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The Paleogene record of Himalayan erosion: Bengal Basin, Bangladesh

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ABSTRACT

A knowledge of Himalayan erosion history is critical to understanding crustal deformation processes, and the proposed link between the orogen's erosion and changes in both global climate and ocean geochemistry. The most commonly quoted age of India–Asia collision is ~50 Ma, yet the record of Paleogene Himalayan erosion is scant — either absent or of low age resolution. We apply biostratigraphic, petrographic, geochemical, isotopic and seismic techniques to Paleogene rocks of the Bengal Basin, Bangladesh, of previously disputed age and provenance. Our data show that the first major input of sands into the basin, in the >1 km thick deltaic Barail Formation, occurred at 38 Ma. Our biostratigraphic and isotopic mineral ages date the Barail Formation as spanning late Eocene to early Miocene and the provenance data are consistent with its derivation from the Himalaya, but inconsistent with Indian cratonic or Burman margin sources. Detrital mineral lag times show that exhumation of the orogen was rapid by 38 Ma. The identification of sediments shed from the rapidly exhuming southern flanks of the eastern–central Himalaya at 38 Ma, provides a well dated accessible sediment record 17 Myr older than the previously described 21 Ma sediments, in the foreland basin in Nepal. Discovery of Himalayan detritus in the Bengal Basin from 38 Ma: 1) resolves the puzzling discrepancy between the lack of erosional evidence for Paleogene crustal thickening that is recorded in the hinterland; 2) invalidates those previously proposed evidences of diachronous collision which were based on the tenet that Himalayan-derived sediments were deposited earlier in the west than the east; 3) enables models of Himalayan exhumation (e.g. by mid crustal channel flow) to be revised to reflect vigorous erosion and rapid exhumation by 38 Ma, and 4) provides evidence that rapid erosion in the Himalaya was coincident with the marked rise in marine $^{87}Sr/^{86}Sr$ values since ~40 Ma. Whether 38 Ma represents the actual initial onset of vigorous erosion from the southern flanks of the east-central Himalaya, or whether older material was deposited elsewhere, remains an open question.

1. Introduction

Study of the erosional history of the Himalayan orogeny is critical to the assessment of models of crustal deformation which differ in the timing and extent of erosion, as well as to the proposed influence of the orogen's erosion on global climate and ocean geochemistry (Raymo and Ruddiman, 1992; Richter et al., 1992).

The most commonly quoted age of India–Asia collision is ~55–50 Ma (Hodges, 2000). However, whilst there is a well dated record of Neogene Himalayan erosion (Burbank et al., 1996; Clift et al., 2001b; France-Lanord et al., 1993), a well-resolved record of Paleogene erosion from the orogen's southern flanks, from sediments in the foreland, remnant ocean, or deep-ocean basins is lacking. Strata are either absent, show only minor detrital input, are of disputed provenance, lack high-precision dating, or are yet to be sampled (Allen et al., in press; Clift, 2006; Clift et al., 2001b; Curray, 1994; Davies et al., 1995; Lindsay et al., 1991; Metivier et al., 1999; Mitchell, 1993; Qayyum et al., 2001; Sinclair and Jaffey, 2001). Sedimentary

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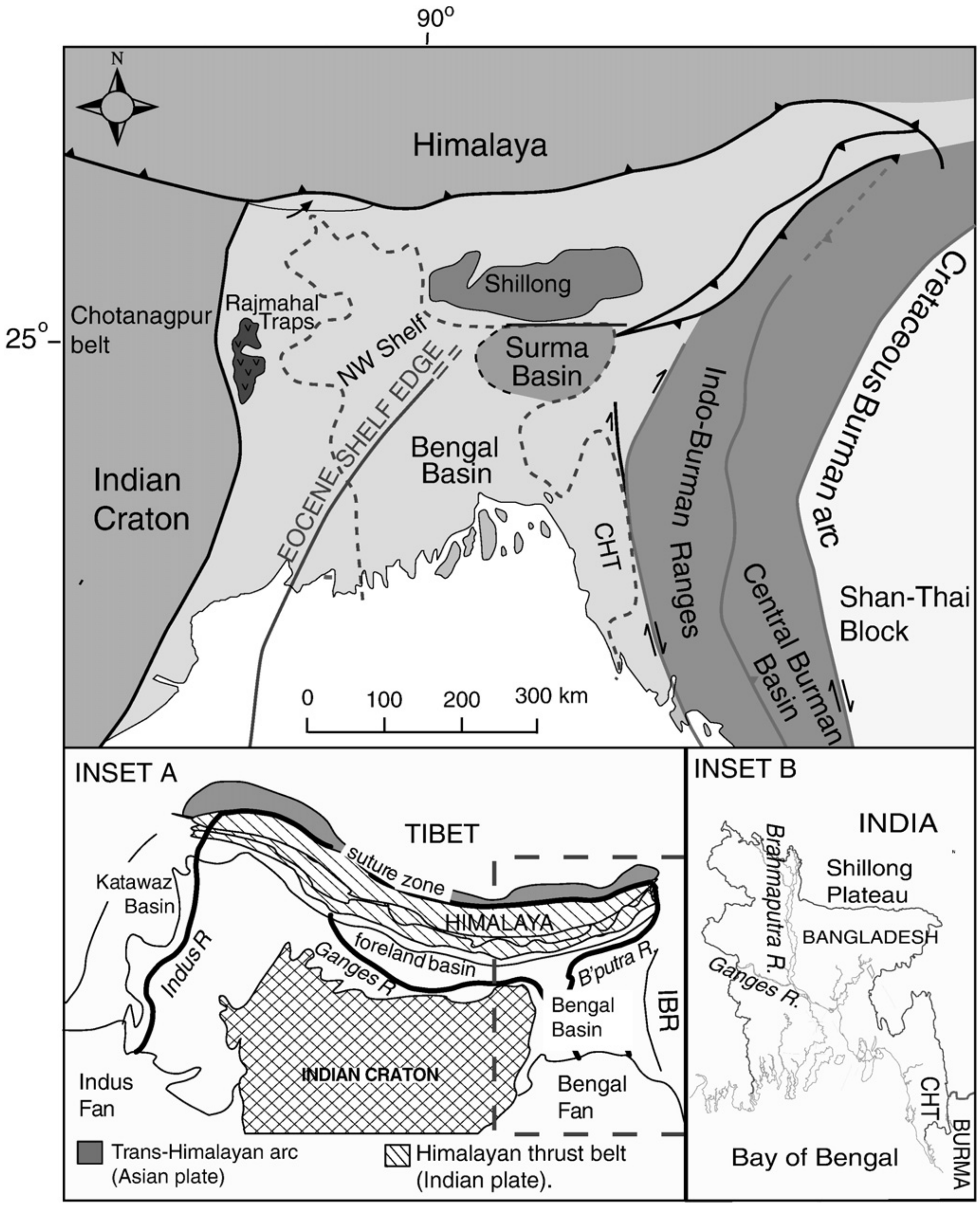

Fig. 1. Map showing the location of the Surma Basin, NW Shelf, main geological features of the wider region, and potential source regions to the basin (Himalaya, Indian craton and Burman margin) during Paleogene sedimentation. Dashed line shows the political boundary of Bangladesh. CHT = Chittagong Hill Tracts. Inset A shows the locations of the main Himalayan sedimentary repositories in the mountain belt's geological context. IBR=Indo-Burman Ranges. Dashed box shows the region of Fig. 1. Inset B shows geographical and political features of the region of Fig. 1.

records pertaining to erosion from the eastern and central part of the orogen are particularly scant. In this paper we identify and date the oldest Himalayan-derived sedimentary rocks in the Bengal Remnant Ocean Basin, Bangladesh (Fig. 1).

2. Geological background

2.1. Himalayan geology

The Himalayan orogen formed when Tethys closed and India and Eurasia collided. In the suture zone, Tertiary molasse separates the Asian plate to the north from the Indian plate to the south (Clift et al., 2001a; Sinclair and Jaffey, 2001) (Fig. 1, Inset A). The Tibetan plateau of the Asian plate is flanked on its southern margin by the Jurassic–Paleogene Trans-Himalayan arc which formed an ancient Andean-type margin to Tethys (Chu et al., 2006; Scharer and Allegre, 1984). South of the suture zone, the Himalaya consists of various lithotectonic units bounded by south-directed thrusts. From north to south these consist of ophiolites and Palaeozoic–earliest Tertiary Tethyan Himalayan sediments (DeCelles et al., 2001; Maheo et al., 2004), the Higher Himalaya characterised by metamorphic rocks with Oligo-Miocene and younger mineral ages resulting from Himalayan metamorphism (Hodges, 2000; Vance and Harris, 1999), the Lesser Himalaya of mostly weakly or non-metamorphosed Indian plate rocks (Hodges, 2000; Richards et al., 2005) , and the Sub-Himalaya which contains foreland basin sediments (Burbank et al., 1996). Flanking the Himalaya in the west and east respectively, are the Katawaz and Bengal remnant ocean basins (Alam et al., 2003; Qayyum et al., 2001).

