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The record of Himalayan erosion preserved in the sedimentary rocks of the Hatia Trough of the Bengal Basin and the Chittagong Hill Tracts, Bangladesh

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ABSTRACT

The Cenozoic sedimentary succession of Bangladesh provides an archive of Himalayan erosion. However, its potential as an archive is currently hampered by a poor lithostratigaphic framework with limited age control. We focus on the Hatia Trough of the Bengal Basin and the adjacent fold belt of the Chittagong Hill Tracts which forms the outermost part of the west-propagating Indo-Burmese wedge. We present a basin-wide seismic stratigraphic framework for the Neogene rocks, calibrated by biostratigraphy, which divides the succession into three seismically distinct and regionally correlatable Megasequences (MS). MS1 extends to NN15-NN16 (*ca.* 2.5–3.9 Ma), MS2 to NN19-NN20 (*ca.* 0.4–1.9 Ma) and MS3 to present day. Our seismic mapping, thermochronological analyses of detrital mineral grains, isotopic analyses of bulk rock, heavy mineral and petrographic data, show that the Neogene rocks of the Hatia Trough and Chittagong Hill Tracts are predominantly Himalayan-derived, with a subordinate arc-derived input possibly from the Paleogene Indo-Burman Ranges as well as the Trans-Himalaya. Our seismic data allow us to concur with previous work that suggests folding of the outer part of the west-propagating wedge only commenced recently, within the last few million years. We suggest that it could have been the westward encroachment and final abutment of the Chittagong Hill Tracts fold belt onto the already-uplifted Shillong Plateau that caused diversion of the palaeo-Brahmaputra to the west of the plateau as the north-east drainage route closed.

INTRODUCTION

The Himalaya ranges are a type example for studying orogenesis, including the coupling and feedback between tectonics and erosion. Understanding the processes of erosion since collision of India and Eurasia at *ca.* 50–55 Ma (Garzanti *et al.*, 1987; Klootwijk *et al.*, 1992; Searle *et al.*, 1997) is vital for discriminating between different models of crustal deformation, which differ in the timing and extent of required or resultant erosion (Tapponier *et al.*, 1982; Dewey *et al.*, 1988; Grujic *et al.*, 1996, 2002; Chemenda *et al.* 2000; Beaumont *et al.*, 2001, 2004; Jamieson *et al.*, 2004, 2006). Studying the erosion record and erosion pathways, is also important for evaluating the role of the uplifting Himalaya on global climate (Raymo & Ruddiman, 1992; Molnar *et al.*, 1993), seawater chemistry (Richter *et al.*, 1992) and palaeodrainage over time (Brookfield, 1998; Clark *et al.*, 2004). The major sediment repositories of the Himalaya where such an erosion record is preserved (e.g. Najman, 2006 and references therein) can provide the only remaining archive of mountain belt evolution, where the record of early orogenesis in the hinterland itself is overprinted due to later metamorphism or tectonism. This article focuses on the sedimentary repository of the Hatia Trough (HT) of the Bengal Basin, and the adjacent Chittagong Hill Tracts (CHT) fold belt, Bangladesh (Fig. 1). Our objective is to provide a robust stratigraphic framework and evolutionary history for the basin, such that further work on the

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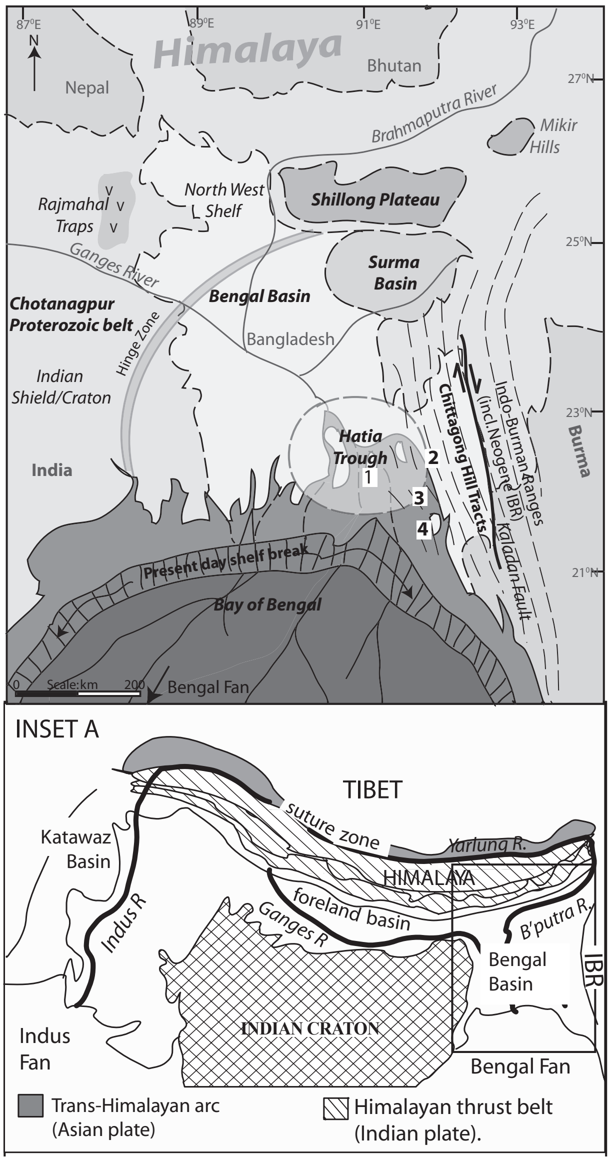


Fig. 1. Regional map of Bangladesh and surroundings (adapted from Johnson & Nur Alam, 1991), showing the locations of the study regions of the Chittagong Hill Tracts and the Hatia Trough of the Bengal Basin . Wells from where samples were analysed are shown (1: Shabazpur 2: Sitakund, 3: Sangu, 4: Sonadia). Inset A shows the regional geological context of the Himalaya. The rectangle in Inset A outlines the region shown in the regional map of Fig. 1 above. IBR = IndoBurman Ranges; suture zone is Yarlung Tsangpo Suture Zone.

Himalayan erosion record preserved in this repository can be interpreted in context.

GEOLOGICAL BACKGROUND

Himalayan geology

The Himalaya (Fig. 1 inset A) were formed in the Cenozoic after the collision of India and Eurasia at *ca.* 55–50 Ma (Garzanti *et al.*, 1987; Klootwijk *et al.*, 1992; Searle *et al.*, 1997). In the north, the Mesozoic-Paleogene Transhimalayan batholith represents the Andean-type continental arc of the Asian palaeo-active margin, and is separated from the Palaeozoic-Eocene Tethyan Sedimentary Series (TSS) deposited on the passive margin of India, by the Indus-Yarlung Suture zone. South from the TSS, the South Tibetan Detachment System, active by the Miocene (Hodges, 2000 and references therein), separates the TSS from the Higher Himalaya below. The Higher Himalaya represents the metamorphosed rocks of the Indian plate. Mineral P-T-t paths indicate prograde metamorphism until at least 25–30 Ma (e.g. Vance and Harris 1999; Godin *et al.* 1999) with exhumation documented by Neogene mineral cooling ages. The Higher Himalaya is thrust over the predominantly lower-grade to unmetamorphosed Indian plate rocks of the Lesser Himalaya along the Main Central Thrust, active since *ca.* 23 Ma (Hodges, 2000 and references therein). The Lesser Himalaya is itself thrust over the palaeo-foreland basin molasse of the Sub-Himalaya along the Main Boundary Thrust, active since at least 10–5 Ma (Meigs *et al.*, 1995; Decelles *et al.*, 1998b). South of the Sub-Himalaya lies the present day foreland basin through which the Ganges river runs.

The Bengal Basin

The Bengal Basin is a remnant ocean basin, bound to the north by the Precambrian basement of the Shillong Plateau, to the east by the Burman Margin and to the west by the Indian shield, whereas the south of the basin (Faridpur and Hatia Troughs) is open and empties into the Bengal Fan (Fig. 1). The sediment repository preserved in the Bengal Basin is predominantly a huge delta complex fed by the coalesced Ganges and Brahmaputra rivers. It preserves a *ca.*16–22 km thick sequence of Cenozoic sediments (Curray & Moore, 1971; Curray, 1994; Gani & Alam, 1999; Uddin & Lundberg, 2004); from oldest to youngest, the Sylhet, Kopili, Bhuban, Bokabil, Tipam and Dupi Tila Formations, which show facies evolution from marine through deltaic to fluvial environments (Fig. 2). The relative contributions to the basin from the Himalaya, Burman margin and Indian craton and Shillong Plateau (Fig. 1), are debated (e.g. Johnson & Nur Alam, 1991; Uddin & Lundberg, 1999, 2004; Gani & Alam, 2003; Najman *et al.*, 2008).

The Bengal Basin can be broadly split into two geotectonic provinces (Fig. 1), (1) the Indian platform or stable shelf in the northwest and (2) the deeper basin, including the Hatia Trough in the southeast and the Surma sub-basin (also called the Sylhet Trough) in the northeast (Uddin and Lundberg, 1998a; Alam *et al.*, 2003). This deeper basin passes east into the onshore Chittagong Hill Tracts (CHT) which is deformed into a series of N–S trending folds and east dipping thrusts. The Neogene strata of the Chittagong Hill Tracts and their easterly continuation in Burma are separated from the Cretaceous-Palaeogene Indo-Burman Ranges to the east by the Kaladan Fault (Sikder & Alam, 2003).

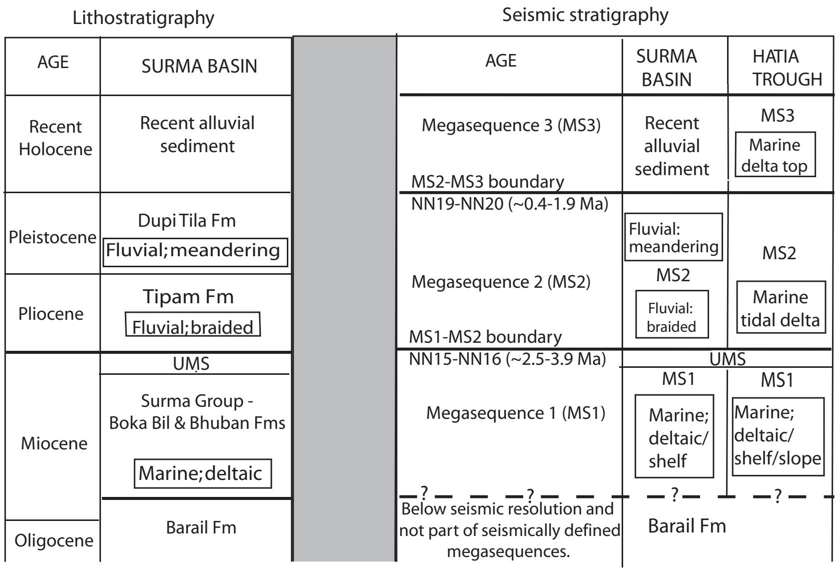


Fig. 2. Neogene stratigraphy of the Bengal Basin. The left hand panel shows the formation names, facies and ages as traditionally depicted using lithostratigraphy (after Johnson & Nur Alam, 1991; Reimann, 1993). The new seismic Megasequence stratigraphy is shown in the right hand panel. The base of MS1 is not defined, as it lies below the limit of seismic resolution and hence the age of the Barail-MS1 contact is not dated. In the Surma Basin, the Barail Formation extends into the early Miocene (Reimann, 1993; Najman *et al.*, 2008), but a significant period of non-deposition may be represented at this boundary. Biostratigraphic constraint for the Megasequence framework, as indicated, is discussed in section Biostratigraphic calibration. UMS = Upper Marine Shale, a basin-wide marker horizon representing a significant marine flooding event.

