Chapter 32

# HEAVY MINERAL CONSTRAINTS ON THE PROVENANCE OF CENOZOIC SEDIMENTS FROM THE FORELAND BASINS OF ASSAM AND BANGLADESH: EROSIONAL HISTORY OF THE EASTERN HIMALAYAS AND THE INDO-BURMAN RANGES

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## ABSTRACT

*The Assam-Bengal Basin system, located near the eastern syntaxis of the Himalayas and the northern end of the Indo-Burman Ranges, has received synorogenic sediments of several kilometres thick from these orogenic belts. These deposits provide valuable information on tectonic events, palaeogeography, and evolution of the sedimentary basin. Studies of heavy minerals document temporal variations in detrital compositions reflecting changes in the hinterland.*

*Heavy mineral weight percentages in the Palaeogene and Neogene samples from the Assam Basin vary from negligible to ~1.5%, and from <1 to 3.5%, respectively. In the complete Cenozoic succession of Assam opaque minerals dominate. Non-opaque heavy minerals in the Assam Palaeogene are zircon, rutile, tourmaline, biotite, chloritoid, epidote, garnet, hornblende, kyanite, staurolite, zoisite, apatite, pumpellyite, and spinel; whereas in the Neogene formations of Assam, these are garnet, chloritoid, topaz, zircon, tourmaline, apatite, kyanite, zoisite, rutile, pyroxenes, and amphiboles. The assemblages become more diverse in Miocene and younger formations. The relatively low diversity and high chemical stability of assemblages in the Palaeogene sediments indicate a homogenous and localised source and, possibly, the effects of intense post-depositional weathering. By contrast, the Neogene successions in Assam show marked variations in heavy mineral distribution.*

*In the Bengal Basin, Oligocene heavy mineral weight percentages are low (0.2%), and most of the grains are opaque; non-opaque minerals are zircon, tourmaline, and rutile, suggesting intense weathering of the Oligocene sediments. Miocene and younger heavy minerals are much more diverse and include garnet, aluminosilicates, epidote group minerals, pyroxenes, chlorite,*

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*hornblende, tremolite-actinolite, micas, prehnite, pumpellyite, and opaques. In contrast to the Assam Basin, provenance-diagnostic minerals from the Cenozoic successions of the Bengal Basin show a distinctive pattern in their distribution, indicating gradual unroofing of the contributing orogenic belts. The presence of blue-green amphiboles in Mio-Pliocene strata from Pakistan, the Assam Basin, the Bengal Basin, and Bengal Fan signal orogen-wide unroofing of arc-type rocks.*

*Modal analysis of framework components and heavy mineral analysis indicate that the sediments in both the Assam and Bengal Basins were derived from discrete sources during the Oligocene. Source areas were the incipient uplifted orogenic belts in the Himalayas for Assam, and the Indian craton for the Bengal Basin. Heavy mineral contents in Miocene and younger successions suggest that both the Bengal and Assam Basins received detritus from orogenic hinterlands, i.e., the Himalayas in the north and the Indo-Burman Ranges to the east. Overall, the Assam Basin appears to represent an earlier and more proximal repository of detritus, shed from the Himalayan convergence, whereas the Bengal Basin was a downstream and somewhat younger depocentre.*

*Keywords:* Assam; Bengal Basin; Himalayas; Eastern Himalayan syntaxis; Indo-Burman Ranges; Cenozoic; Himalayan orogeny; Bengal fan; provenance; Himalayan unroofing

## 1. INTRODUCTION

The east-west trending Alpine-Himalayan mountain belts document important Cenozoic orogenic events as a result of continent/continent collision. Our study area lies in the eastern segment of the Himalayas. The junction of the easternmost Himalayas and the northern tip of the north-south trending Indo-Burman Ranges forms the eastern syntaxis (Fig. 1). To the southwest of this syntaxis is the Assam-Bengal Basin, which records the orogenic and unroofing events of the mountain belts in the synorogenic sediments of the evolving foreland basins.

The Assam Basin is located in close proximity to the eastern syntaxis of the Himalayas, whereas the Bengal Basin is situated farther southwest. Several imbricate thrust faults of the Schuppen Belt of the Assam Basin strongly influenced the evolution of this important basin (Fig. 2). The Bengal Basin is bounded by the Precambrian Indian craton to the west and the Indo-Burman Ranges to the east, and opens to the south into the Bay of Bengal and the Bengal deep-sea fan (Figs. 1 and 2). Kilometres of Tertiary sediments are present in the Assam and Bengal Basins, both as exposures and explored by drillings. The stratigraphic successions of these large foreland basins have not been studied well compared with those of the western Himalayas. Synorogenic Cenozoic sediments filled the Assam and Bengal Basins, which were probably, in part, remnants of an ocean basin during early development (Graham et al., 1975). The sediment in both basins preserves a more or less continuous record of the orogenic events. As a result of collision and sedimentation in the basins, tectonic events, such as flexural loading and basement faulting, led to the formation of complex foreland basins of dramatic topographic relief and geometry (Evans, 1964; Uddin and Lundberg, 2004). The topographic relief is clearly attributed to under-thrusting of India beneath Asia, resulting in buoyant doubly crustal thickness at the base of the Himalayas.