2.2. Existing Paleogene records of Himalayan erosion

2.2.1. The orogen's western region

In the suture zone, the age of the Indus Group molasse is only precisely constrained by Nummulitic limestones, dated at 54.9 Ma, near the base of the succession (Fig. 1, Inset A; Sinclair and Jaffey, 2001). The molasse comprises detritus predominantly from the Asian

Table 1
Summary table showing stratigraphy and facies of the sedimentary rocks of the Surma Basin and NW Shelf of the Bengal remnant ocean basin, Bangladesh, and Himalayan foreland basin, India and Nepal

	Bengal Basin Tertiary Stratigraphy (Surma Basin and NW Shelf)			Foreland Basin Stratigraphy (India and Nepal)	
Age	**Formation**	**Lithology**	**Facies**	**Formation**	**Facies**
Neogene	Dupi Tila	Ssts, msts	Fluvial	Siwalik Gp	
Neogene	Tipam	Ssts, msts	Fluvial	Dharamsala Fm/ Dagshai and Kasauli Fms (India) Dumre Fm (Nepal)	Fluvial
Neogene	Surma Group (Bhuban and Bokabil Fms)	Ssts, msts	Deltaic		
Late Eocene–early Miocene	Barail Fm	Sst, minor mst	Deltaic	Disconformity	
Late Eocene	Kopili Fm	Shales, minor lst	Shallow marine		
Early–mid Eocene	Sylhet Fm	Lst	Shallow marine	Subathu Fm (India) Bhainskati Fm (Nepal)	Shallow marine
Paleocene–early Eocene	Tura Fm	Qtz arenites	Shallow marine		

Summarised from our study, and Alam et al. (2003), Banerji (1984), Johnson and Alam (1991) and Reimann (1993).

Trans-Himalaya to the north, and only subordinately from the Indian crust to the south (Garzanti and Vanhaver, 1988; Wu et al., 2007). In the foreland basin south of the Himalaya, substantial Himalayan detritus first appears sometime after 36 Ma in Pakistan (Najman et al., 2001) and after 31 Ma in India (Najman et al., 2004), above a basin-wide unconformity. Paleogene deposits are also found in the Katawaz Remnant Ocean Basin and Indus Fan (Clift et al., 2001b; Qayyum et al., 2001). However, the sediments in the Katawaz Basin are of disputed provenance (Sinclair and Jaffey, 2001) and are poorly dated. The timing of Himalayan input to the Indus Fan can be dated no more accurately than mid Eocene (Clift et al., 2001b), and at this stage Himalayan detritus is predominantly derived from north of the suture zone.

2.2.2. The orogen's central and eastern regions

Paleogene molasse appears to be absent from the central and eastern suture, with previously reported Eocene conglomerates now redated as Miocene (Aitchison et al., 2002). The earliest orogenic detritus consists of Asian-derived material recorded in Eocene Tethyan strata (Ding et al., 2005; Zhu et al., 2005). The oldest accessible record documenting significant erosion from the central and eastern Himalaya's southern flanks lies in the foreland basin and is dated at 21 Ma in Nepal (DeCelles et al., 2001) above the basin-wide unconformity. Bengal Fan deposits have not been drilled to base and Paleogene deposits of the Indo-Burman Ranges are not composed of offscraped Bengal Fan material as previously thought (Allen et al., in press). In the Bay of Bengal, a regional unconformity is "tentatively" dated at early Eocene, above which, "post-Paleocene" aged sediments are interpreted as Bengal Fan deposits (Curray et al., 2003) (Section 4.3.2). Paleogene deposits of the Bengal remnant ocean basin, Bangladesh, are poorly dated and of disputed provenance, with both Himalayan and cratonic sources proposed (Banerji, 1984; Johnson and Alam, 1991; Uddin and Lundberg, 1998a).

2.3. Tertiary strata of the northern Bengal Basin, Bangladesh

The Bengal Basin is dominated by the Ganges–Brahmaputra delta. Sediments were deposited on a continental margin consisting of the NW Shelf which deepened to a basinal environment to the SE (Fig. 1). The basinal facies are preserved in the north in the Surma Basin, and further south in the Hatia Trough, and Chittagong Hill Tracts accretionary prism (Alam et al., 2003). In the Surma Basin the Paleogene rocks comprise the shallow marine Tura, Sylhet and Kopili Formations and the overlying >1 km thick deltaic Barail Formation. Deltaic facies continue in the Neogene Surma Group (Bhuban and Bokabil Formations) overlain by the fluvial Tipam and Dupi Tila Formations (Banerji, 1984; Johnson and Alam, 1991; Reimann, 1993) (Table 1).

The Tura Formation consists of quartz arenites of Paleocene–early Eocene age, the early–mid Eocene Sylhet Formation and late Eocene Kopili Formations consist of limestones and predominantly black shales respectively, and the Barail Formation sandstones are considered to be Oligocene aged. However, whilst the ages of the Sylhet and Kopili Formations are well constrained by biostratigraphy, biostratigraphy of the Barail Formation is poor, and its Oligocene age is largely based on its position above the Kopili Formation and, along with the Neogene Formations above it, a loosely defined lithostratigraphic correlation with rocks in Assam. Previous workers have noted the severe limitations to this approach, given the potential unconformity between Kopili and Barail Formations (Uddin and Lundberg, 1998b), and the highly time-transgressive nature of facies in a prograding delta which precludes accurate lithostratigraphic correlation (Alam et al., 2003; Reimann, 1993).

The source of the clastic input, which becomes significant at the start of Barail Formations times, is disputed. Most workers agree that by Neogene times (i.e. from the time of deposition of the Surma Group onwards) the Himalaya were contributing large amounts of detritus to the Bengal Basin sediments (e.g. Johnson and Alam, 1991; Rahman and Faupl, 2003; Uddin and Lundberg, 1998a,b), but the provenance of the Paleogene rocks remains unresolved. Researchers consider the composition of the Paleogene rocks to be affected by intense chemical weathering, but disagree as to whether the material is derived from the Indian craton (Uddin and Lundberg, 1998a,b) or the Himalaya (Johnson and Alam, 1991).

3. Approach, methodologies and results

The aim of the research, to use the Paleogene sedimentary record in the Surma Basin to unravel hinterland tectonics, requires determination of both the age and provenance of the rocks. Here, biostratigraphy is used to date the sediments where possible, but in the sparsely fossiliferous Barail Formation, the middle and upper parts of the sequence are assigned a maximum depositional age based on the isotopic cooling ages of detrital mineral grains within the rocks.

Table 2
Summary table showing salient characteristics of the Paleogene rocks of the Northern Bengal Basin, and those of their potential source regions; northern (Himalayan), western (Indian craton) and eastern (Burmese arc/Indo-Burman Ranges), as determined from bedrock or sediments eroded from these regions

	Petrography & heavy minerals	U–Pb zircon ages (Ma)	Ar–Ar mica ages (Ma)	Zircon FT age (Ma)	Bulk rock εNd (0)	$^{187}Os/^{188}Os$	Spinel geochemistry
Sources							
Himalayan							
Metamorphosed Higher Himalaya	Medium–high grade metamorphic rocks and minerals.	Cambro-Ordovician to Archean	Tertiary (dominant)	Neogene	−19 to −5. Av: −15	0.80–1.85	
Unmetamorphosed cover; Tethyan & Haimanta Gp.	Sedimentary & low grade metamorphic lithic fragments.	Cambro-Ordovician to Archean.	Pre-Tertiary; <950 Ma, mostly <500 Ma		Similar to Higher Himalaya	Tethyan: 0.60–1.97	
Arc & suture zone	Batholith, ophiolite	Jurassic–Eocene	Cretaceous & Tertiary		+1 to +8	Suture 0.5 Batholith 1.4	Very low TiO_2
Indian craton							
Chotanagpur Proterozoic gneissic belt[a,b]	Arkosic. Cr-spinel & metamorphic lithic fragments are absent.	Proterozoic	Proterozoic	Most-metamict. Proterozoic (peak). 170, 40 Ma (v. rare)	−13.8		Deccan CFB: high TiO_2. Rajmahal Trap similar?
Shillong Plateau[a,b]	Arkosic. Metamorphic lithic fragments and Cr-spinel are absent.	Proterozoic & Cambro-Ordovician	Cambro-Ordovician	Palaeozoic. Rare Jurassic & Cretaceous grains	−14.6	1.55–1.65	Sylet Traps: CFB values similar to Deccan (above)?
Indo-Burman Ranges							
Eocene "accretionary prism"[a]	Appreciable volcanic detritus. Few heavy minerals. No mica	Precambrian–Cretaceous, Paleocene	n/a	Cretaceous, Paleocene,	−4 (mode)	0.3[b] 0.2–0.9	
Paleogene Surma Basin rocks							
Barail Fm.[b] Late Eocene–Early Miocene	Metamorphic lithic fragments present. Cr-spinel is sporadic	Paleocene to Archean	Cambro-Ordovician to Neogene. Youngest Tertiary grain age decreases upsection	Peaks from 23–423, including Cretaceous . Youngest Tertiary peak decreases upsection	−11.3 to 14.6	0.6–0.8	Low TiO_2
Kopili Fm.[b] Late Eocene	Cr-spinel. Metamorphic lithic fragments absent.	Cretaceous to Archean	n/a	Cambrian to Cretaceous.	−12.3, −13	0.5	Low TiO_2
Sylhet Fm.[b] Early–Mid Eocene	v. limited detrital material	n/a	Cambro-Ordovician	n/a	−15	1.0–1.2	
Tura Fm.[b] Paleoc–E. Eocene	Metamorphic lithics absent. Qtz, fsp dominant.	Proterozoic to Ordovician	Cambro-Ordovician	Peaks at 225, 350, 580 Ma	−15.8, −17.7		

Extensive petrographic, geochemical and isotopic data summary, with full referencing, is given in Supplementary Material Item 1.
Data taken from this study, and Allen et al. (in press), Barnes and Roeder (2001), Chu et al. (2006), Clift et al. (2001a), DeCelles et al. (2004), Garzanti et al. (2004), Hodges (2000), Johnson and Alam (1991), Maheo et al. (2004), Misra and Johnson (2005), Najman (2006), Najman and Garzanti (2000), Pierson-Wickman et al. (2000), Richards et al. (2005), Scharer and Allegre (1984), Singh et al. (2003), Uddin and Lundberg (1998a,b) and White et al. (2002).
[a] Data from modern river sediment draining the source area.
[b] Data from current study, described fully in text and Supplementary Items.