This study focuses on the Hatia Trough and Chittagong Hill Tracts, where only the Neogene facies are exposed. Although the Hatia Trough currently remains a site of sediment deposition, the Chittagong Hill Tracts consist of sediments deposited in the Bengal Basin, and subsequently uplifted and incorporated into the accretionary prism during subduction of the Indian oceanic plate beneath the Burma platelet to the east (Gani & Alam, 1999).

A REVISED STRATIGRAPHY FOR THE CENOZOIC ROCKS OF BANGLADESH – A SEISMIC STRATIGRAPHIC APPROACH

Interpretation and use of the Bengal Basin sedimentary archive is currently limited by our inadequate knowledge of the stratigraphy of the basin. The limited biostratigraphic/palynological control (e.g. Baksi 1972; Banerji, 1984; Reimann, 1993) necessitated the construction of a stratigraphic framework (Fig. 2) based only on tenuous lithostratigraphic correlation with rocks far to the north in Assam (Evans, 1932). It is on this lithostratigraphic approach that the current published geological map is based (Fig. 3a). However, in a prograding deltaic environment, facies will be highly time-transgressive. Previous workers recognized this limitation to lithostratigraphic correlation in such an environment (Salt *et al.*, 1986; Reimann, 1993; Gani & Alam, 1999; Uddin & Lundberg, 1999; Alam *et al.*, 2003), and although a seismic stratigraphic approach was suggested to overcome the problem (Gani & Alam, 2003), its use for long distance correlation was hampered by a lack of regional marker beds and limited biostratigraphic control in the area under study.

The basin-wide seismic stratigraphic approach (Figs 2 and 3b) employed by Cairn Energy Plc. has further overcome the limitations of the aforementioned methods by dividing the rocks of the upper Neogene into three geometric packages termed megasequences (MS1, 2 and 3), each with its own distinct seismic character and bounded by unconformities and their correlative conformities which are regionally correlatable over thousands of kms from the offshore to onshore facies (Fig. 4; Cairn Energy PLC (Edinburgh, Scotland), 2000). The seismic character reflects the influence of delta morphology, shelf-edge position, sedimentation rates and relative sea level. Older Cenozoic rocks are not included in the scheme due to a lack of seismic resolution with increasing depth. Within the megasequences, topset and foreset horizons can be dated with biostratigraphic data from wells drilled in the Bengal Basin. The framework has been applied to the Hatia Basin and extended to the Surma Basin (Fig. 4, Cairn Energy PLC (Edinburgh, Scotland), 2000) and, for the current study, was then extended onshore into the Chittagong Hill Tracts of eastern Bangladesh (see Fig. 3) .

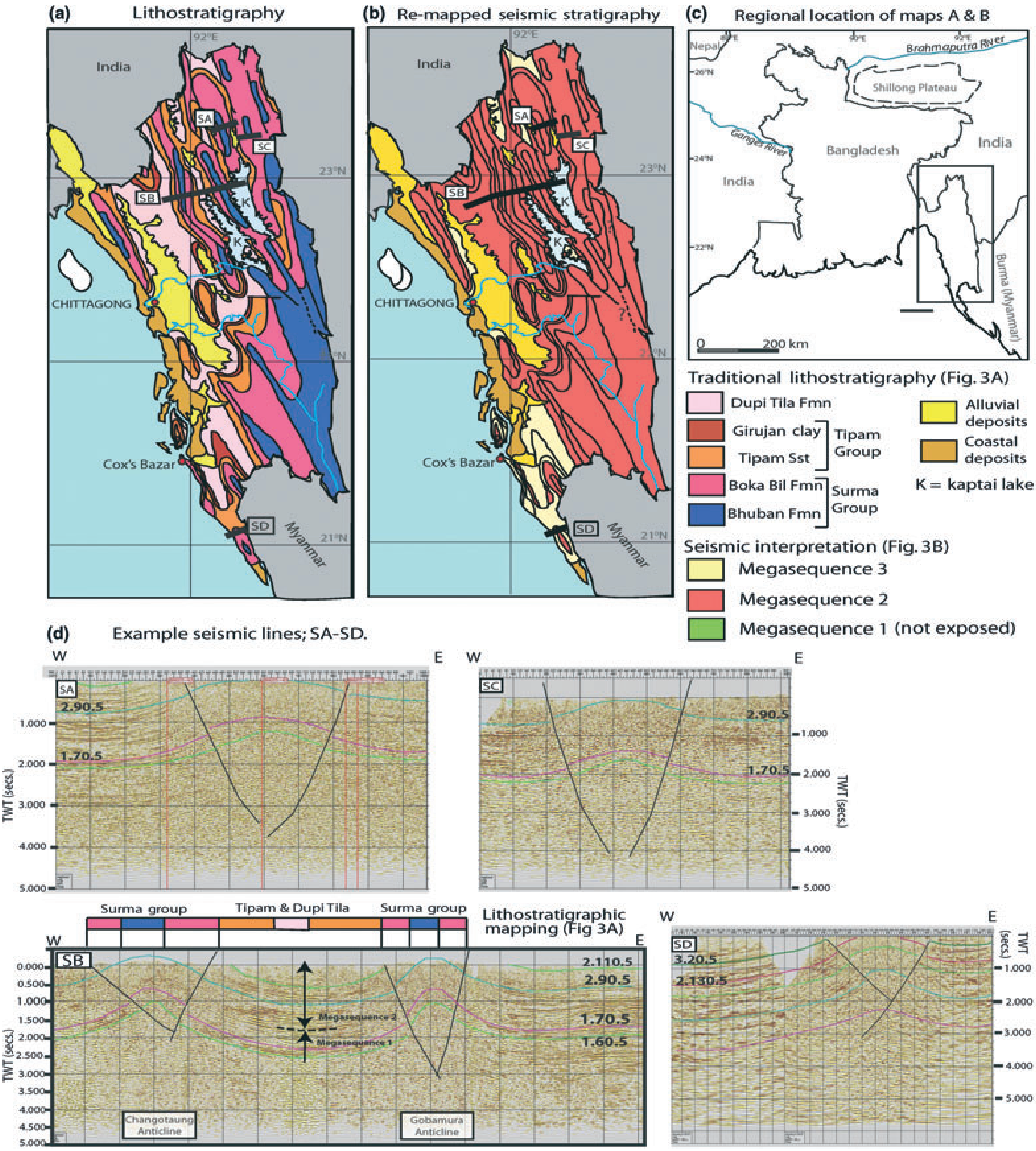
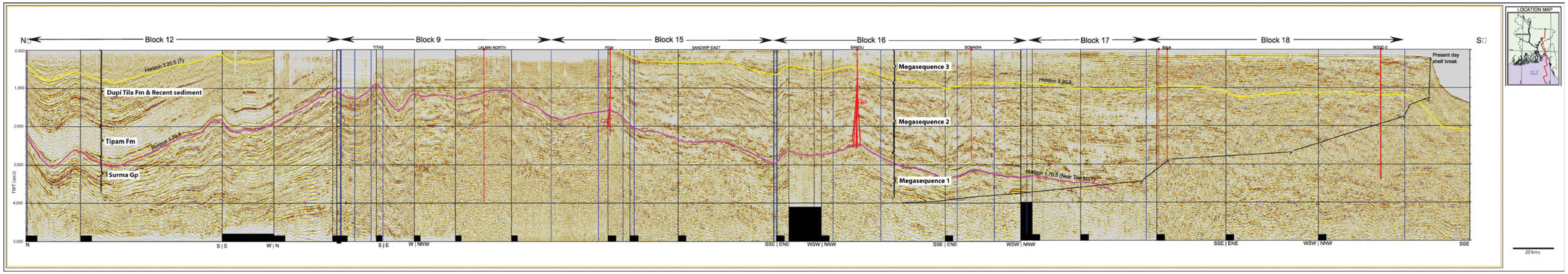


Fig. 3. (a) shows the published lithostratigraphic surface geology map of the Chittagong Hill Tract region (taken from Geological Map of Bangladesh, published by the Geological Survey of Bangladesh 1990, digitally compiled by the United States Geological Survey in 2001). (b) is the current remapped seismic stratigraphy developed in this study using a Megasequence framework. The location of maps A and B are depicted by the box in (c). Note that re-mapping of the region using seismic data has resulted in a younger geology at surface than previously thought, with widespread exposure of MS2, although some exposure of MS1, although not depicted, may be present – see discussion in text. (d) shows examples of the seismic lines used to constrain the stratigraphic framework in this area, labelled SA-SD and shown on the maps, from which the scales can be determined. Picked horizons (coloured lines) are numbered 1.xx.x for horizons which lie within MS1, 2.xx.x for those that lie within MS2 and 3.xx.x for those within MS3. Suffix numbers increase upsection. Line SB is used in this figure to illustrate the mismatch between lithostratigraphic and seismic mapping. Seismic mapping shows that the boundary between MS1 and MS2 lies within the subsurface, with MS2 sediments exposed at surface in the antiforms and upper MS2/MS3 in the synforms. This is different to the published lithostratigraphy (shown in the bar along the top of the seismic line) that shows the Surma Group (MS1) exposed at surface in the crests of the anticlines (cf Fig. 3a).


N
Block 12
Block 9
Block 15
Block 16
Block 17
Block 18
S
TITAS
LALMAI NORTH
FENI
SANDWIP EAST
SANGU
SONADIA
BINA
BODO-3
Horizon 3.20.5 (?)
Horizon 3.20.5
Dupi Tila Fm & Recent sediment
Tipam Fm
Surma Gp
Megasequence 3
Megasequence 2
Megasequence 1
Present day shelf break
TWT (secs)
0.000
1.000
2.000
3.000
4.000
5.000
S | E
W | N
W | NNW
SSE | ENE
WSW | NNW
SSE
LOCATION MAP
20 kms

Seismic stratigraphy: the megasequences

MS1, 2 and 3 are distinct seismically mappable units (Figs 4 and 5) bound by prominent regional unconformities or their correlative conformities. The seismic facies are calibrated to lithostratigraphic units by well penetrations in both the Surma Basin and Hatia Trough, and dated using biostratigraphy (see section Biostratigraphic calibration).

Megasequence 1 is the deepest unit, and is recognized seismically throughout the Bengal Basin by high amplitude continuous parallel reflectors representing marine shelf to slope conditions in a forestepping, progradational sequence stack. The top of MS1 is defined by a major marine flooding event across NE Bangladesh recorded in the Upper Marine Shale.