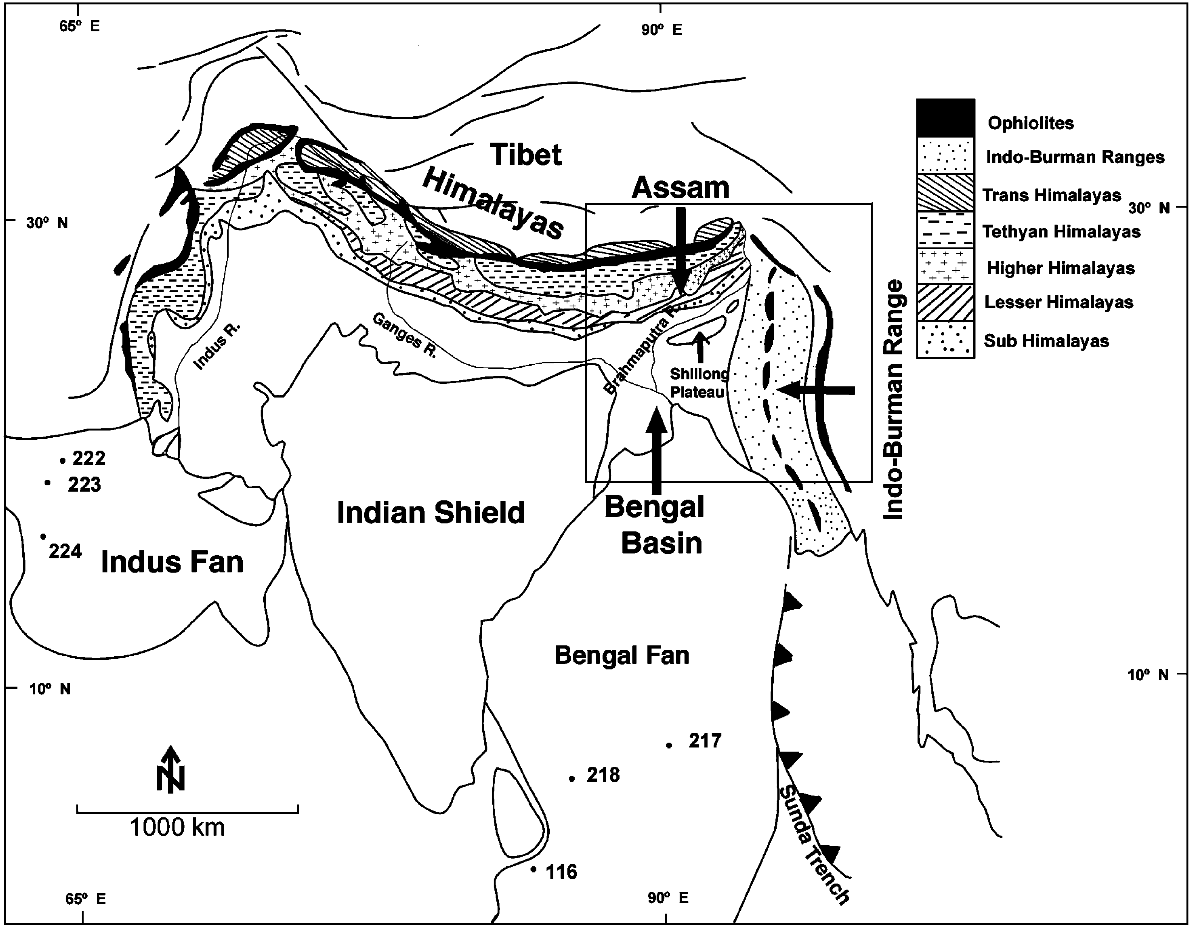

Fig. 1. Map showing the major tectonic framework of the study area, including the Assam and Bengal Basins. Also shown are locations of the DSDP and ODP sites in the northern Indian Ocean (modified after Uddin and Lundberg, 1998b).