Provenance identification requires discrimination between the potential source regions of the Himalaya to the north, Indian craton to the west and Burmese margin to the east of the basin. These regions have distinct petrographic and isotopic characteristics (Table 2 and Supplementary Item 1), reflecting their different lithologies and geological histories: The Indian craton signature reflects old (predominantly Precambrian) continental crust (Misra and Johnson, 2005) whereas Indian continental crust caught up in the Himalayan orogeny displays evidence of Tertiary metamorphism (Hodges, 2000). By contrast, the Burman margin is characterised by a Cretaceous arc (Mitchell, 1993), which continues north-west in the Himalayan belt as the Trans-Himalayan ancient active margin of Asia. In order to determine the provenance of the Surma Basin Paleogene sedimentary rocks, we used seismic data to determine sediment input direction, and petrographic, geochemical and isotopic techniques to characterise the sediments which can then be compared with the corresponding signatures from the three potential source regions. In addition to analyses on Surma Basin sediments, some analyses were also made on modern river sediments draining the proposed source regions where published information on a source signature was insufficient.

3.1. Biostratigraphy

Newly quarried exposure of the Sylhet limestones and Kopili shales yielded *Alveolina globula* and *Opertorbitolites* sp. at the top of the Sylhet Formation indicating planktonic foraminiferal Zone P9 age (48–50 Ma) and *Morozovella spinulosa*, *Assilina* sp. and *Pellatispira* sp in the Kopili Formation immediately overlying the Sylhet Limestone indicating P14 age (38–39 Ma) (Supplementary Item 2). In previous work (Ismail, 1978; Reimann, 1993) *Morozovella spinulosa* and *Pellatispira* sp were not recorded in the Kopili Formation and thus P14 age was not assigned, and the upper Sylhet Formation was considered middle Eocene based on *Nummulites gizehensis* and *N. murchisoni* which is now redated P9–P12 (Schaub, 1981), consistent with our data. Our data reveal a nine million year gap between the Sylhet and Kopili Formations at this location that may represent a disconformable or faulted contact, consistent with the marked lithological change (Field photos, Supplementary Item 2). Poor exposure and unstable slopes precluded more detailed study at this location. Previous authors considered the transition to be generally conformable, but faulted in this area (Reimann, 1993).

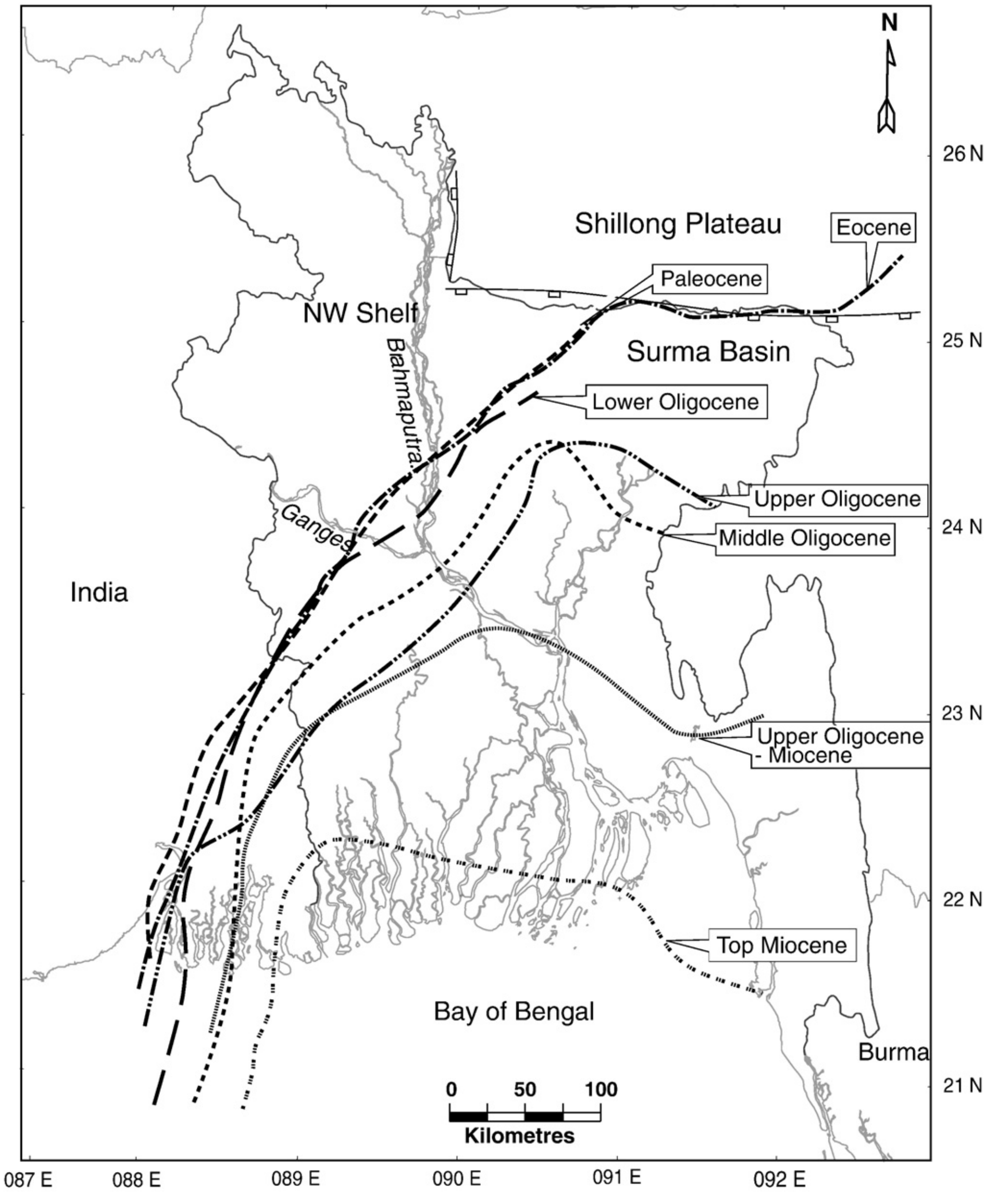

Fig. 2. Progradation of the deltaic shelf-slope break from NW to SE through time, identified from stratal geometries and systems tracts. Patterned lines indicate the prograding position of the shelf-edge break at given time intervals. Outline of Bangladesh and major rivers shown in grey lines. From Bower et al. (2006).

Based on the presence of *Turborotalia pomeroli*, *Pellatispira* sp. and *Assilina* sp, we assign a planktonic foraminiferal Zone P14 age (38 Ma) to a limestone intercalated within the thick sandstones of the Barail Formation a few 10s of metres above the base of the succession. Small patches of micrite are reworked in to the matrix, but all foraminifera are in situ within the matrix and not reworked. No biostratigraphic information was obtained from higher up the succession.

3.2. Seismic data

Over 300 2D seismic lines covering the NW Shelf and Surma Basin were interpreted in order to identify clinoform progradation and map the direction of progradation of the delta's shelf-slope break (Bower et al., 2006; Chisty, 2007, this study). Clinoforms show sediment input direction to the basin from the NW, consistent with progradation of the delta to the SE over time as mapped by the shifting position of the shelf-slope break (Fig. 2 and Supplementary Item 3). Potential sediment sources consistent with such an input direction are the Himalaya and Indian craton.

3.3. Petrographic and heavy mineral data

Analyses were carried out to determine the first order characteristics of the bedrock being eroded. Twenty samples from Paleogene rocks of the Surma Basin and NW Shelf were analysed, along with four modern river samples draining the Shillong Plateau and Indian craton. For petrographic analysis, 400 points were counted for each sample by the Gazzi Dickinson method (Ingersoll et al., 1984) The 63–250 μ sand fraction was used for heavy mineral analyses, with 200–250 transparent heavy minerals counted using the ribbon-counting or Flett methods (Mange and Maurer, 1992). Full methodology is given in Supplementary Item 4.

The Barail Formation plots in the Recycled Orogenic Province of the standard QFL plot (Dickinson, 1985) (Fig. 3, Table 2, and Supplementary Item 4). Lithic fragments of metamorphic, as well as sedimentary and volcanic origin are present. Heavy minerals are dominated by the "ultrastables" — zircon, tourmaline and rutile, and Cr-spinel occurs occasionally. By contrast, the underlying Kopili and Tura Formations contain no evidence of metamorphic detritus. The Kopili Formation contains Cr-spinel. Detrital material is minimal in the Sylhet Formation.