The boundary with *Megasequence 2* reflects a major change in conditions across the whole of Bangladesh resulting from a basinward shift in facies. In the Surma Basin, the boundary has been calibrated by well penetration to the Boka Bil – Tipam Formation boundary. In the Surma Basin basin, the seismic character of Megasequence 2 is that of a predominantly homogenous, transparent, reflection free package representing the braided fluvial facies of the Tipam Formation, overlain by a more heterogeneous package reflecting a change to the more meandering facies of the Dupi Tila Formation (Fig. 4). In the Hatia Trough, the basinward shift in facies is more subtle (Fig. 5). Here, Megasequence 2 consists of tide-dominated sediments, and is characterized by discontinuous geological outliers (sequence remnants) preserved between large, multiple, downcutting, infilled submarine canyons that incise into MS1 below with considerable relief. The repeated cut and fill indicates fluctuating relative sea levels during the megasequence deposition, superimposed on an overall relative sea level rise which allowed fills to be preserved and topsets to be stacked.

Megasequence 3 is characterized in the Hatia Trough by a return to a package of laterally continuous seismic reflectors and an absence of canyons. It represents a delta top environment, where sedimentation and accommodation are generally in equilibrium and the nature of the shelf-slope break is predominantly aggradational. In the Surma Basin, Holocene sediments comprise MS3.

Biostratigraphic calibration

Despite a lack of age data on the region, the Surma Group has traditionally been considered as Miocene in age (Evans, 1932; Reimann, 1993), the Tipam Formation as Pliocene aged and the Dupi Tila as Plio-Pleistocene aged (Fig. 2). Our sequence stratigraphic Megasequence framework is calibrated to well penetrations across the Bengal Basin and age constrained by nannoplankton dating [based on the Nannoplankton Zonation Scheme of Martini (1971); Cairn Energy Internal Reports No. 26026 (undated), 27810 (2001) and 27903 (2002), Appendix S1]. An overview is provided in Fig. 2, and detailed biostratigraphy and correlations are presented in Appendix S1.

Although the age of reported Nannoplankton species with a long time range (*Discoaster quinqueramus*, *Discoaster asymmetricus*, *Helicosphaera sellii and Pseudoemiliania lacunose ovata*) cannot be used to precisely date a succession, the time of their extinctions can still provide a tool for dating where a continuous sediment record exists. In Bangladesh, their First Downhole Appearances (FDA; defined as first downhill appearance from well top) is identified in well core and thus has been used to date the Megasequence succession. The FDA of Forms used in the wells Begumganj 1 and 2, Sitakund 1, Shabazpur 1, Muladi 1, Sangu 1–5 and South Sangu 1 and 2, located in Appendix S1, Fig D inset, are interpreted as true extinction events rather than a hiatus in deposition at the well site due to their stepped first appearance in the wells. At no location are all forms first recorded at the same depth in a well, which would be indicative of a depositional hiatus.

These data combined with recorded short range species (*Discoaster quinqueramus, Discoaster asymmetricus, Helicosphaera sellii*) have allowed Cairn Energy to determine that the MS1-MS2 boundary lies within Nannoplankton zones NN15-16 (*ca.* 2.5–3.9 Ma) and the MS2-MS3 boundary to lies within zones NN19-20 (*ca.* 0.4–1.9 Ma) (Cairn Energy PLC. (Edinburgh, Scotland), 2005). MS3 continues through to present day, and the oldest nanofossils recorded in MS1 belong to NN11 zone (Late Miocene Tortonian, *ca.* 8.25 Ma). These data are in agreement with magnetostratigraphic data by Worm *et al.* (1998) from the Surma Basin, where the Neogene succession is allocated younger ages than previously reported (Reimann, 1993).

Correlation of offshore geology with the onshore Chittagong Hill Tracts, SE Bangladesh

The seismic stratigraphic framework created for the offshore portion of the Bengal Basin and calibrated with biostratigraphic data from well penetrations, was correlated with the onshore stratigraphy of the Chittagong Hill Tracts for this study. Onshore–offshore correlation was achieved by mapping a total of nine seismic horizons across the region from the southern Hatia Trough,

Fig. 4. Regional North–South correlation of the Megasequence framework from the offshore Hatia Trough to the onshore Surma Basin (from Cairn Energy PLC (Edinburgh, Scotland) (2000) EDEX00 1176). Examples of picked horizons lie within MS1 (purple line 1.70.5) and MS3 (yellow line 3.20.5). Wells are located (vertical red lines) and named above the seismic image. Inset shows location of line.

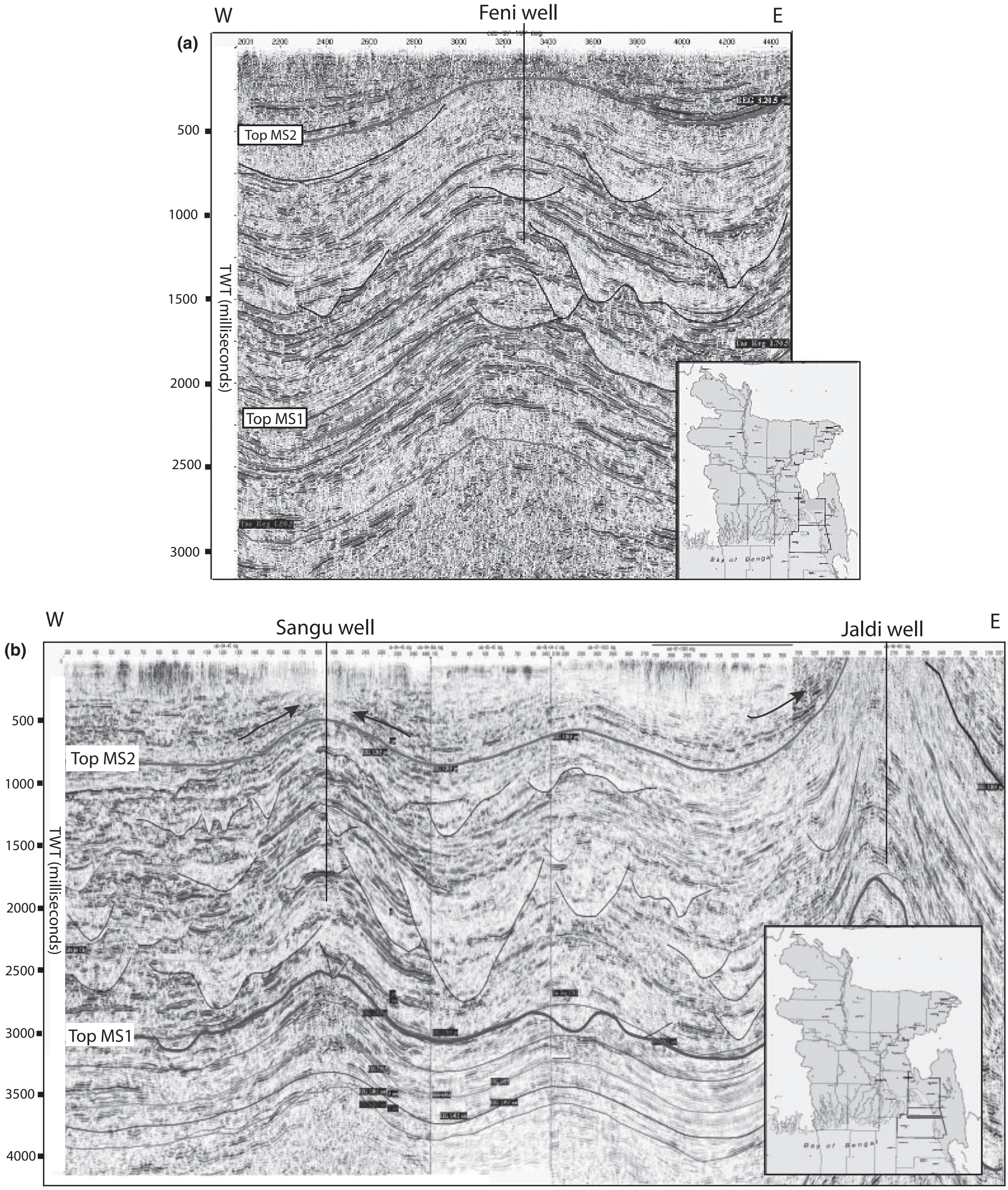


Fig. 5. Depiction of seismic character of MS1, MS2 and MS3 in the south (Hatia Trough). Seismic character of the Megasequences in the north (Surma Basin) is visible in Fig. 4 and is not duplicated here. MS1 is recognized throughout the Bengal Basin by high amplitude continuous parallel reflectors. MS2 is represented in the Hatia Trough by sequence remnants preserved between infilled incised submarine canyons, and in the Surma Basin by a predominantly homogenous transparent reflection free package overlain by a more heterogeneous package (Fig. 4). MS3 is chacterised in the Hatia Trough by a return to a package of laterally continuous seismic reflectors. Insets show the location of the seismic line (red line) and approximate scale. Blue arrows show the location of onlapping/thinning of MS3 strata over/onto MS2 anticlines, thereby providing a constraint to the timing of fold generation (see section Evolution of the Neogene accretionary prism). Thinning within uppermost MS2 may also occur; identification is difficult in view of the intense canyonization, as for example, shown in Fig. 5a, where the yellow dashed line in upper MS2 would represent thinning, but the reflector can also be interpreted as the side wall of a canyon (adjacent black line). Please see the online version of this article for a colour version of this figure.

