Program, College Station, TX, pp. 257–263. <http://dx.doi.org/10.2973/odp.proc.sr.117.126.1991>.
- Limonta, M., Resentini, A., Carter, A., Bandopadhyay, P.C., Garzanti, E., 2017. Provenance of Oligocene Andaman sandstones (Andaman–Nicobar Islands): Ganga–Brahmaputra or Irrawaddy derived? In: Bandopadhyay, P.C., Carter, A. (Eds.), *The Andaman–Nicobar Accretionary Ridge: Geology, Tectonics and Hazards*. In: *Mem. Geol. Soc. Lond.*, vol. 47, pp. 143–154.
- McNeill, L.C., Henstock, T.J., 2014. Forearc structure and morphology along the Sumatra–Andaman subduction zone. *Tectonics* 33, 112–134. <http://dx.doi.org/10.1002/2012TC003264>.
- Miller, K.G., Komzin, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. *Science* 310, 1293–1298. <http://dx.doi.org/10.1126/science.1116412>.
- Moore, D.G., Curry, J.R., Raitt, R.W., Emmel, F.J., 1974. Stratigraphic–Seismic Section Correlations and Implications to Bengal Fan History. In: *Init. Rep. DSDP*, vol. 22. U.S. Govt. Print. Off., pp. 403–412. <http://dx.doi.org/10.2973/dsdp.proc.22.116.1974>.
- Najman, Y., Bickle, M., Boudagher-Fadel, M., Carter, A., Garzanti, E., Paul, M., Wijbrans, J., Willett, E., Oliver, G., Parrish, R., Akhter, H., Allen, R., Ando, S., Christy, E., Reisberg, L., Vezzoli, G., 2008. The Paleogene record of Himalayan erosion, Bengal Basin, Bangladesh. *Earth Planet. Sci. Lett.* 273, 1–14. <http://dx.doi.org/10.1016/j.epsl.2008.04.028>.
- Najman, Y., Allen, R., Willett, E.A.F., Carter, A., Barfod, D., Garzanti, E., Wijbrans, J., Bickle, M.J., Vezzoli, G., Ando, A., Oliver, G., Uddin, M.J., 2012. The record of Himalayan erosion preserved in the sedimentary rocks of the Hatia Trough of the Bengal Basin and the Chittagong Hill Tracts, Bangladesh. *Basin Res.* 24, 1–21. <http://dx.doi.org/10.1111/j.1365-2117.2011.00540.x>.
- Najman, Y., Bracciali, L., Parrish, R.R., Chisty, E., Copley, A., 2016. Evolving strain partitioning in the Eastern Himalaya: the growth of the Shillong Plateau. *Earth Planet. Sci. Lett.* 433, 1–9. <http://dx.doi.org/10.1016/j.epsl.2015.10.017>.
- Parsons, J.D., Schweller, W.J., Stelling, C.W., Southard, J.B., Lyons, W.J., Grotzinger, J.P., 2002. A preliminary experimental study of turbidite fan deposits. *J. Sediment. Res.* 72, 619–628. <http://dx.doi.org/10.1306/032102720619>.
- Peirce, J., Weissel, J., et al., 1989. Proc. ODP Init. Repts., vol. 121. Ocean Drilling Program, College Station TX. <http://dx.doi.org/10.2973/odp.proc.ir.121.1989>.
- Peterson, L.C., Backman, J., 1990. Late Cenozoic carbonate accumulation and the history of the carbonate compensation depth in the western equatorial Indian Ocean. In: Proc. ODP Sci. Res., vol. 115. Ocean Drilling Program, College Station, TX, pp. 467–508. <http://dx.doi.org/10.2973/odp.proc.sr.115.163.1990>.

- Pälike, H., Norris, R.D., Herrle, J.O., Wilson, P.A., Coxall, H.K., Lear, C.H., Shackleton, N.J., Tripathi, A.K., Wade, B.S., 2006. The heartbeat of the Oligocene climate system. *Science* 314, 1894–1898. <http://dx.doi.org/10.1126/science.1133822>.
- Prell, W.L., Kutzbach, J.E., 1992. Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution. *Nature* 360, 647–652. <http://dx.doi.org/10.1038/360647a0>.
- Racey, A., Ridd, M.F., 2015. *Petroleum geology of Myanmar*. *Mem. Geol. Soc. Lond.* 45, 63–81.
- Schwenk, T., Spiess, V., 2009. Architecture and stratigraphy of the Bengal Fan as response to tectonic and climate revealed from high-resolution seismic data. *SEPM Spec. Pub.* 92, 107–131.
- Stow, D.A.V., Amano, K., Balson, P.S., Brass, G.W., Corrigan, J., Raman, C.V., Tiercelin, J.-J., Townsend, M., Wijayananda, N.P., 1990. Sediment facies and processes on the distal Bengal Fan, Leg 116. In: *Proc. ODP Sci. Res.*, vol. 116. Ocean Drilling Program, College Station, TX, pp. 377–396. <http://dx.doi.org/10.2973/odp.proc.sr.116.110.1990>.
- Vermeesch, P., 2013. Multi-sample comparison of detrital age distributions. *Chem. Geol.* 341, 140–146. <http://dx.doi.org/10.1016/j.chemgeo.2013.01.010>.
- von der Borch, C.C., Sclater, J.G., et al., 1974. *Init. Rep. DSDP*, vol. 22. U.S. Govern. Print. Office, Washington. <http://dx.doi.org/10.2973/dsdp.proc.22.1974>.
- Weber, M.E., Wiedicke, M.H., Kudrass, H.R., Hübscher, C., Erlenkeuser, H., 1997. Active growth of the Bengal Fan during sea-level rise and highstand. *Geology* 25, 315–318.