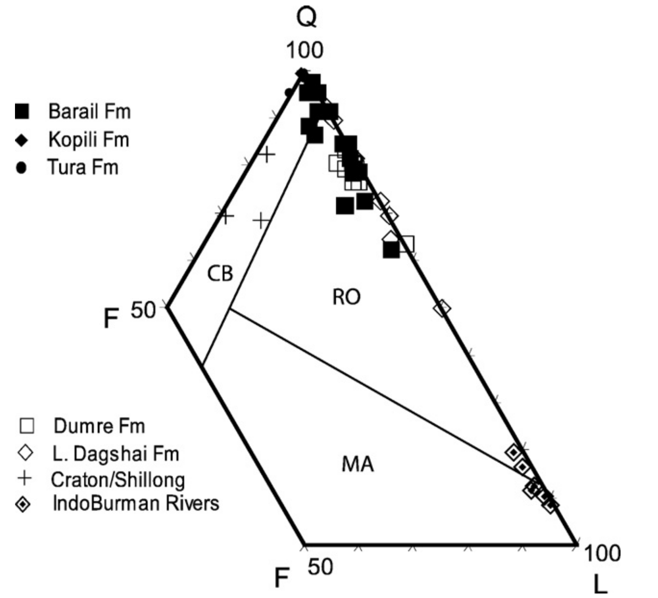

Fig. 3. Petrography of the Tura, Kopili and Barail Formations plotted on a standard QFL plot (Dickinson, 1985). Q = Quartz, F = feldspar, L = lithic fragments. CB = Cratonic Block provenance. RO = Recycled Orogen provenance. MA = Magmatic Arc provenance. Also shown for comparison are values from potential source regions: rivers draining the Indian shield and Shillong Plateau (this study), rivers draining the Paleogene Indo-Burman Ranges (Allen et al., in press), and early Miocene Himalayan foreland basin sedimentary rocks of the Dagshai (India) and Dumre (Nepal) Formations (DeCelles et al., 1998; Najman and Garzanti, 2000).

3.4. Zircon U–Pb data

The closure temperature in the zircon U–Pb system is ~750 °C, and therefore the grain age reflects the time of crystallization or near peak metamorphism. The method is therefore ideal for discriminating between the Jurassic–Paleogene arc and Proterozoic Indian continental crust. Between 24 and 64 grains from each of 8 samples spanning the Paleogene formations of the Surma Basin and NW Shelf as well as one post-Barail Neogene sample, and modern river sediments draining the Indian craton and Shillong Plateau, were analysed by Laser Ablation ICP-MC-MS methods. Methodology and full results are given in Supplementary Item 5.

Grains in the Barail Formation are predominantly of Proterozoic age, but with discernable populations of Late Jurassic–Cretaceous and Cambro-Ordovician ages, and rare Archean grains. A similar grain assemblage is present in the Kopili Formation. By contrast, Jurassic–

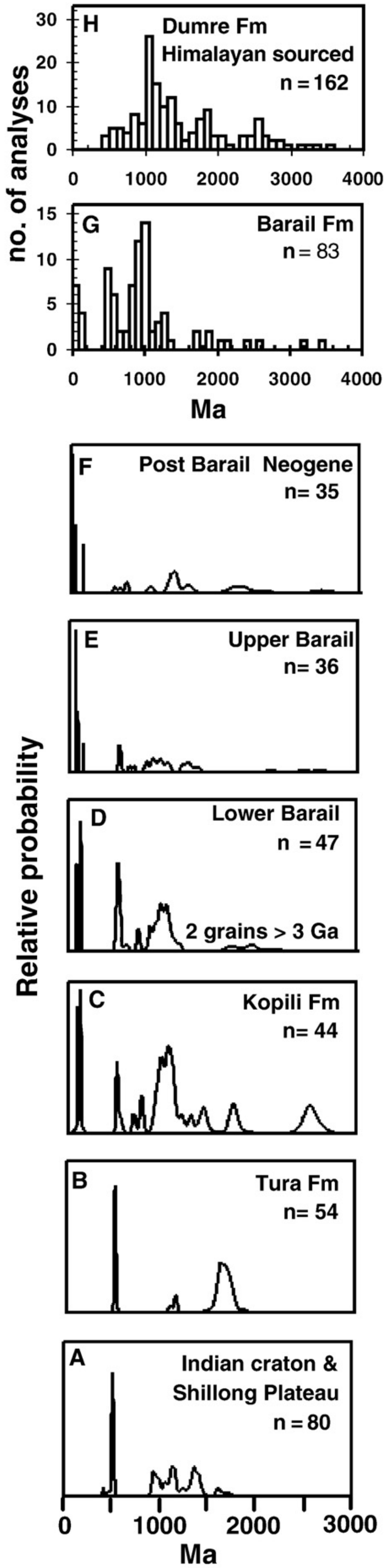

Fig. 4. ^{206}Pb–^{238}U analyses of detrital zircons showing the evolution of provenance in the Bengal Basin sediments from Indian craton to Himalayan sourced. Graphs A–F; Probability density plots taking into account individual uncertainties. Grains from the late Paleocene–early Eocene Tura Formation (sample BA05-19E; Graph B) show similarity with an Indian cratonic signature (combined samples from the Chotanagpur belt ICDAM and Shillong Plateau BA05-13B and 20A; Graph A). A new source, shedding Cretaceous grains, is first evidenced in the late Eocene Kopili Formation (NW Shelf Core sample 1; Graph C), also documented in the late Eocene–early Miocene Barail Formation (BA06-6B; Graph D, BA03-13A; Graph E) and interpreted as eroded from the Trans-Himalayan arc. Cretaceous grains are rare in the post-Barail Neogene sample (BA05-5A; Graph F), consistent with the concept of the rising orogen diluting the arc signal and providing a barrier to transport of arc detritus from the north. The age distribution of the remainder of the grains in this sample (excluding a new Neogene source most probably that of Himalayan leucogranites) is in the range 500–>3000 Ma, similar to that of the Barail Formation. Assignment of these grains to a Himalayan source is validated by the similarity between grain age distributions in the Barail Formation and Himalayan-derived Dumre Formation of the foreland basin. Due to differences in analytical precision between analyses from these two sample sets, comparison is facilitated by representing the data in histograms. Barail Formation samples from Graphs D and E are replotted as a histogram in Graph G, and data from the Himalayan-derived Dumre Formation is given in Graph H (data from DeCelles et al., 2004).

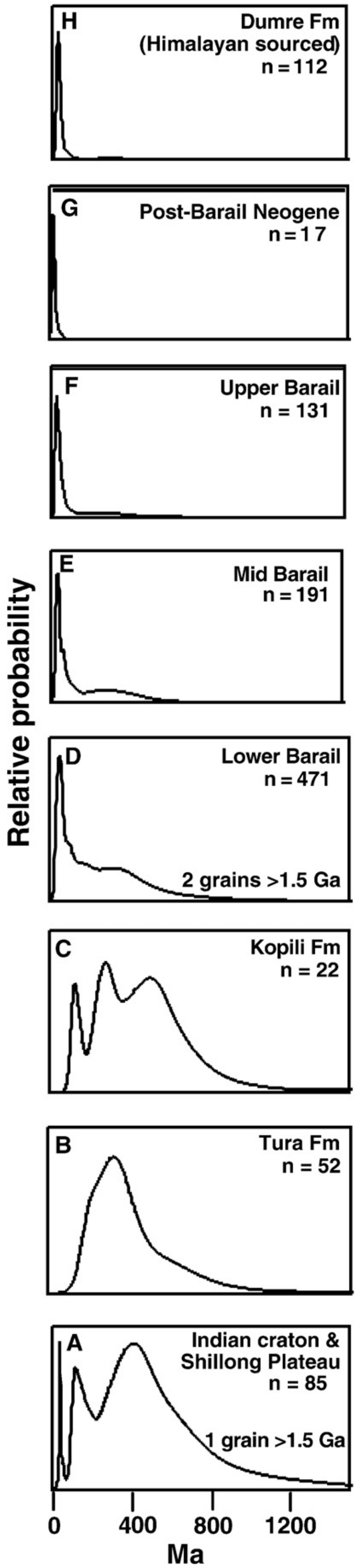

Fig. 5. Probability density plots of detrital zircon fission track ages taking into account individual uncertainties. Data illustrate the first input of material from Himalayan metamorphosed rocks in the Barail Formation, as evidenced by appearance of Tertiary aged grains. Tertiary aged grains are extremely rare in the Indian craton (combined samples ICDAM, BA05-1B, 13B & 20A from Indian craton and Shillong Plateau; Graph A) and absent from the L. Paleocene–E. Eocene Tura Formation (BA05-19A; Graph B) and L. Eocene Kopili Formation (NW Shelf Core sample 1; Graph C). First appearance and upward increase in proportion of Tertiary aged Himalayan grains occurs in the Barail Formation and into the overlying post-Barail Neogene rocks (combined samples BA03-9A, 10A, 12A, BA05-15D, 15F, 16A, 17A, BA06-5A, 6B; Lower Barail Graph D. Combined samples BA06-8A, 8B, 10A; Mid Barail Graph E. Combined samples BA03-13A, BA05-9A, BA06-16A; Upper Barail Graph F. BA03-18A; Post Barail Neogene sample Graph G), resembling the signature of material eroded from the Himalaya during Neogene times (Dumre Formation, data from Najman et al., 2005; Graph H). Whilst ZFT data are shown as probability plots for simple comparison, we note that for mixed age data, where individual age uncertainties vary, peak height may not relate to grain age abundance and in some cases can mask minor age modes. Radial plots which permit more robust visualisation of grain age distributions can be seen in Supplementary Item 5.

Cretaceous and Archean grains are absent from the Tura Formation (Fig. 4, Table 2, and Supplementary Item 5).

3.5. Zircon fission track data

Zircon fission track ages record the time the mineral cooled through its partial annealing zone of ~200–320 °C (Tagami et al., 1998). Assuming that the grain has not been subjected to temperatures in excess of this post-deposition (we use illite crystallinity and clay mineralogy to determine post-depositional temperatures; see Section 3.10), the age will reflect the time of exhumation of the detrital grain in its source region. The method is therefore particularly useful in the discrimination between old stable cratonic areas versus young igneous or recently metamorphosed regions. 22 samples from Paleogene formations and 1 post-Barail Neogene sample, from the Surma Basin and NW Shelf, and modern river sediments draining the Shillong Plateau and Indian craton, were analysed using the external detector method (Hurford, 1990). Methodology and full results are given in Supplementary Item 6.