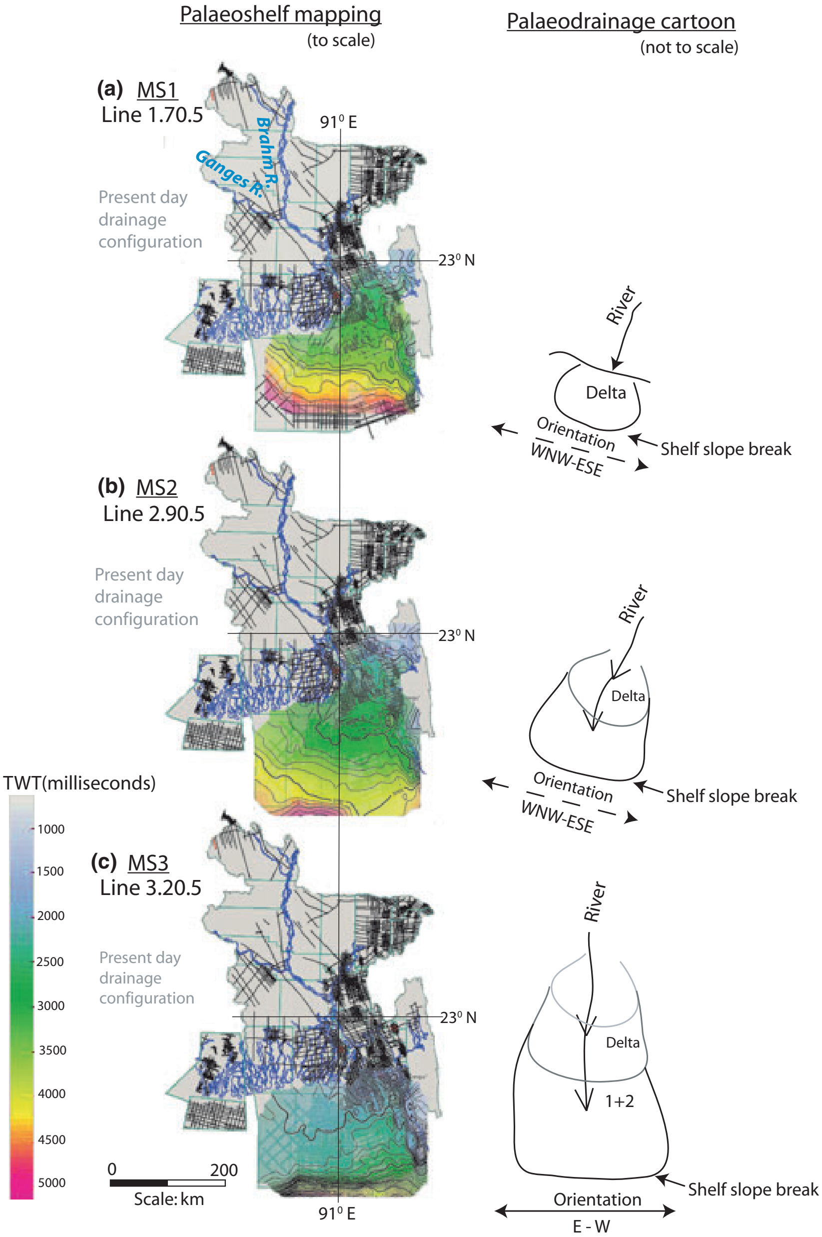


Fig. 6. The southward progradation of the palaeoshelf and its changing orientation over time is shown for MS1(a), MS2 (b) and MS3 (c). Increasing depth is indicated by a change from blue-green to yellow-pink on the maps. Input direction from the NNE is dominant throughout the Neogene, with a subtle shift to a more northerly input direction by MS3. This potential shift may be the result of the palaeo-Brahmaputra rerouting west of the Shillong Plateau resulting from closure of the northeast drainage route due to abutment of the encroaching CHT fold belt against the plateau (see section Possible palaeodrainage scenerios in the Bengal Basin and Fig. 12). The cartoons to the right of the figure show a representation of the shelf break orientation relative to the input direction.

eastwards in the Chittagong Hill Tracts and offshore towards the proximal parts of the Bengal Fan. Five horizons were interpreted and mapped from within MS1, three from MS2 and one from MS3. One horizon from each megasequence was also converted to two-way time structure maps to study changes in the palaeoshelf over time (see section Seismic palaeoshelf mapping; determination of sediment input directions). Our correlation shows that the published geological map of the Chittagong Hill Tracts based on lithofacies correlation attributes too old a rock unit to crop out at surface (Fig. 3). For example, in Fig. 3, Seismic line SB illustrates a location where the published geology map shows the Surma Group (MS1 equivalent) cropping out at surface, whereas the seismic mapping shows that there are no MS1 outcrops. We therefore used the seismic data to remap the area, as shown in Fig. 3b. However, we recognize that this is a coarse-scale map interpretation; there is evidence of at least the presence of some limited MS1 aged rocks in the region, as determined from biostratigraphy [e.g. occurrence of short range species *Discoaster quinqueramus*, Zone NN11 in the crest of the Sitakund anticline north of Chittagong (Cairn Energy PLC (Edinburgh, Scotland), undated)] and

Table 1. Provenance data for Neogene samples of the Chittagong Hill Tracts (surface and drill core) and Hatia trough drill core samples

Rock description, heavy mineral and petrography	εNd (0) bulk rock (mudstone/siltstone)	^{40}Ar–^{39}Ar on detrital white mica	Fission track on detrital zircon	U-Pb on detrital zircons
Fine to coarse grained micaceous sst, siltst & msts. Plots within Recycled Orogen of the QFL plot (Dickinson, 1985). Metamorphic heavy minerals present, garnet prevalent.	All samples lie in the range −11.1 to −14 except for one sample at −15.2. For the most studied well (Sangu), MS1 average and median value is −11.8, MS2 average value is −12.1 and median value is −12.2.	Grains predominantly < 55 Ma, with the majority of those ages Neogene with subordinate Palaeogene ages. Rare Cretaceous grains in one MS3 sample.	The dominant populations are Cenozoic in age, with significant Neogene and Paleogene populations. Subordinate populations, commonly Cretaceous, stretch back as old as the Paleozoic.	Lower Palaeozoic-Precambrian grains to *ca.* 1800 Ma dominate MS2 & MS3 samples, with a prominent *ca.* 500 Ma peak. Rare grains >2500 Ma in MS2 samples which also have a subsidiary component of Paleogene–Jurassic grains. Only one such grain is present in the MS3 sample. One Late Miocene grain is found in MS2 sample. MS1 not analysed.

palynology (Maurin & Rangin, 2009). It is also possible that Megasequence 1 may crop out in areas further east in the Chittagong Hill Tracts or in the Indo-Burma Ranges where there is no coverage from our available seismic data, and older strata would be expected.

As a result of this discrepancy between the lithostratigraphic map and the seismic mapping, we reclassified all surface samples taken for analysis into the megasequence stratigraphic framework. The samples, and their lithostratigraphic nomenclature, as well as their new Megasequence classification are listed in Appendix S2. The samples used for analysis in this study will thus be referred to by their Megasequence terminology and not by their lithostratigraphic nomenclature.

PROVENANCE OF THE ROCKS OF THE CHITTAGONG HILL TRACTS AND EASTERN HATIA TROUGH

Although the principal input to the Bengal Basin overall is clearly the Himalaya during Neogene time (e.g. Uddin & Lundberg, 1999; Davies *et al.*, 2003), some previous workers have considered input to the eastern part of the basin from the Indo-Burman Ranges to be significant (Uddin & Lundberg, 1999, 2004), with some researchers considering that such an input was dominant at certain times (Gani & Alam, 2003). A Shillong Plateau source has also been proposed for the Pliocene sediments (Johnson & Nur Alam, 1991). Previous provenance approaches have included determination of input directions using lithofacies maps (Uddin & Lundberg, 1999), isopach maps constructed from well data (Uddin & Lundberg, 2004) and petrography, heavy mineral analysis and Ar-Ar dating of micas (Uddin & Lundberg, 1998a, b; Rahman & Faupl, 2003; Uddin *et al.*, 2010). In this study, as detailed below, we combine seismic data with various isotopic techniques to achieve an integrated provenance study.

Seismic palaeoshelf mapping; determination of sediment input directions

Palaeoshelf mapping and clinoform orientation provide evidence of delta progradation and clastic input direction through time. Seismic reflectors were interpreted and mapped across a geographical region on a grid of 2D seismic lines. The reflectors mapped regionally are interpreted as the topsets and foresets of a prograding delta. Mapping clinoforms across the region defines the position of the shelf-slope break and its progradation with time. Input direction is taken to be orthogonal to the shelf-slope break.

From a total of nine horizons used to correlate offshore stratigraphy with the onshore (see section Correlation of offshore geology with the onshore Chittagong Hill Tracts, SE Bangladesh), three were chosen as representative of the position of the palaeoshelf during deposition of MS1, MS2 and MS3. Figure 6 shows a sequence of two-way

Table 2. Typical provenance signature of possible source regions

Source region	Heavy mineral and petrography	Whole rock εNd(0)	^{40}Ar-^{39}Ar ages of white mica	Zircon fission track ages	U-Pb ages of zircons
Himalayan Southern Flanks (Indian crust)					
Miocene to recent Siwalik Fm, Himalayan foreland basin, Nepal.	Common metamorphic lithics and metamorphic minerals. Recycled orogen on QFL plot[1]	−14.6 to −18[2–4]	Predominantly Cenozoic, peak at 15–20 Ma. Ages span to 1200 Ma[4]	Neogene, & subordinate Cretaceous populations[5]	Ages 500–>2500 Ma[5]
Modern river sediments Ganges (G) and/or its tributaries (T)	Higher Himalayan detritus dominates in major rivers (T)[6]. Low epidote: garnet[7] (G)	−17.2 to −17.7[8] (G). Ganges-Brahm below confluence: −14.8, −17.4[8]	Neogene peak. Subordinate grains ranging to Precambrian[9]. (T).		Dominance of Proterozoic & L. Palaeozoic ages. No grains 55–150 Ma[10]
Trans-Himalaya (Asian crust)					
Yarlung (Y) & Brahmaputra (B) rivers which drain both Asian & Indian crust.	Metamorphic lithics present. High epidote: garnet[6, 7] (B).	−12.5 to −16.9[8, 11] (B). −10[12] (Y)	Cretaceous and Cenozoic[13] (Y)	Neogene peak[5] (T).	Cenozoic to Proterozoic. Appreciable Cretaceous grains[14]
Indo-Burman ranges (Palaeogene) (from bedrock and modern river sands draining IBR)	Very fine grained sst, siltst & mst. Plots in Magmatic Arc and recycled Orogen provinces of QFL plot. Very few heavy minerals[15]	−4.0, −4.1 and −4.2[15]	Unmicaceous	Palaeogene & Cretaceous populations, with subordinate Palaeozoic populations[15]	Significant Cretaceous and Lower Palaeozoic-Precambrian populations (500–>3000 Ma). Youngest grains:Paleogene[15]
Indian shield: Chotanagpur Proterozoic mobile belt & Shillong Plateau (from modern river sands draining the formations)	Arkosic. Metamorphic lithic fragments absent[15]	−13.8, −14.6[16]	Proterozoic, Cambro-Ordovician[16]	Proterozoic. Rare Mesozoic & Palaeogene grains[16]	Proterozoic & Cambro-Ordovician[16]

[1]Decelles *et al.*, 1998b.
[2]Huyghe *et al.*, 2001.
[3]Decelles *et al.*, 1998a.
[4]Szulc *et al.*, 2006.
[5]Bernet *et al.*, 2006.
[6]Garzanti *et al.*, 2004.
[7]Heroy *et al.*, 2003.
[8]Galy & France-Lanord, 2001.
[9]Brewer *et al.*, 2003.
[10]Campbell *et al.*, 2005.
[11]Singh & France-Lanord, 2002.
[12]Pierson-Wickman *et al.* 2000.
[13]Najman & wijbrans unpublished data.
[14]Liang *et al.* 2004.
[15]Allen *et al.*, 2008.
[16]Najman *et al.*, 2008.