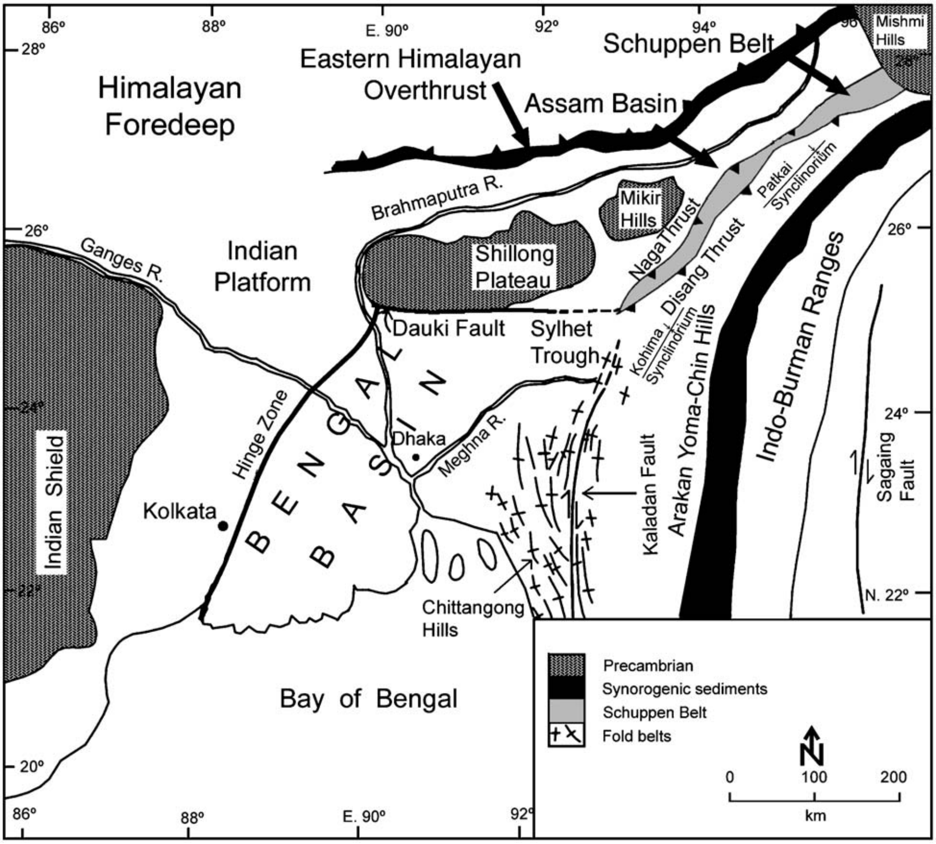

Fig. 2. Map showing the Assam and Bengal Basins and their tectonic elements such as the Eastern Himalayas and Indo-Burman Ranges. Areas enclosed by the Naga and Disang thrusts form the Schuppen Belt. Samples for this study were collected from the northeastern part of the Schuppen Belt of the Assam Basin and from outcrops in the eastern hills (Sylhet Trough and Chittagong Hills), and from cores from petroleum exploration drill holes in the Bengal Basin. The Shillong Plateau, Mikir Hills, and Mishmi Hills are uplifted blocks of Precambrian massifs. The Naga Thrust is also known as Naga Hills. The Dauki Fault demarcates the Shillong Plateau from the Sylhet Trough of the Bengal Basin. The Kaladan Fault, located east of the Bengal Basin, separates the Burmese side from the Bengal Basin (modified after Hutchison, 1989).

Detrital heavy minerals can provide important provenance information by complementing overall modal analysis of sandstones (Morton, 1985; Najman and Garzanti, 2000). In the case of relatively proximal synorogenic sediments, which are typically eroded prior to extensive weathering, transported over relatively brief intervals, and deposited rapidly, heavy mineral assemblages may closely reflect the petrology of source area complexes. In previous studies, heavy mineral analysis has proven to be effective in provenance reconstruction of sediments in the Himalayan foredeep in the east (e.g., Sinha and Sastri, 1973; Uddin and Lundberg, 1998a) and the west (e.g., Chaudhri, 1972; Cerveny et al., 1989), and in deep-sea cores of the

Bengal Fan (Yokoyama et al., 1990; Amano and Taira, 1992). Their analysis has been instrumental in determining the nature of source rocks, in reconstructing the paths of ancestral fluvial systems, and in establishing relationships of source rocks to unroofing of the Himalayas.