All formations (Tura, Kopili and Barail) contain Paleozoic aged grains. In addition, grains with Cretaceous fission track ages are present in the Kopili and Barail Formations, and Tertiary grains are only present in the Barail Formation (Fig. 5, Table 2, and Supplementary Item 6). The youngest age population decreases upsection whilst the proportion of grains <55 Ma increases.

3.6. White mica Ar–Ar data

White micas have a closure temperature of ~350 °C and application of this technique to provenance analysis is therefore similar to that of zircon fission track analysis. The two techniques are complementary, together broadening the range of lithotectonic units of different mineralogy that can be sampled. $^{40}Ar/^{39}Ar$ analyses were carried out on single white mica grains by laser total fusion. Around 40 grains/sample were analysed. The 13 samples analysed spanned the Surma Basin Paleogene formations as well as one post-Barail Neogene sample, and modern river sands draining the Indian craton and Shillong Plateau. Methodology and full results are given in Supplementary Item 7.

Micas from the Tura and Sylhet Formations have uniform Cambro-Ordovician Ar–Ar ages. Cambro-Ordovician and Tertiary grains are present throughout the Barail Formation, except in basal unmicaceous strata (Fig. 6; Table 2, and Supplementary Item 7). The proportion of grains <55 Ma increases upsection.

3.7. Sm–Nd bulk rock data

Nd isotopic compositions are given in εNd units, the deviation from the bulk earth (CHUR with $^{143}Nd/^{144}Nd = 0.512638$ at $t = 0$) times

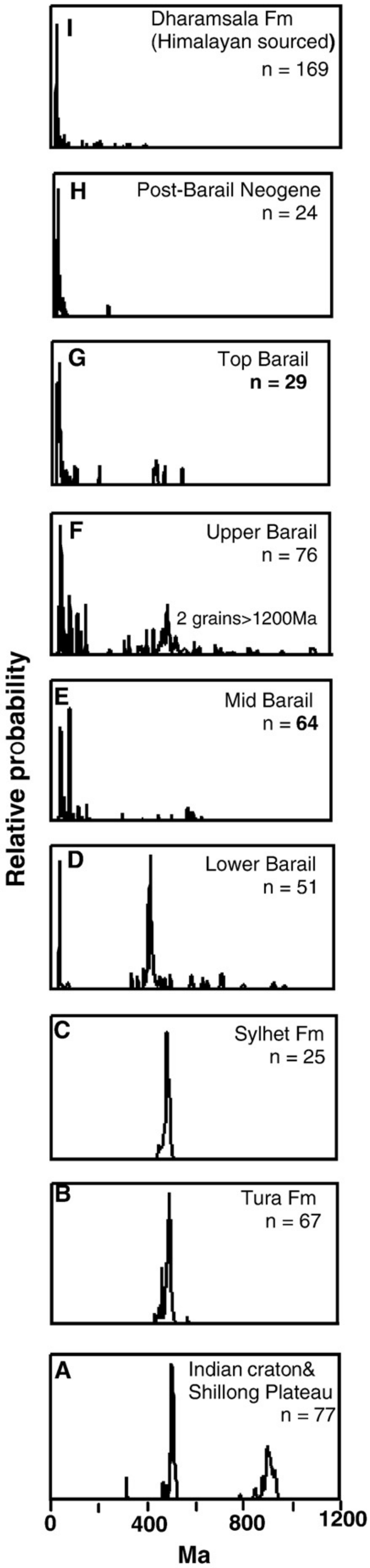

Fig. 6. Probability density plots showing Ar–Ar total fusion analyses of detrital white micas, taking into account individual uncertainties. Graphs show the evolution of provenance in the Bengal Basin sediments from Indian craton to Himalayan sourced. Age populations of the late Paleocene–early Eocene Tura Formation (samples BA05-19A & E combined; Graph B) and early–mid Eocene Sylhet Formation (BA03-8A; Graph C) show similarity with the Indian cratonic signature (Chotanagpur belt sample ICDAM and Shillong sample BA05-13B combined; Graph A). A new source is identified with first input of Tertiary aged Himalayan grains in the late Eocene lower Barail Formation (BA03-10A & BA05-17A combined; Graph D), a trend which continues upsection to the top of the Barail (early Miocene) (BA06-8A & 8B combined; Graph E, BA05-8A & 9A combined; Graph F, BA03-13A; Graph G) and into the post-Barail Neogene rocks (BA03-18A; Graph H). Assignment of the Barail Formation to a Himalayan provenance is validated by comparison with Ar–Ar detrital white mica data from the Himalayan-derived 20 Ma Dharamsala Formation of the foreland basin (Graph I, data from White et al., 2002).

10^4. For most crustal rocks with low Sm/Nd ratios compared to mantle sources, εNd therefore is a function of the time (or average time) at which the crustal source separated from the mantle. Eleven samples were analysed by thermal ionisation mass spectrometry. Samples consisted of mudstones and siltstones of the Paleogene formations of the Surma Basin and NW Shelf, and a sand from a modern river draining the Indian craton. Methodology and full results are given in Supplementary Item 8.

εNd(0) values for the Tura and Sylhet Formations lie between −15 and −18. Less negative values were recorded in the Kopili Formation (−12 to −13), with a spread of values from ~11 to −15 in the Barail Formation (Table 2 and Supplementary Item 8).

3.8. $^{187}Os/^{188}Os$ bulk rock data

Fractionation within the Re–Os system results in high $^{187}Os/^{188}Os$ values being typical of crustal material and lower values typical of mafic or arc material. Seven samples, spanning the Paleogene of the Bengal Basin and two modern river sands draining the Shillong Plateau, were analysed by negative thermal ionisation mass spectrometry (Creaser et al., 1991; Volkening et al., 1991), after Carius tube digestion (Shirey and Walker, 1995) and Os extraction with liquid bromine (Birck et al., 1997). Values for the Kopili and Barail Formations contrast with those of the Sylhet Formation, with the former values <1 and the latter values >1. Results are summarised in Table 2. Methodology and full results are given in Supplementary Item 9.

3.9. Cr-spinel geochemistry

TiO_2 values in Cr-spinel can provide discrimination between potential source types, with low TiO_2 values characteristic of Cr-spinels from arc/ophiolitic rocks and high values characteristic of continental flood basalts (Kamenetsky et al., 2001) such as those found in the Indian craton, e.g. the Rajmahal Traps (Fig. 1). Four spinel grains from the Barail Formation and four grains from the Kopili Formation were analysed by electron microscopy. Cr-spinels analysed from both the Kopili and Barail Formations have low TiO_2 values, similar to the signature of spinels from the Himalayan suture zone (Maheo et al., 2004) and foreland basin detritus (Najman and Garzanti, 2000), and dissimilar to the geochemistry of spinels from the Deccan Traps (Krishnamurthy and Cox, 1977; Mukherjee and Biswass, 1988; Sen, 1986) (Table 2 and Fig. 7). Methodology and full results are given in Supplementary Item 10.

3.10. Clay mineralogy and illite crystallinity data

The thickness of illite crystals is dependent on metamorphic grade (Weber, 1972). Thus, XRD analyses on the <2 μ (diagenetic) fraction of rocks, to determine illite crystallinity as well as clay mineralogy (which is also diagnostic of metamorphic grade), enable post-depositional burial temperatures of the rocks to be determined. This allows us to assess if the detrital mineral isotopic ages reflect timing of

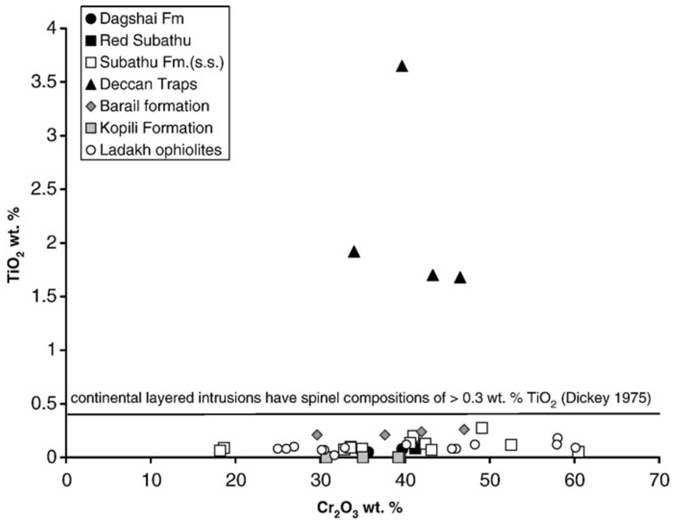

Fig. 7. Geochemistry of detrital Cr-spinel from the Barail and Kopili Formations. Data show that composition is similar to that of spinels eroded from the Himalayan arc/ophiolite (such environments typically have low TiO_2) and grains found in the Subathu and Dagshai Formation foreland basin strata (Maheo et al., 2004; Najman and Garzanti, 2000) and dissimilar to geochemistry of spinels present in CFBs such as the Deccan Traps (Krishnamurthy, 1977;Mukherjee, 1988; Sen, 1986), which typically have high TiO_2 content (Dickey, 1975; Kamenetsky et al., 2001).

exhumation in the source region or post-depositional resetting. Analyses were undertaken on the <2 μ fraction of 18 samples from the Surma Basin and NW Shelf. Siltstones were analysed due to the scarcity of mudstones. Whilst the illite crystallinity data indicate epizone to upper anchizone conditions, the clay mineralogy of these same samples shows mixtures of kaolinite, illite and mixed layer chlorite/smectite and illite/smectite which are diagnostic of the diagenetic zone of burial. The discrepancy appears to be due to the presence of <2 μ detrital micas in the <2 μ sediment fraction which swamp the diagenetic illite signal. The clay mineralogy indicates that burial temperatures were <200 °C and therefore our zircon fission track and mica Ar–Ar ages reflect the time of exhumation in the source region. Full methodology and results are given in Supplementary Item 11.