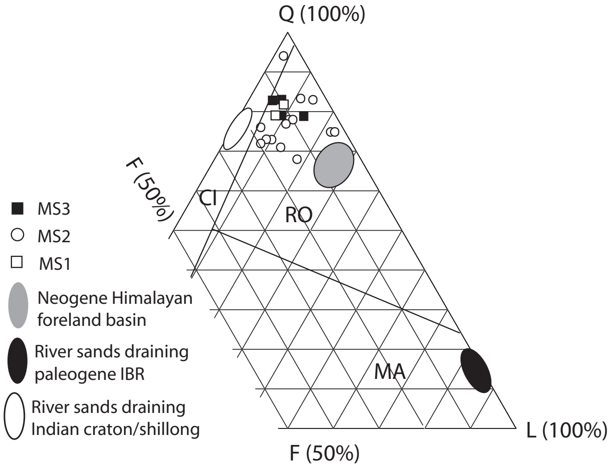


Fig. 7. Petrography of the sedimentary rocks from the Hatia Trough and CHT. Q = quartz, F = feldspars, L = lithic fragments. Provenance fields (CI = Craton Interior, RO = Recycled Orogen, MA = Magmatic A) after Dickinson (1985). Also shown for comparison are the fields plotted for modern river sands draining the Indian craton and Shillong Plateau (from Najman *et al.*, 2008), modern river sands draining the Paleogene Indo-Burman Ranges (IBR) (from Allen *et al.*, 2008) and Neogene Siwalik rocks of the Himalayan foreland basin (Decelles *et al.*, 1998a; Szulc *et al.*, 2006).

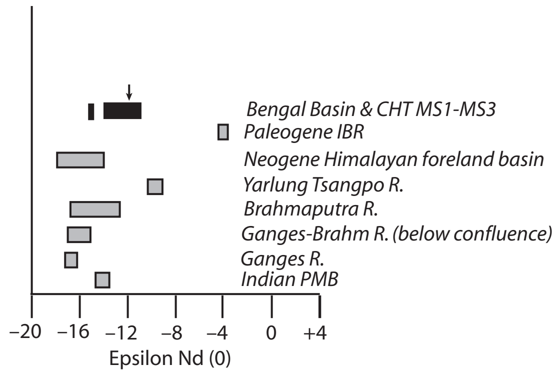


Fig. 8. Epsilon Nd (0) values for bulk rock (mudstone) samples from the Bengal Basin and CHT, shown in black rectangles. Arrow indicates approximate position of average and median value for the bulk of the data collected from MS1 and MS2 samples from Sangu Well. For comparison, data from potential source regions are also shown as grey rectangles. Values from the Paleogene rocks of the IndoBurman ranges (IBR) are from Allen *et al.* (2008), values from the southern flanks of the Himalaya ranges are represented by the Neogene Himalayan foreland basin sediments from Decelles *et al.* (1998a), Szulc *et al.* (2006). The Yarlung Tsanpo river runs along the suture zone and thus drains both the Trans-Himalaya of the Asian plate as well as the Indian plate (data from Pierson-Wickman *et al.*, 2000). By the time the river has flowed through the syntaxis, its epsilon Nd values are more negative, reflecting the rapid exhumation of the syntaxis today. This is illustrated in the values from the Brahmaputra River (Galy & France-Lanord, 2001; Singh & France-Lanord, 2002). Modern day river values become less negative again after confluence with the Ganges River (Galy & France-Lanord, 2001), which has a contribution both from the Himalaya and the highly negative Archaean Indian craton. However, note the data from modern rivers draining the Proterozoic mobile belts (PMB) of the Indian craton/Shillong Plateau, which have values similar to that of the Himalaya (Najman *et al.*, 2008).

time structure maps generated for these time intervals that show the overall southward migration of the shelf-slope break from MS1 to MS3 reflecting delta progradation and subtle changes in sediment input direction across the Bengal Basin since Miocene times. Note that whilst these maps illustrate the overall delta progradation with time, this is superimposed on smaller scale aggradation/backstepping and progradation cycles as detailed in Cairn Energy PLC. (Edinburgh, Scotland) (2005).

The palaeoshelf mapping commenced with a seismic horizon in late MS1. Seismic data quality was insufficient to map the palaeoshelf break before this time. During the time periods represented by MS1 line 1.70.5 to MS2 line 2.90.5, the palaeoshelf orientation was WNW-ESE, indicative of a major input direction from the NNE (Fig. 6a and b). By MS3 times (line 3.20.5 Fig. 6c), there appears to be a subtle shift in palaeoshelf break orientation towards a more E-W orientation. More time lines would need to be mapped to assess whether this shift is progressive over time or whether the change occurred abruptly.

Petrographic and isotopic data from the Neogene Chittagong Hill Tracts and Hatia Trough, SE Bangladesh

The data presented are from Neogene rocks of the onshore Chittagong Hill Tracts (surface samples and drill core) and offshore drill cores in the Hatia Trough. A total of 50 samples were used, and where possible, these were tied with seismic lines to fit them within the seismic stratigraphic/Megasequence framework (Appendix S2): The data are summarized in Table 1. The petrographic and isotopic characteristics are then compared with the characteristics of the potential source regions (Himalaya, Burman margin, Indian craton/Shillong plateau) which differ in their isotopic and petrographic signatures (Table 2).

Heavy mineral and petrographic study

A heavy mineral and petrographic study was conducted on a total of nine drill core samples and 13 surface samples spanning MS1-3. This was augmented by analyses from samples from two wells (Sangu and Sonadia) already documented in Cairn Internal Reports HMA/99/01 and J978/052 (Cairn Energy PLC (Edinburgh, Scotland), 1998, 1999). The full methodology is presented along with the data in Appendix S3, which is summarized below. Petrographic point-count data are shown in Fig. 7.

All samples plot within the recycled orogen province of the standard QFL plot of Dickinson (1985) except for one sample that lies on the boundary with continental interior derivation. The samples are characterized by significant potassium feldspar that increases up-

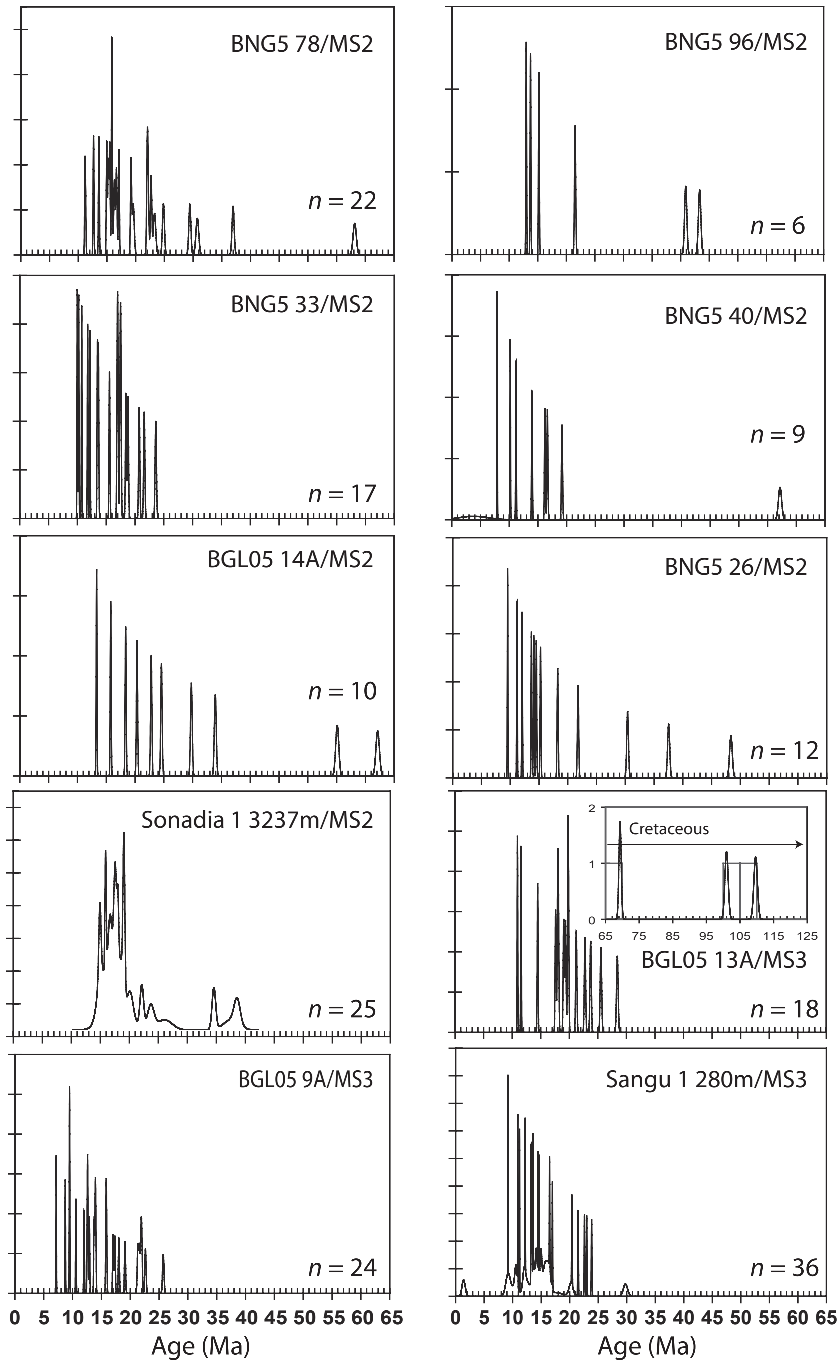
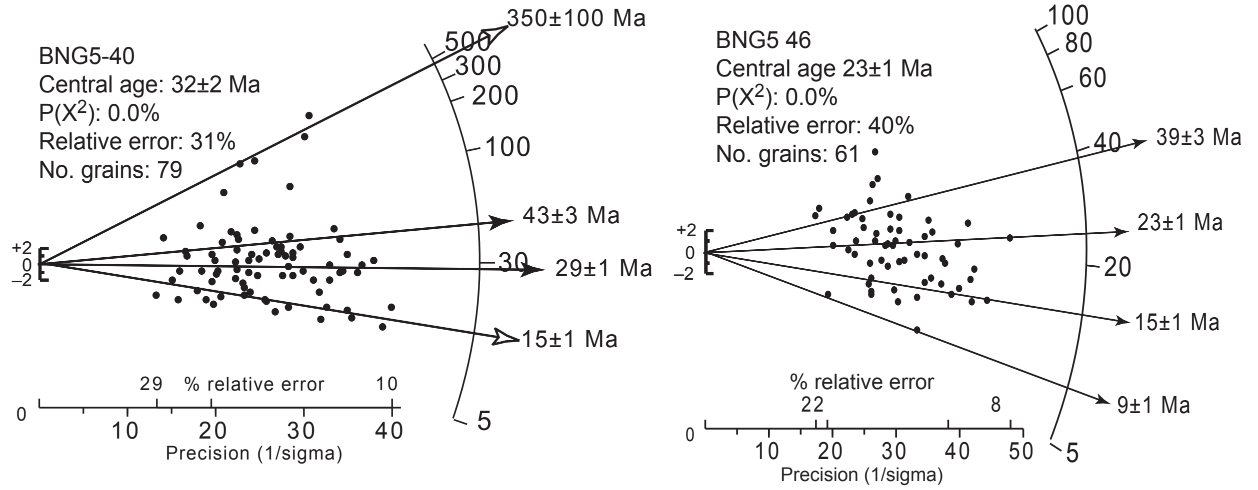


Fig. 9. Probability density plots for ^{40}Ar-^{39}Ar detrital white mica data show a dominance of Neogene aged grains. Palaeogene grains are present but uncommon, and Cretaceous grains are rare.

section, and a high proportion of low-medium grade metamorphic minerals, such as garnet, which is present in all samples and particularly prevalent in core samples of MS1 age. The higher-grade metamorphic minerals staurolite and kyanite become more common in upper MS2 and MS3 samples higher in the section (Cairn Energy Internal Reports HMA/99/01; J978/052). In core samples, heavy mineral abundance and variety was found to decrease notably with depth, whereas degree of etching and alteration of the unstable and semi-stable minerals (e.g. amphiboles, epidote, staurolite and kyanite) markedly increases. Specifically, amphibole, which is the most abundant detrital mineral in modern Bengal estuary sands, is rapidly depleted at core depth over 1–1.5 km, and disappears at core depth >2–3 km. Epidote is also depleted at depths below 2–2.2 km, whereas the relative percentages of garnet progressively and markedly increase. These changes are undoubtedly the mark of widespread and intense intrastratal dissolution, which must be taken into account in the interpretation of heavy mineral assemblages for provenance determination.