4. Interpretations

4.1. Age of the Paleogene rocks of the Surma Basin

As discussed in Section 3.1, the exposed Sylhet Formation is dated at 48–50 Ma, and the exposed Kopili Formation at 38–39 Ma in the area of study. Biostratigraphic data date the lowest Barail at 38 Ma. In the upper Barail Formation, detrital mica Ar–Ar ages of 21±3 Ma, and zircon fission track ages of 23±1 Ma (Sections 3.5 and 3.6) provide a maximum depositional age for the rock. The Barail Formation thus spans the late Eocene to early Miocene (38–<21 Ma).

4.2. Provenance of the Paleogene rocks of the Surma Basin

We compare the petrographic and isotopic characteristics of the Surma Basin rocks with the equivalent characteristics from the potential source regions of the Himalaya, the Indian craton and the Burman arc/Indo-Burman Ranges (Fig. 1). The characteristics of these potential source regions are given below, summarised in Table 2 and in full in Supplementary Item 1, defined both from the published literature and by our analyses of modern river sediments draining the potential sources.

In tectonically active regions, ongoing tectonism may have overprinted some of the isotopic and petrographic signatures of the rocks that were providing the source during the Paleogene period of interest. We therefore also compare our data to sedimentary rocks eroded from the source regions of interest during the Paleogene. Paleogene material, confidently assigned to a Himalayan provenance, is preserved in the foreland basin in the ~Paleocene–mid Eocene Bhainskati Formation (Nepal) and Subathu Formation (India), which have limited detrital input, and the disconformably overlying thick Himalayan-derived sandstones of the late Oligo-Miocene Dumre Formation (Nepal), correlative with the Dharamsala, Dagshai and Kasauli Formations of India (DeCelles et al., 2004; 2001; Najman and Garzanti, 2000; Najman et al., 2004; White et al., 2002). Table 1 shows the correlation between foreland basin and Bengal Basin stratigraphy. The Paleogene segment of the Indo-Burman Ranges, interpreted as an accretionary prism or forearc, contains the history of erosion from the Cretaceous Burman margin during this time interval (Allen et al., in press). Compared to the Cretaceous part of the Burmese margin, the more westerly located Indo-Burman Ranges are the more likely potential source to the Bengal Basin during the Paleogene given their proposed exhumation during the late

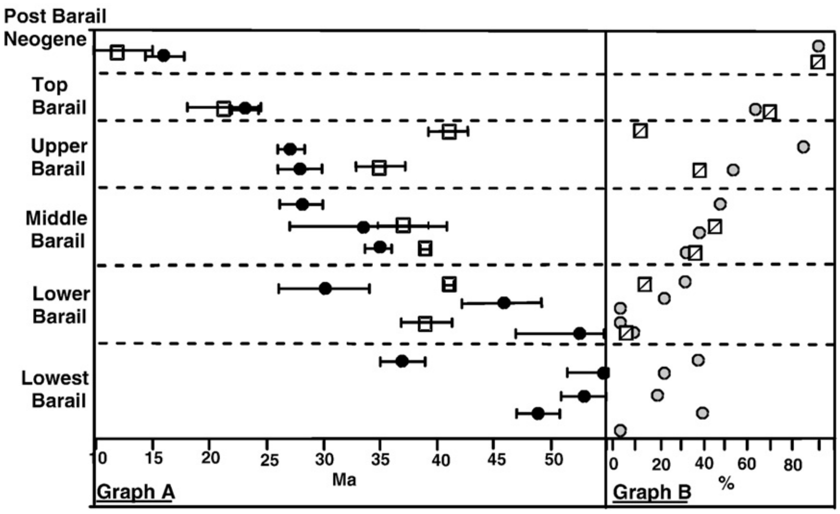

Fig. 8. Detrital parameters illustrating exhumation to deeper metamorphic levels in the orogen through time, from lowest Barail (38 Ma) into the overlying post-Barail Neogene deposits. Within each sub-unit of the Barail (lowest, lower, mid, upper, top), no stratigraphic order is implied from the vertical succession of samples shown on the graph. Graph A: youngest mica Ar–Ar age (squares) and youngest zircon fission track mode (circles) decreases upsection. Error bars at 2 sigma level for Ar–Ar data and 1 sigma level for fission track data. Graph B: percentage of grains <55 Ma increases upsection; squares represent mica Ar–Ar data, circles represent zircon fission track data.

Eocene–early Oligocene (Mitchell, 1993) which would have provided a barrier to sediment transport from further east.

We also compare our data from the Palaeogene rocks of the Surma Basin with the isotopic and geochemical characteristics of the overlying post-Barail Neogene strata in the Surma Basin, which are generally agreed to be Himalayan-derived (e.g. Johnson and Alam, 1991; Rahman and Faupl, 2003; Uddin and Lundberg, 1998a,b).

4.2.1. Characteristics of the potential source regions (Table 2 and supplementary item 1)

Much of the Indian craton has Archean mineral ages (Auge et al., 2003; Mishra et al., 1999) and very negative εNd values (more negative than −30) (Table 2 and Supplementary Item 1; Peucat et al., 1989; Saha et al., 2004). However, the Indian continent adjacent to the Bengal Basin is the Chotanagpur Proterozoic mobile belt (Acharyya, 2003; Misra and Johnson, 2005) (Fig. 1), distinct from the Archean craton. We have analysed modern sediment from the Damodar River draining the Chotanagpur belt and from the Jadhu Kata, Shari and Dauki Rivers draining the southern Shillong Plateau (an extension of this belt; Fig. 1), to better characterise this part of the shield. The arkosic sediments contain overwhelmingly Palaeozoic and Proterozoic mineral grains, with εNd values significantly less negative than those analysed from the Archean part of the shield. These new data are summarised in Table 2, presented in Figs. 3–6 and recorded in Supplementary Items 4–7.

By contrast, the potential eastern (Burman) source is considerably younger. The active margin in western Burma is represented by the Tertiary Mt. Popa belt (Stephenson and Marshall, 1984) and an older Cretaceous belt which continues north into the Mogok belt, and correlates north-west with the Trans-Himalayan arc (Gangdese Batholith, Lhasa and Karakoram Terranes) (Fig. 1 Inset A) (Barley et al., 2003; Mitchell, 1993). West of the Cretaceous belt, the Burmese arc-derived Paleogene Indo-Burman Ranges (Fig. 1) sedimentary rocks provide a signature for the material eroded from this arc during the Eocene–Oligocene (Allen et al., in press), as explained above. Characteristics are summarised in Table 2.

Finally, detritus from the potential northern source is today dominated by material from the Higher Himalaya, metamorphosed during Tertiary orogenesis, and with mineral cooling ages (mica Ar–Ar and zircon fission track) reflecting this. However, during earlier stages of orogenesis, a greater proportion of weakly or unmetamorphosed Higher Himalayan cover and Tethyan sedimentary rocks unaffected by Himalayan metamorphism would have been eroded, reflected in a higher proportion of grains with pre-Tertiary ages. Additionally, a proportion of material located further to the north and derived from the Jurassic–earliest Tertiary batholith of the Trans-Himalaya (Scharer and Allegre, 1984) and ophiolitic suture zone was transported southward to the basins, a signal that became less pronounced with time as the thrust belt becoming a significant topographic barrier (Guillot et al., 2003) and the arc/suture zone material became increasingly swamped by dilution with Indian-plate detritus. Published data on the characteristics of the Himalayan source, derived from bedrock and Himalayan detritus preserved in the foreland basin, is summarised in Table 2 and Figs. 3–7. We augmented these data with analyses from Surma Basin post-Barail Neogene strata, of Himalayan provenance. These new results are presented in Figs. 4, 5, 6 and 8, and recorded in Supplementary Items 5–7.

These three potential source regions are thus distinguishable in terms of petrography, isotopic signatures and mineral ages (Table 2 and Supplementary Item 1). Material shed from the Indian craton is predominantly arkosic, with minerals of Precambrian–L. Palaeozoic age, whilst material eroded from the east contains a strong signature from the Mesozoic–Tertiary Burman arc. By contrast, the Himalayan source provides predominantly metamorphic material with Tertiary mineral cooling ages reflecting the orogeny, plus subordinate material from the non-metamorphosed sedimentary cover of Precambrian–Cretaceous age, and Jurassic–earliest Tertiary arc and ophiolitic material.

4.2.2. Provenance of the Paleogene Surma Basin rocks: interpretation and integration of the data

The earliest significant detritus in the basin above the carbonate Sylhet Formation is recorded in the deltaic Barail Formation. A NW sediment input direction, determined from seismic data, indicates a major source was either the Indian craton or the Himalaya.

4.2.2.1. A cratonic provenance for the Barail Formation? Provenance indicators for the Barail Formation are inconsistent with derivation from a cratonic source (Table 2). Cratonic river sediments are arkosic with rare lithic fragments, and detrital zircons and micas have fission track and Ar–Ar cooling ages mostly >300 Ma. This contrasts with the Barail Formation where metamorphic lithic fragments and grains with Tertiary cooling ages are prevalent, and feldspar is relatively uncommon. The cratonic samples lack a zircon population with U–Pb ages >1800 Ma, of which there is a small population in the Barail Formation. Barail Formation $^{187}Os/^{188}Os$ values are lower than those of the Shillong Plateau (no data are available for the extension of the Proterozoic belt in India).

4.2.2.2. A Himalayan provenance for the Barail Formation. The Barail rocks' petrographic and isotopic signatures are typical of Himalayan detritus, showing close resemblance to that of the early Miocene Dumre and Dharamsala Formations — foreland basin deposits in Nepal and India respectively, of known Himalayan derivation (Section 4.2, Table 1). Most distinctive is the prevalence of minerals with Tertiary cooling ages in the Barail Formation, typical of Himalayan provenance (Table 2). The Barail Formation contains a significant number of zircons with Tertiary fission track ages. The age range is similar to that of the Dumre Formation (Najman et al., 2005) (Fig. 5), but with a higher proportion of pre-Tertiary grains, reflecting greater erosion from the non/weakly-metamorphosed Himalayan cover rocks rather than the deeper metamorphic levels of the Himalayan core (Section 4.2.1). Similarly, Ar–Ar mica ages from the Barail Formation have a Tertiary population, but show a higher proportion of pre-Tertiary ages compared to the typical Tertiary distribution which dominates the Dumre and Dharamsala Formations, although some pre-Tertiary grains are found in the foreland basin as well (DeCelles et al., 2001; White et al., 2002) (Fig. 6).

Zircon U–Pb ages are broadly similar between Barail and Dumre Formations (Fig. 4) consistent with Himalayan bedrock data (Table 2; DeCelles et al., 2004). A greater proportion of grains aged around ~500 Ma in the Barail Formation compared to the Dumre Formation could reflect a higher contribution from Tethyan Himalayan cover compared to Higher Himalayan core, whilst the small population of Cretaceous "arc-aged" grains indicates that at this time the mountain belt did not provide a complete barrier to the suture zone in this area. The Barail Formation contains metamorphic lithic fragments, and samples plot in the same "Recycled Orogen" region as the Dumre Formation on the QFL plot (Fig. 3). Cr-spinel geochemistry is similar to that of detrital spinels found in the Eocene Himalayan foreland basin rocks and suture zone ophiolites (Maheo et al., 2004; Najman and Garzanti, 2000) and dissimilar to the geochemistry of grains found in continental flood basalts such as those of the Indian craton. εNd(0) values are similar to those of the Paleogene Himalayan foreland basin deposits and Himalayan bedrock (DeCelles et al., 2004; White et al., 2002), with the bias towards slightly lower values expected in view of subordinate arc/ophiolitic input (see below), although the data would also be consistent with derivation from the Indian shield (Table 2). Thus, overall, the data show convincing evidence that the Barail Formation is predominantly Himalayan-derived.

Data from the Barail Formation are entirely consistent with the progressive erosion to deeper levels of the Himalayan orogen through time (Fig. 8). Himalayan input is already evident in lower Barail samples which contain very low grade metamorphic lithic fragments, and detrital grains with Tertiary "Himalayan" zircon fission track and mica Ar–Ar ages. However, such detritus is subordinate in these samples, and in the lower part of the Barail Formation, minerals with pre-Tertiary ages characteristic of the weakly/unmetamorphosed orogenic cover are more dominant. Ratios of Tertiary to pre-Tertiary mineral cooling ages increase upsection in the Barail Formation and youngest mineral cooling ages decrease, reflecting progressive exhumation of the orogen — trends that continue into the overlying post-Barail Neogene rocks of the Surma Basin (Fig. 8). However, even at the onset of Barail deposition, orogenic exhumation was rapid, as evidenced by the short lag time between sediment depositional age (38 Ma) and the fission track age of the youngest detrital zircon population (37±2 Ma) from a sample a few 10s of metres above the Barail limestone.

4.2.2.3. Subordinate arc/ophiolitic input to the Bengal Basin. A subordinate contribution of arc/ophiolite source to the Barail and Kopili detritus is indicated by relatively unradiogenic $^{187}Os/^{188}Os$ values, presence of Cr-spinel with low TiO_2 geochemistry, zircons with Cretaceous fission track and U–Pb ages, and volcanic lithic fragments. Such a source was in all probability the Jurassic–Tertiary arc and ophiolite belt that in the west characterises the India–Asia collision zone in the Himalaya, continuing south-east into Burma. On the basis of composition, it is not possible to differentiate from which part of the arc this subordinate mafic component was derived. A Northern (Himalayan) source rather than an eastern (Burman) source would be consistent with seismic evidence of a dominant input direction from the NW. Transport of arc/ophiolitic detritus south from the Himalaya at this time is evidenced in the Eocene Himalayan foreland basin sediments in India (Najman and Garzanti, 2000) (Section 4.3.3), with decreased igneous influence upsection as the nascent Himalayas evolved into a significant range that acted as a barrier to southward transport of arc material and produced detritus that diluted and swamped the arc signal. Nevertheless, an additional subordinate input from the east may lie undetected in available seismic images. However, palaeogeographic considerations suggest derivation from the eastern (Burman) part of the arc to be the less likely option: detritus would have had to be transported across the subduction trench to the Surma Basin, and additionally transported updip/oblique to the shelf-slope break in order to be incorporated into samples of the NW Shelf (Fig. 1). Regardless of whether the arc source lay to the north or east, the emerging Indo-Burman Ranges as a *substantial* source to the Barail Formation can be ruled out because the much finer grained facies of the Paleogene Indo-Burman Ranges, absence of white mica, paucity of zircons with fission track ages older than Cretaceous, scarcity of heavy minerals, and εNd and $^{187}Os/^{188}Os$ values that indicate appreciable mafic igneous contribution (Allen et al., in press, Table 2) contrast markedly with Barail Formation characteristics.

The distinct change in provenance at the Sylhet–Kopili boundary reflects the lack of arc-derived detritus to the basin below the Kopili Formation. In contrast to the Kopili Formation, the Sylhet and Tura Formations show no evidence of arc/ophiolitic input in terms of petrography (no evidence of Cr-spinel), isotopic signature (higher $^{187}Os/^{188}Os$ ratios compared to the relatively unradiogenic values in the Kopili Formation) or mineral ages (no evidence of Cretaceous or Tertiary grains). Instead, the rocks display a striking similarity to the Indian cratonic signature. The Tura Formation is comprised mostly of quartz and feldspar, similar to the cratonic samples but dissimilar to the lithics-bearing Barail. Zircon U–Pb ages from the Tura Formation lie in the same restricted range as those of rivers draining the Shillong Plateau (500–1800 Ma). Micas from the Tura and Sylhet Formations, and from rivers draining the Shillong Plateau, are all characterised by Ar–Ar ages ~500 Ma. The Sylhet Limestones contain little other detrital material.

These data therefore show that the major change from cratonic to arc provenance, most probably of Trans-Himalayan origin, occurs at the Sylhet–Kopili transition, which is dated at sometime between 48 and 39 Ma. However the detritus is very limited in the Kopili Formation. It is not until the start of the Barail Formation at 38 Ma that significant erosion of the Himalaya is recorded in the >1 km thick sands, containing evidence of significant erosion from metamorphic sources, and rapid exhumation of the hinterland.

4.3. Regional applicability: correlation and comparison with data from the southern Bengal Basin, Bengal Fan and Himalayan foreland basin

4.3.1. The southern Bengal Basin

Our data from the northern Bengal Basin can be correlated over a large area of the delta where previous workers, utilising seismic lines calibrated to well data in India, have taken the Sylhet–Kopili boundary to represent the proto-delta to transitional-delta transition, above which major Himalayan-derived input initiated sometime around 40 Ma (Lindsay et al., 1991).

4.3.2. The Bengal Fan

Data collection from the Bengal Fan over a number of decades has resulted in continual refinement of interpretations (Curray, 1994). In this discussion we use the most recent published paper and references therein (Curray et al., 2003), augmented by personal communication with J. Curray (2007).

A regional onlap unconformity in the Bay of Bengal is postulated to represent the time of first deposition of Bengal Fan material above continental rise sediments. The age of these oldest Himalayan-derived Bengal Fan sediments cannot currently be accurately ascertained as the Fan has not been drilled to its base. The unconformity is “tentatively” dated at early Eocene, based on seismic correlation with dated sediments on the Ninety East Ridge. However, whilst sediments overlying the unconformity in the basin are considered to be Himalayan-derived turbidites, sediments overlying the probable equivalent unconformity on the ridge are pelagic, and unrelated to Himalayan deposition. Therefore, the timing of onset of Himalayan-sourced sedimentation after the hiatus in the basin cannot be directly determined from the age of pelagic sediments post-hiatus on the ridge. Thus, Bengal Fan researchers refer to the age of the continental rise deposits only as “pre-Eocene” and the overlying Bengal Fan unit as “post-Paleocene”.

Given the progradational nature of the Bengal delta-fan, deposition of Himalayan-derived material in the basin should occur earlier in the north than the south, and the duration of the hiatus should increase southward. This is in agreement with, for example, the postulated Oligocene age of the base of the Fan at distal ODP Site 116, calculated by extrapolation of deposition rates. Our 38 Ma age of first arrival of Himalayan detritus in the Bengal Basin is younger than the early Eocene age of the seismically identified unconformity in the Bay of Bengal. However, if we follow the conservatism of previous worker's age assignment of the Bengal Fan Unit as “post-Paleocene”, our data are not contradictory.