Sample #		No of crystals	Central age (Ma) ±1σ	Age components 1st	2nd	3rd	4th	5th
SB 3016	MS1	*63*	**23.6±1.7**	13±1 (13)	18±1 (40)	31±2 (12)	99±18 (2)	190±21 (2)
Sangu 3840	MS1	*43*	**30.9±3.1**	13±1 (7)	23±1 (17)	36±2 (17)	210±38 (2)	
BGL0512A	MS2	9	**22.9±6.8**	6.1±0.8 (3)	29.6±2.0 (5)	225±119 (1)		
BGL0514A	MS2	33	**27.5±4.0**	12.5±0.5 (13)	24.6±1.3 (16)	64.0±7.3 (1)	423.7±90.5 (2)	
BGL055A	MS2	26	**31.1±5.2**	14.8±0.5 (10)	26.9±1.1 (8)	64.7±5.5 (3)	205.9±28.4 (3)	
BGL056A	MS2	28	**27.0±3.6**	9.0±0.5 (4)	18.7±1.1 (10)	31.2±1.3 (8)	67.9±7.7 (5)	388±101 (1)
BNG5 123	MS2	50	**25.1±1.7**	16.5±0.8 (15)	23.2±0.8 (24)	42.1±2.8 (9)	242±39 (1)	
BA0521A	MS2	46	**35.0±4.1**	12.8±0.8 (9)	23.4±0.8 (18)	41.0±1.7 (13)	355.7±39.5 (4)	
BA0522A	MS2	23	**26.3±3.4**	15.2±0.8 (8)	25.9±1.2 (8)	45.1±4.0 (2)	125±14 (2)	
BA0523A	MS2	51	**17.2±1.6**	7.0±0.5 (3)	10.5±0.9 (14)	14.6±0.9 (13)	25.6±0.9 (13)	133.5±14 (5)
BNG5 33	MS2	63	**25.5±1.7**	16.6±0.5 (30)	28.7±0.9 (24)	48.1±4.0 (6)	110±15 (3)	
BNG5 40	MS2	79	**31.5±2.4**	15.0±0.3 (24)	28.5±1.1 (30)	42.6±2.6 (21)	146±23 (3)	
BA0527A	MS2	31	**29.0±2.6**	9.9±1.5 (3)	19.2±1.7 (7)	30.7±1.9 (13)	51.2±5.0 (6)	
BA0528A	MS2	24	**24.1±2.8**	14.5±1.3 (8)	23.7±0.9 (15)	531±173 (1)		
BGL0511A	MS3	8	**39.7±8.8**	21.3±1.7 (3)	42.9±4.0 (3)	181±46 (1)		
BNG5 46	MS3	61	**23.1±1.3**	9.3±0.9 (2)	14.7±0.5 (16)	23.0±0.7 (30)	39.3±3.1 (12)	
BA0525A	MS3	53	**21.4±2.2**	5.3±0.4 (7)	13.8±0.7 (14)	21.8±0.8 (16)	32.8±1.2 (12)	85.4±13.2(2) 228±28 (2)
BA0524A	MS3	20	**26.3±5.0**	9.5±0.6 (8)	28.8±1.6 (9)	264.9±27.3 (2)		

Fig. 10. Detrital zircon fission track data are presented in the lower table with representative radial plots of MS2 (left) and MS3 (right), above. Component populations are shown. Cenozoic populations dominate all samples.

Bulk rock (mudstone/siltstone) Sm-Nd study

Fifty-five samples spanning MS1 and MS2 from the offshore Hatia Trough Sangu well, documented in Cairn Internal Report J978/052 (Cairn Energy PLC (Edinburgh, Scotland), 1998) (Fig. 8), were augmented in this study by six onshore MS2 surface samples, two onshore MS1/>MS1 (Barail Formation) core samples and eight offshore samples spanning MS1-MS3, analysed for whole rock Sm-Nd isotope compositions using Thermal Ionisation Mass Spectrometry. One modern river sand from the Ganges was also analysed. Our full method and data tables are presented in Appendix S4, and results are summarized below.

Forty-four MS1 samples from the offshore Sangu Well analysed by Cairn have ε_{Nd} values that range from −11.1 to −13.7 (average and median both −11.8), and 14 MS2 samples have values that range from −11.3 to −13.3 (average−12.1, median −12.2). Our MS3 data from Sangu well (two samples, both with ε_{Nd} values −13.4) are within the range of Cairn's dataset. Our additional Sangu well data from MS1 and MS2 are also comparable with Cairn's data, bar one MS1 sample with an ε_{Nd} value of −14. Our data do, however, lie towards the more negative side of Cairn's range, but as our own dataset is small, this may not be significant. Two additional data points from the offshore well Shabazpur are also more negative than average compared with Cairn's data from Sangu well (−15.2 for MS1 and −13.4 for MS2). Onshore, whilst two MS1/>MS1 samples from Sitakund drill core have values of −13.8 and −13.6, six MS2 surface samples have values that range between −11.1 and −12.9 (average −12.3, median −12.5).

Single grain ^{40}Ar-^{39}Ar dating of detrital white micas

Detrital white mica from ten Neogene surface bedrock sandstone samples from the Chittagong Hill Tracts and three drill core sandstone samples from the Hatia Trough spanning MS 2 and 3, were used for ^{40}Ar-^{39}Ar dating. Most data were collected on a GVi instruments Argus

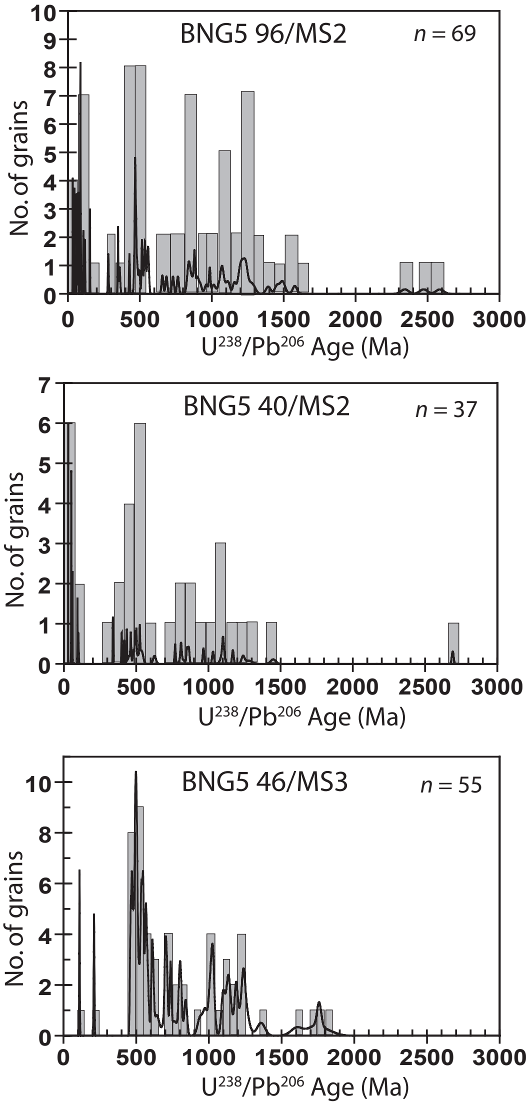


Fig. 11. Detrital zircon U^{238}-Pb^{206} probability density plots with overlain histograms for three samples from MS2 and MS3 shows the majority of zircons fall between 500 and 2800 Ma with subordinate Cenozoic aged populations (<15%) and Cretaceous aged grains (<10%) making up the remainder of each sample.

multi-collector mass spectrometer using a variable sensitivity Faraday collector array in static (non-peak hopping) mode. However, additional samples were run on a Balzers 217 SEM detector. The full laser fusion method and data tables are presented in Appendix S5 and results summarized below.

All samples show that Cenozoic aged grains are dominant, making up between 79% and 100% of all grains per sample. Of this, Neogene grains typically make up between *ca.* 70% and 100% of the grains, with the remainder Palaeogene in age (Fig. 9). Rare older grains of Cretaceous age are present in one MS3 sample. The youngest mineral ages in surface bedrock samples of MS2 and MS3, range between 4 and 14 Ma, with no obvious spatial trend. One grain of 1 Ma is found in a drill core sample of MS3 in one of the youngest anticlines in the region, which has not yet broken surface.

Fission track ages of detrital zircons

Detrital zircon fission track data from seventeen surface bedrock samples and two drill core samples spanning MS1-3 are presented in Fig. 10, and Appendix S6 along with a full methodology.

Measured zircon fission track ages are consistent with those from Ar-Ar white mica dating. The dominant populations are Cenozoic in age, with significant Neogene and Paleogene populations. Subordinate populations, commonly Cretaceous, stretch back as old as the Paleozoic. The youngest age population obtained is 5 Ma in a sample of MS3, but youngest population in other samples ranges down to 21 Ma. Within Bangladesh, there is no evidence of youngest mineral population showing any spatial trend.

U-Pb dating of detrital zircons

The data and method for U-Pb dating on detrital zircons from three surface sandstone samples from MS2 and 3 is presented in Fig. 11 and Appendix S7. Samples were analysed by LA-ICPMS using a New Wave 213 aperture imaged frequency quintupled laser ablation system (213 nm) coupled to an Agilent 750 quadrupole-based ICP–MS. Lower Palaeozoic–Precambrian grains as old as *ca.* 1800 Ma dominate all three samples, and there is a prominent *ca.* 500 Ma peak. Rare grains >2500 Ma are found in MS2 samples. MS2 samples also have a subsidiary component of Paleogene–Jurassic grains, making up 13–19% of the total population. Only one such grain is present in the MS3 sample. One grain of Late Miocene age is found in one MS2 sample.

X-ray diffraction

An X-ray diffraction (XRD) clay analysis and an illite crystallinity study were performed on the <2 μ fraction (which concentrates the diagenetic component) of 48 samples from six well locations in the Hatia Trough and CHT, which cover the full stratigraphy from MS1 to MS3. The objective was to determine whether post-burial temperatures exceeded detrital mineral closure temperatures (white micas have a closure temperature of ca 350°C for the Ar–Ar system; zircons have a partial annealing zone between *ca.* 200°C and 320°C for fission track ages), and thus whether these mineral ages, as described above, can be interpreted as representing the timing of cooling in their source area or are the result of post-burial resetting. Procedural details and the data table are presented in Appendix S8.