4.3.3. The foreland basin

The late Eocene–early Miocene Barail Formation represents that part of the Himalayan erosion record which corresponds to a disconformity in the foreland basin (Table 1; DeCelles et al., 2001; Najman et al., 2004; 2001). In the foreland basin, Paleocene–Eocene shallow marine limestones, mudstones and minor sandstones of the Subathu Formation (India) and Bhainskati Formation (Nepal) lie below the disconformity. These formations contain detectable but limited Himalayan detritus (Najman, 2006 and references therein; Najman et al., 2005; Najman and Garzanti, 2000). Substantial Himalayan input is first observed above the foreland basin disconformity, in alluvial facies dated from 21 Ma in Nepal (Dumre Formation), with equivalent formations in India dated from 21 Ma (Dharamsala Formation) and <30 Ma (correlative Dagshai and Kasauli Formations) (DeCelles et al., 2001; Najman et al., 2004; White et al., 2002). The upper Barail Formation, which extends into the early Miocene, therefore most likely overlaps with the oldest alluvial rocks of the foreland basin, and the Barail Formation as a whole plugs the hitherto missing part of the Paleogene record of Himalayan erosion, allowing a more complete orogenic unroofing history to be documented.

In our studied area of the Bengal Basin the earliest arc-derived input, albeit of limited extent, is recorded in the Kopili Formation. Initial arrival of detritus therefore occurs sometime within the interval between 48 and 39 Ma, which corresponds to the ages of our samples from the Sylhet and Kopili Formations respectively. This is not inconsistent with the foreland basin record. The time of initial input of limited Himalayan detritus to the foreland basin, of arc/suture zone provenance in India and metamorphosed core in Nepal, cannot be dated more precisely than sometime within the period late Paleocene to lower-mid Eocene (the age of the Subathu Formation) and sometime within the lower to mid Eocene (the age of the Bhainskati Formation). There is no assertion that Himalayan detritus is found throughout these formations, and the upper ranges of their ages extend into the period between the dates of our Sylhet and Kopili Formation samples, for which we have no data.

38 Ma sees first evidence of substantial Himalayan erosion in the thick Barail sandstones. Sedimentary/low metamorphic grade Himalayan cover material dominates the detritus at the base of the succession. Progressive unroofing of the orogenic core is reflected in the increasing proportion of Tertiary grains upsection and decreasing cooling ages of the youngest minerals (Figs. 5, 6 and 8). This trend is continued in the foreland basin record above the disconformity (Szulc et al., 2003). The top of the Barail Formation (dated at <21 Ma) is approximately coeval with the Dharamsala and Dumre Formations, the bases of which are dated at 21 Ma and which, like the Barail Formation, have youngest mica Ar–Ar ages of 20 Ma, decreasing upsection (DeCelles et al., 2001; White et al., 2002). Garnet grade material appears in the foreland basin in India by ~20 Ma, and later in Nepal (DeCelles et al., 1998), but its earlier sporadic occurrence throughout the Barail Formation should not necessarily be interpreted in terms of Himalayan erosion since garnet is also found in the cratonically-derived Paleocene–early Eocene Tura Formation. Therefore Barail garnets may have been eroded from a non-Himalayan subordinate source.

5. Discussion

Our data reduce the time interval between collision, and the oldest precisely-dated record of significant erosion and rapid exhumation of metamorphosed material from the central-eastern Himalaya's southern flanks, from >20 Myr (calculated from the oldest substantial Himalayan sediments in the foreland basin in Nepal) to 12 Myr. This explains the previous puzzling discrepancy between the lack of erosional evidence of early thrust stacking and crustal thickening south of the suture zone which is clear in the hinterland record (zircon U–Pb ages associated with peak metamorphism are dated at 35 Ma (Lee and Whitehouse, 2007) in southern Tibet, and in the central Himalaya garnet growth in the Higher Himalaya is recorded at ~35–30 Ma (Foster et al., 2000; Vance and Harris, 1999) consistent with thrusting by ~40 Ma).

Southward extrusion of low-viscosity Indian middle crust at the Himalayan topographic front by channel flow coupled to surface denudation (Beaumont et al., 2006) requires this early crustal shortening (Willett et al., 1993) to provide sufficient heating of the lower-mid crust such that flow can occur. Onset of erosion is delayed in this model in order to build up adequately thick crust to allow sufficient heating of the lower-mid crust. Onset of channel flow and plateau development occurs later if moderate erosion commences at the start of the model run. Models optimised to produce results compatible with observations of metamorphism in the Himalaya initiate erosion at 30 Ma (Jamieson et al., 2004). Advancing the start of erosion to 38 Ma will enable revision of this model, with adjustment of other poorly known input parameters (e.g. convergence rate, initial crustal thickness) in order to retain conditions suitable for channel flow, and at timescales compatible with known Himalayan evolutionary events.

Advancing the onset of rapid erosion to at least 38 Ma brings the erosion record into better alignment with that of the marine $^{87}Sr/^{86}Sr$ record, where the marked rise in $^{87}Sr/^{86}Sr$ since ~40 Ma has been attributed to Himalaya erosion (Richter et al., 1992). Still earlier erosion occurred from the north slopes of the Himalaya and Trans-Himalaya, as evidenced in the suture zone molasse and possibly the Indus Fan (Section 2.2.1), yet these western and northern drainage basins today consist of a high proportion of less radiogenic lithologies and could not explain the marked Tertiary rise in marine $^{87}Sr/^{86}Sr$ values (Pande et al., 1994).

Whether 38 Ma represents the actual initiation of vigorous erosion from the southern flanks of the east-central Himalaya, or whether older Himalayan detritus was deposited elsewhere, remains an open question. The obvious repositories for detritus eroded from the southern flanks of the Himalaya are the foreland, Indus and Bengal Basins. It seems unlikely that older deposits will be found in the Bengal Basin given the regional applicability of our data (Section 4.3.1). The foreland basin contains no substantial early Paleogene Himalayan detritus (Section 4.3.3). Whilst the imprecise dating of the first appearance of Himalayan detritus in the Indus Fan allows its viability as a repository for older east-central Himalayan detritus to be retained, a major drainage reversal in the foreland basin between Paleogene and present day would be required. A Paleogene drainage pattern with rivers flowing from the southern slopes of the east-central Himalaya westward into the Indus Fan has been proposed (Yin, 2006) to explain the supposed earlier arrival of Himalayan detritus to western basins compared to the Bengal Basin; a pattern interpreted by other workers as the result of diachronous collision (Uddin and Lundberg, 1998a). However, this east–west diachroneity of Himalayan input was based on the understanding that the Paleogene rocks of the Bengal Basin are cratonic rather than Himalayan-derived, an interpretation that our data do not agree with. Thus, in our view, there is now no reason to invoke major palaeodrainage changes or diachronous collision on the basis of sedimentary data from the Bengal Basin.

Considering that the Surma Basin lay ~1000 km south of the collision zone at 40 Ma, a likely location for any older detritus eroded from the Himalaya's southern flanks would be north of the currently studied locations buried by the south-propagating thrust belt. Thus, it may be difficult to resolve whether significant erosion of the central-eastern Himalaya's southern flanks occurred prior to 38 Ma. That the first ~12 Myr of Himalayan evolution may have been characterised by negligible erosion is supported by regional evidence for a transition from slow to exponentially increasing accumulation rates at the start of the Oligocene, determined from mass accumulation rates in mainly offshore basins surrounding the collision zone (Metivier et al., 1999). The cause of such possible negligible early erosion has been variously ascribed to either an arid climate (Guillot et al., 2003), early subdued topography which may have resulted from eclogite facies metamorphism of cold lower crust (Richardson and England, 1979), accommodation of convergence by extrusion rather than crustal thickening (Metivier et al., 1999), a low angle continental subduction plane (Guillot et al., 2003), presence of a cold dense root prior to slab break-off (Kohn and Parkinson, 2002) or collision later than generally quoted (Aitchison et al., 2007). Given the hinterland evidence of metamorphism (Foster et al., 2000; Lee and Whitehouse, 2007; Vance and Harris, 1999) which requires early crustal thickening, we would favour those models that allow such thickening but retard erosion or uplift, if early erosion was indeed negligible.

6. Conclusions

In the area of study within the Surma Basin, the Sylhet Formation limestones extend to 48–50 Ma and the basal section of the overlying Kopili Formation marine shales are 38–39 Ma. It is not possible to determine the nature of the intervening contact at the location of study. The overlying Barail Formation deltaic sandstones are dated at late Eocene to early Miocene (38 Ma to <21 Ma) and plug the gap in the Himalayan erosion record represented by a disconformity in the foreland basin.

Provenance data show that the Barail Formation represents the first significant input of Himalayan-derived material to the Bengal Basin. Petrographic and mineral age data indicate erosion to deeper metamorphic levels of the orogen through time, and lag time data show that the orogen was exhuming rapidly by 38 Ma. There is a subordinate input of arc-derived material, which is more likely to be from the Himalayan Trans-Himalaya rather than Burman portion of the arc. Limited arc-derived material is also identified in the underlying Kopili Formation, but not in the Sylhet limestones below. Thus we identify first arrival of arc-derived material to the basin, probably of Himalayan origin and of limited extent, sometime between 50 and 38 Ma, and substantial input of detritus from the metamorphosed Himalaya from 38 Ma in thick Barail Formation sandstones. This is consistent with the detrital record from the foreland basin and Bengal Fan.

These rocks hold the oldest precisely-dated record of erosion from the southern flanks of the eastern/central Himalaya. Our data allow the erosion record to be brought into better alignment with the Himalayan hinterland bedrock record of Paleogene crustal thickening; invalidate previously proposed evidences of diachronous collision based on the tenet that Himalayan-derived sediments were deposited earlier in the west than the east; allow refinement of those models of crustal deformation that invoke tectonic-erosion coupling in the Himalaya; and provide support to the hypothesis that the marked rise in marine $^{87}Sr/^{86}Sr$ values since ~40 Ma may have resulted from Himalayan erosion. Whether these deposits represent the initial onset of the orogen's erosion, subsequent to collision at 55–50 Ma, or whether earlier deposits may be found elsewhere, remains an open question.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2008.04.028.

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