It is standard practice to use mudstones for illite crystallinity studies (Kubler, 1967). However, mudstones in these wells are rare and therefore siltstones have been used. The illite crystallinity approach involves the measurement of the thickness of illite crystals, which is dependent on metamorphic grade. Such values are expressed in Hb_{rel} values (Weber, 1972). Values of *ca.* 147–278 for all samples from MS1 to MS3 suggest that burial temperatures corresponding to the anchizone and epizone facies metamorphic grade (>200°C) were attained (Blenkinsop, 1988). However, XRD clay identification of the same <2 μ fraction from these siltstones identifies mixtures of kaolinite, illite and mixed layer chlorite/smectite and illite/smectite in all boreholes, which is diagnostic of the diagenetic zone of burial and thus temperatures below 200°C. Diagenetic temperatures are confirmed by unpublished vitrinite reflectance data from Muladi, Shabazpur and Sangu wells from Cairn Energy plc (Cairn Energy PLC (Edinburgh, Scotland), 1977, 1996a, b.

The discrepancy appears to have resulted from occurrence in the <2 μ diagenetic fraction of detrital micas, which are abundant in the siltstone samples. The separation procedure had not sufficiently separated the clay fraction from the mica, and as such, the mica appears to be swamping the clay illite peaks at the 10Å position giving Hb_{rel} values that are a mixture of minor illite and major detrital mica. Occurrence of 'inherited' clays in the <2 μ supposedly diagenetic component has already been noted in similar studies (Huyghe *et al.*, 2005). Clay identification using XRD appears to be a more robust method than illite crystallinity for palaeotemperature determination in situations where mudstone samples are unavailable, as the mixtures of kaolinite, illite and mixed layer chlorite/smectite and illite/smectite observed indicate that temperatures above diagenetic grade were never attained post-burial, regardless of the original origin of the clays. Where mudstone samples were available for illite crystallinity (one mudstone sample from Shabazphur well), it gave a diagnostic Hb_{rel} value of 303, in line with diagenetic palaeotemperatures.

We conclude that the samples in this region have not been reheated above 200°C (diagenetic zone of burial). Therefore, the zircon fission track ages and ^{40}Ar–^{39}Ar ages used in this study are interpreted to reflect the timing of cooling in the source region and do not show post-burial resetting.

Interpretations

To determine the provenance of the Neogene sediments of the Chittagong Hill Tracts and Hatia Trough, our data are compared with published data of the proposed source regions of the Himalaya, the Palaeogene Indo-Burman Ranges of Myanmar and the Indian shield including the Shillong Plateau. The petrographic and isotopic characteristics of these source regions are distinct and distinguishable, as summarized in Table 2. The southern flanks of the Himalaya ranges are composed of Indian crust metamorphosed during the Cenozoic orogeny. We use data from the Himalayan Neogene foreland basin deposits, as well as from the modern Ganges River, to characterize the detritus being eroded from the southern slopes of the orogen through time. Himalayan detritus displays metamorphic petrographic and heavy mineral characteristics including common garnet (Decelles *et al.*, 1998b), its εNd signature −14.6 to −18 is that of typical continental crust (Decelles *et al.*, 1998a; Galy & France-Lanord, 2001; Szulc *et al.*, 2006) and its zircons have peaks of Proterozoic and Paleozoic U-Pb ages (Campbell *et al.*, 2005; Bernet *et al.*, 2006), whereas the grains' fission track ages are predominantly Cenozoic (Bernet *et al.*, 2006), as are the Ar-Ar ages of detrital white micas (Brewer *et al.*, 2003; Szulc *et al.*, 2006), reflecting metamorphism and exhumation during the Himalayan orogeny. To the north of the suture zone lies the Mesozoic-Paleogene Trans-Himalayan batholiths (Fig. 1), detritus from which drains to the Bengal Basin via the Yarlung Tsangpo/River and its downstream continuation, the Brahmaputra River. The Trans-Himalaya can be distinguished from the orogen's southern flanks by the common occurrence of zircons with Cretaceous U-Pb ages (Liang *et al.*, 2008) and less negative bulk rock εNd values (−10; Pierson-Wickman *et al.*, 2000), consistent with contribution from juvenile igneous rock of the arc (Galy & France-Lanord, 2001; Singh & France-Lanord, 2002).

The characteristics of the Paleogene Indo-Burman Ranges reflect their derivation from the Burmese Mesozoic arc which extends south-east from the Trans-Himalaya (Allen *et al.*, 2008). The εNd signature of these unmicaceous very fine grained sandstones, siltstones and mudstones is therefore considerably less negative (−4; Allen *et al.*, 2008) than the signature of the Himalaya's southern flanks and, similar to detritus from the Trans-Himalaya, their zircons include a substantial peak of Mesozoic age, also reflected in the fission track ages (Allen *et al.*, 2008).

A large part of the Indian shield consists of Archaean craton typified by highly negative εNd signature and zircons with Archaean U-Pb ages (Peucat *et al.*, 1989; Mishra *et al.*, 1999; Auge *et al.*, 2003; Saha *et al.*, 2004). However, NE India, adjacent to Bangladesh, is composed of the Chotanagpur Proterozoic belt, and its extension as the Shillong Plateau (Acharyya, 2003; Mishra & Johnson, 2005). The characteristics of the Proterozoic mobile belt share similar signatures to that of the southern flanks of the Himalaya. However, the Proterozoic mobile belt differs from the Himalaya in the arkosic petrography of its detritus, and the lack of zircons and micas with Cenozoic cooling ages (Najman *et al.*, 2008).

Like the Himalayan foreland basin deposits, the Neogene sandstones of the Chittagong Hill Tracts and Hatia Trough plot in the Recycled Orogen provenance field of the petrogaphic QFL plot (Fig. 7). The significant proportion of low to medium-grade metamorphic lithic fragments and metamorphic minerals (Table 1) is also consistent with orogenic provenance and similar to the characteristics of the Neogene Himalayan-derived foreland basin deposits (Table 2). Similar petrography and heavy mineral assemblages characterize coeval sediments of the Surma Basin, and have previously been attributed to unroofing of the Himalaya since the Miocene (Uddin & Lundberg, 1998a, b). In contrast, the assemblage is unlike that of the arkosic modern river sediments draining the Indian craton and Shillong Plateau and the heavy mineral poor Paleogene Indo-Burman Ranges which plot in the Craton Interior and Magmatic Arc fields of the QFL plot respectively (Fig. 7).

Cenozoic (dominantly Neogene <23 Ma, with subordinate Palaeogene) and uncommon older ages in the zircon fission track and white mica Ar-Ar isotopic data of the Neogene samples from the Hatia Trough and Chittagong Hill Tracts are also similar to those found in the Neogene sediments of the Himalayan peripheral foreland basin, and unlike age populations of the Indian shield, Shillong Plateau and unmicaceous Paleogene Indo-Burman Ranges where ages are entirely pre-Neogene. Our Bengal Basin data show consistency in results with Ar-Ar ages derived from bulk mica separated from the Surma Basin (Sylhet Trough) of coeval age, attributed to derivation from the Higher Himalaya (Rahman & Faupl, 2003) and also with data from the Bhuban Formation at various locations in Bangladesh analysed by Uddin *et al.* (2010), although the uncommon pre-Cretaceous grains they record are not represented in our samples.

Rare Cenozoic ages and a dominance of grains dated between 500 and 2800 Ma in the zircon U-Pb age populations from the Neogene Chittagong Hill Tracts, are consistent with data from the Himalayan foreland basin, Himalayan bedrock and modern river sediments from the Ganges. The subordinate Cretaceous grains are rarely, however, found in the southern flanks of the Himalaya, in either detritus or bedrock, and reflect contribution from an additional source – that of the Cretaceous arc which stretches from the Trans-Himalaya to Burma or detritus eroded from it, now preserved in the Paleogene Indo-Burman Ranges. This additional arc component is also reflected in the ε_{Nd} values of the Hatia Trough and CHT samples which are notably less negative than the average signature of the coeval Himalayan foreland basin Siwalik Group sediments (Table 2), and which contain detritus derived almost exclusively from the southern flanks of the orogen. We tentatively suggest that this additional component may have included a contribution from the Paleogene Indo-Burman Ranges in addition to the Trans-Himalaya (the latter assuming the Yarlung Tsangpo was draining into the Bengal Basin by this time; Clark *et al.*, 2004; He & Chen, 2006), given ε_{Nd} values of the Bengal Basin/CHT sediments stretch to less negative values than those from the modern day sediment in the Brahmaputra and the coalesced Ganges-Brahmaputra Rivers which drain the Trans-Himalaya. However, it cannot be ruled out that the Trans-Himalaya contributed more material to the Brahmaputra in the past, than it does in the syntaxial-dominated load today, which could have resulted in palaeo-Brahmaputra values similar to those documented in the CHT and Hatia Trough sedimentary rocks. In such a case, contribution from the Paleogene Indo-Burman Ranges need not be invoked.

Thus, palaeoshelf mapping and petrographic, heavy mineral and isotopic data confirm the dominant source for the Late Neogene-Recent Hatia Trough and CHT sediments to be the Himalaya. A minor arc-derived source, eroded from the Trans-Himalaya/arc-sourced Paleogene Indo-Burman Ranges sedimentary rocks is also detectable.

Without doubt, exhumation of the Shillong Plateau since 9–15 Ma (Biswas *et al.*, 2007; Clark & Bilham, 2008; Avdeev *et al.*, 2011) must have resulted in erosion of its detritus to the basin, and some workers believe that the amount of material contributed is considerable, at least to the northern part of the Bengal Basin (Surma Basin) in post-Miocene times (e.g. Johnson & Nur Alam, 1991). Previous work on modern river sediments draining the Shillong plateau show that, at least today, it is basement lithologies (of Indian craton signature) rather than recycled Cenozoic Himalayan-derived sedimentary cover, that overwhelmingly constitutes the detritus being eroded (Najman *et al.*, 2008), and detritus of Indian craton signature is clearly not the dominant source to the Hatia Trough and CHT sediments. The contribution from Cenozoic Himalayan-derived sediments, deposited on top of the Shillong Plateau cratonic rocks and recycled into the Bengal Basin when the plateau was exhumed and uplifted, would be difficult to distinguish from Himalayan-derived sediments deposited directly into the basin.

We rule out significant recycling of older (MS1) more eastern CHT Bengal Basin derived sediments into much of the Chittagong Hill Tracts and Hatia Trough rocks, on the basis that deformation of the Bengal Basin sediments, propagating from east to west, did not start until latest MS2 times (see section Evolution of the Neogene accretionary prism), but the timing of CHT deformation further east in Burma remains unconstrained.

REGIONAL IMPLICATIONS

Evolution of the Neogene accretionary prism

Provenance data are consistent with the interpretation that the Neogene sediments of the Chittagong Hill Tracts and Hatia Trough were sourced by the rising Himalaya. The fold belt represents a Neogene accretionary prism, whereby the eroded sediments were incorporated into the proto-Bengal Fan and then subducted and accreted along the zone of convergence between India and Asia, as suggested by Curray *et al.* (1979). The Neogene fold belt extends east as far as the Kaladan fault in Burma (Fig. 1), and the Neogene facies of the Burmese portion of the fold belt have similar petrographic and isotopic characteristics to the Neogene of the Hatia Trough and CHT and are considered to be predominantly Himalayan-derived (Allen *et al.*, 2008).

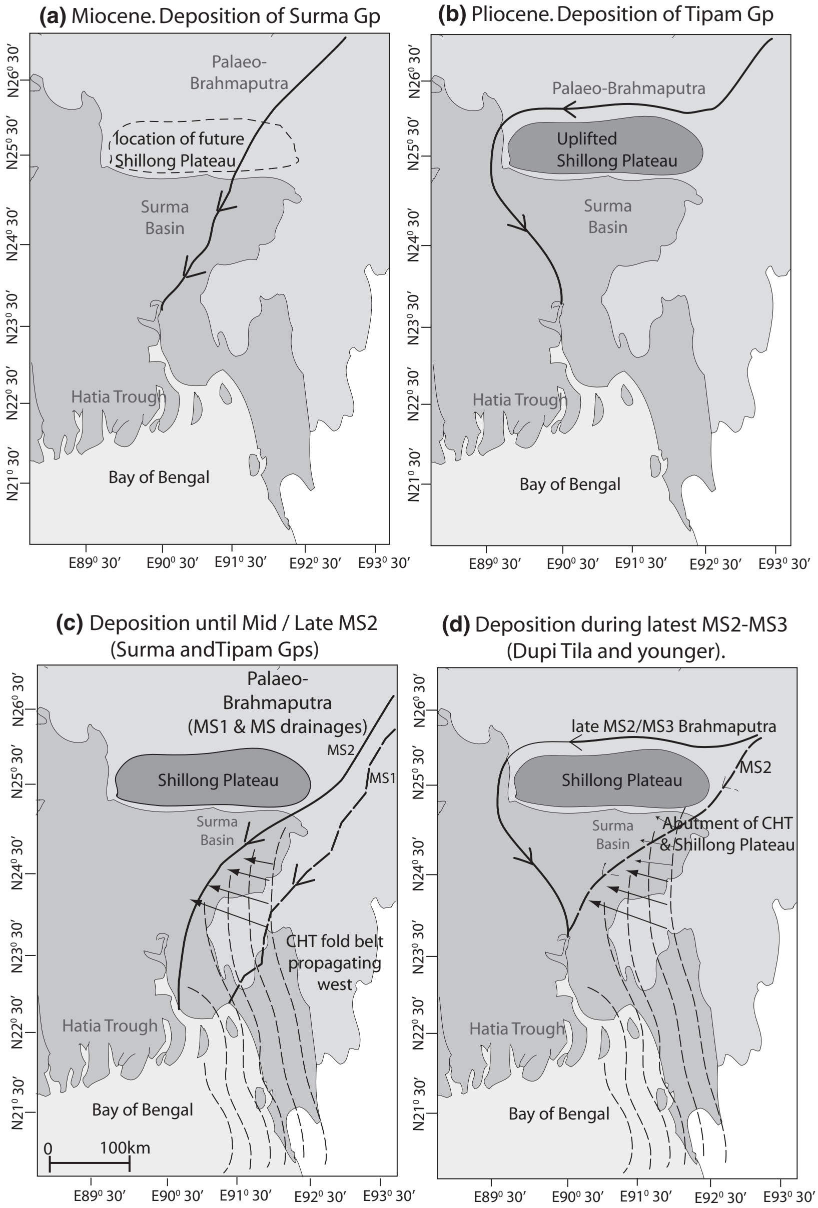


Fig. 12. The diversion of the palaeo-Brahmaputra to the west of the Shillong plateau. (a) and (b) illustrate the traditional view, that uplift of the Shillong Plateau in the Pliocene caused diversion of the river to the west, (c) and (d) provide a potential alternative theory, that abutment of the west-propagating CHT fold belt against the already-uplifted Shillong Plateau resulted in closure of the NE drainage route and diversion west of the Plateau. See section Possible palaeodrainage scenerios in the Bengal Basin for complete discussion.

Zircon fission track ages show a decrease in age of youngest population westward, with youngest populations of samples ranging between 28 and 38 Ma in the Burmese Neogene Indo-Burman Ranges (Allen *et al.*, 2008), and from 5 to 17 Ma in the Bangladesh Chittagong Hill Tracts. This westward decrease in age is consistent with earlier cessation of deposition/earlier exhumation in the east as would be expected in this accretionary prism tectonic environment, as deformation progressed westward.

Hiller (1988) and Lohmann (1995) considered folding of the Chittagong Hill Tracts to have taken place in the late Miocene-Pliocene. Sikder & Alam (2003) argue for multiphase fold development, with a main deformation phase during deposition of the Tipam Formation, which is then followed by two further phases after deposition of the Tipam Formation and the Dupi Tila Group respectively. Maurin & Rangin (2009) consider that deformation of the Neogene wedge occurred not before 2 Ma. Our seismic data concur with this very young age of deformation. Seismic lines stretching from coastal onshore to offshore (Fig. 5) show MS3 synformal strata onlapping onto/thinning over MS2 anticlines. Thinning may also be prevalent in upper MS2 (Fig. 5a) but channelisation makes interpretation difficult. However, an upper MS2 time of deformation is corroborated when the data are subjected to seismic flattening techniques (Clarke, 2001). The time of deformation is constrained by the age of the

MS2-MS3 boundary, dated biostratigraphically at *ca.* 0.4 –1.9 Ma (see section Biostratigraphic calibration).

Dating deformation further east is hampered in the CHT (1) by erosion on the anticline crest that has removed the record of thinning and onlapping sediments and (2) by the quality of seismic data that preclude the identification of any onlap surfaces within MS2. In Burma, it is hampered by a lack of seismic data available to us.

Possible palaeodrainage scenarios in the Bengal Basin

Seismic palaeoshelf mapping and interpretation of seismic lines through the Hatia Trough and Chittagong Hill Tracts highlight input from a clastic source to the north/north-northeast throughout the Neogene (Fig. 6). Given the present configuration of major drainage in the region today, provenance data and consensus with previous work using isopach maps and lithofacies maps (Uddin & Lundberg, 1999, 2004), it seems likely that this input is from the palaeo-Brahmaputra. εNd values from MS1-3 sediments are less negative than values for the Brahmaputra today. This indicates additional input to the MS1-3 sediments from an arc source; either the result of greater input from the Trans-Himalaya to the Brahmaputra sediment load compared with today, [assuming the Yarlung Tsangpo which drains the arc was flowing into the Brahmaputra by this time (REF; Clark *et al* (2004); He and Chen (2006))] or from the arc-derived Paleogene Indo-Burman Ranges to the east, with the detritus transported either directly to the Surma Basin from westerly draining rivers, or by IBR-draining rivers that flowed into the Brahmaputra and thence to the Surma Basin.

Previous workers have proposed that uplift of the Shillong Plateau around the Surma Group – Tipam Formation boundary (our MS1-MS2 boundary) caused diversion of the palaeo-Brahmaputra west of the plateau (Johnson & Nur Alam, 1991) (Fig. 12a and b). We suggest a possible alternative scenario, that westward encroachment and final abutment of the CHT accretionary prism against the already-uplifted Shillong Plateau caused diversion of the palaeo-Brahmaputra from east of, to west of the plateau (Fig. 12c and d). More recent work suggests that exhumation of the Shillong Plateau occurred *ca.* 8–15 Ma, with associated uplift either occurring synchronously or delayed until *ca.* 3–4 Ma (Biswas *et al.*, 2007; Clark & Bilham, 2008; Yin *et al.*, 2010; Avdeev *et al.*, 2011). Given the timing of abutment constrained by the age of deformation of the CHT not before latest MS2 times (see section Evolution of the Neogene accretionary prism), this scenario would result in river diversion later than if caused by Shillong Plateau uplift at the MS1-MS2 boundary. Our proposed scenario would be consistent with (1) the seismically defined major change in facies from braid plain to meandering within late MS2 times (Tipam to Dupi Tila Formation) in the Surma Basin (see section Seismic stratigraphy: the megasequences) as the major braided river diverted away from the region, leaving it to be drained by smaller meandering rivers and (2) the subtle shift in clastic input direction from NNE to N between MS2 and MS3 times (see section Seismic palaeoshelf mapping; determination of sediment input directions), although such a shift could also have been caused solely by gradual progressive encroachment of the Chittagong Hill Tract into the area at this time.

Further work, currently ongoing, in the more proximal part of the floodplain (Surma Basin) is needed, to interpret the influence of uplift of the Shillong plateau on basin facies, the timing of proposed river capture of the Yarlung Tsangpo by the Brahmaputra and the timing of deformation of the CHT further north, in this critical region.

SUMMARY AND CONCLUSIONS

(1) The Cenozoic sediments of Bangladesh were previously subdivided based on a lithostratigraphic framework correlating facies with rocks in Assam. We present a new seismic stratigraphic framework for these sediments that is regionally applicable and correlatable and biostratigraphically constrained. The sedimentary succession is divided into three Megasequences (MS), the boundary between MS1 and MS2 dated at NN15-16 (between *ca.* 2.5 and 3.9 Ma), and that between MS2 and MS3 dated at NN19-20 (between *ca.* 0.4 and 1.9 Ma).

(2) On the basis of seismic stratigraphy, we suggest that MS1 sediments are considerably less well represented at surface in the studied region of the Chittagong Hill Tracts compared with previous mapping based on lithostratigraphy.

(3) Petrographic and isotopic analyses confirm dominantly Himalayan provenance that is consistent with derivation from the offscraped (palaeo-) Bengal Fan in an accretionary prism during the Neogene. Subordinate arc-derived material is also detectable, possibly contributed from the Burmese arc-derived Paleogene Indo-Burman Ranges to the east as well as the Trans-Himalaya. Any contribution from the Himalayan-derived Cenozoic cover of the uplifting Shillong Plateau would be difficult to distinguish from Himalayan detritus deposited directly in the basin.

(4) Folding of the western CHT began in latest MS2/MS3 times. This, and the westward younging of youngest zircon fission track ages in samples from the Neogene Indo-Burman Ranges to the CHT of Bangladesh, is consistent with the pattern of deformation expected in the west-vergent accretionary prism.

(5) We tentatively suggest that it could have been the westward encroachment and final abutment of the CHT fold-thrust front against the already-uplifted Shillong Plateau in latest MS2–MS3 times that caused the closure of the NE drainage route and diversion of the Brahmaputra to the west of the Shillong Plateau.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Biostratigraphy of Bangladesh sedimentary rocks.

Appendix S2. Sample database.

Appendix S3. Petrography and heavy mineral data for Bangladesh sedimentary rocks.

Appendix S4. Sm-Nd bulk rock data for Bangladesh sedimentary rocks.

Appendix S5. Ar-Ar white mica data from Bangladesh sedimentary rocks.

Appendix S6. Zircon fission track data from Bangladesh sedimentary rocks.

Appendix S7. U-Pb zircon data from Bangladesh sedimentary rocks.

Appendix S8. Illite crystallinity data from Bangladesh sedimentary rocks.

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