In this study, we report semi-quantitative analyses of heavy mineral assemblages in representative sandstones from Oligocene through Pleistocene strata of the Assam Basin, and compare these with existing heavy mineral data from coeval Cenozoic successions from the Bengal Basin (Uddin and Lundberg, 1998a), in order to help constrain the erosional history of the eastern Himalayas and the Indo-Burman orogens. This was accomplished by determining the relative abundance of all important heavy mineral species preserved in each stratigraphic unit, by recognising dominant members of mineral groups, identifying the first stratigraphic appearances of key minerals, evaluating associations or parageneses of specific heavy minerals, and establishing diagnostic minerals for stratigraphic levels in selected sections. Our further aim was to evaluate progressive changes in the rock types exposed to erosion through the history of the mountain belt. We also compared the results with existing data sets on equivalent sediments in the Siwalik deposits of Pakistan (Cerveny et al., 1989), northwest India (Chaudhri, 1972) and northeast India, including Assam (Sinha and Sastri, 1973). Data are compared with available information on regional source rock lithologies in the Indian craton and adjacent orogens (Fig. 1). One of the prime objectives of our project was to gain an insight into the pre-Miocene unroofing history of the eastern Himalayas and the Indo-Burman Ranges, as preserved in the successions of the Assam and Bengal Basins which predate the oldest (17 Ma) strata recovered by deep-sea drilling in the Bengal Fan (Yokoyama et al., 1990).

## 2. GEOLOGICAL FRAMEWORK OF THE ASSAM-BENGAL SYSTEM

The Assam-Bengal system is bounded to the west by the Indian craton. Crystalline rocks, predominantly of gneisses of Precambrian age make up the bulk of the Indian craton that is sporadically overlain by Permian Gondwana deposits and Cretaceous flood basalts of the Rajmahal trap (Hutchison, 1989). The Himalayan mountain ranges are located to the north of the mammoth Assam-Bengal system. The Himalayas have six longitudinal lithotectonic units juxtaposed along generally north-dipping thrust faults (Le Fort, 1996). From north to south, these are: (1) Trans-Himalayas consisting of calc-alkaline plutons; (2) Indus suture zone, exposing ophiolitic bands representing the zone of collision between India and Eurasia; (3) Tibetan Himalayas, represented by fossiliferous Cambrian to Eocene sediments; (4) Higher Himalayas, located north of the Main Central Thrust, composed of schists, gneisses, and leucogranites; (5) Lower or Lesser Himalayas, composed of unfossiliferous Precambrian and Palaeozoic sedimentary rocks, and crystalline rocks; and (6) Sub-Himalayas, representing Miocene to Pleistocene molasse-type deposits of the Siwaliks. The north-south trending Indo-Burman Ranges, toward the east and south of the Assam-Bengal system consist of early Tertiary synorogenic sediments, with turbidites and schists including also ophiolitic belts.

The Assam Basin, located in northeastern India, is bounded by the eastern Himalayas in the north, the Mishmi Hills in the northeast, the Indo-Burman Ranges in the east and southeast, the Bengal Basin in the southwest, and the Shillong Plateau in the west (Fig. 2). Crustal material of a pre-Gondwana landmass outcrops in the Mikir Hills, the Shillong Plateau, and the Mishmi Hills, most of which lie outside Assam. Geomorphologically, the Assam and Bengal Basins are separated by the Mikir Hills, the Shillong Plateau, and the Schuppen Belt. These crustal rocks form the basement upon which Cretaceous to Holocene sediments were deposited. The Brahmaputra River has been a major geomorphic feature and has influenced the sedimentological characters of the Assam and Bengal Basins.

The study area in Assam is in Digboi-Margherita, located in the northeastern part of India, in the northeastern part of the Schuppen belt, which consists of a series of imbricate thrust faults located between the Naga Thrust in the northwest and the Disang thrust in the southeast (Fig. 2; Rangarao, 1983). The Digboi-Margherita area is geologically important, as it is located in close proximity to both the Himalayan and Indo-Burman Ranges. Similar to the Himalayas, the Indo-Burman Ranges have experienced geological events resulting from multiple convergence of the Indian plate with the Eurasian plate and the Burmese platelet (Curray et al., 1979). Several kilometres of sediment have been deposited in the Digboi-Margherita area since the Eocene as a direct response to the collision-induced uplift of the Himalayas and the Indo-Burman Ranges.

The tectonics of northeastern India and northwestern Myanmar are controlled by north-south plate convergence along the Himalayas and east-west plate convergence along the Indo-Burman Ranges. A 230 km-wide active orogenic belt associated with eastward subduction of the Indian plate beneath the Burma plate developed as a result (Fig. 1) (Brunnschweiler, 1966; Le Dain et al., 1984; Sengupta et al., 1990; Johnson and Nur Alam, 1991). The northernmost extension of the Indo-Burman Ranges merges with the east-west-trending Himalayas at the eastern Himalayan syntaxis. The eastern Himalayan overthrust, initiated in the late Miocene or Pliocene (Le Fort, 1996), forms the northern margin of the Indo-Gangetic foredeep (Figs. 1 and 2). The continental crust of India forms the basement of the sediments in the Assam and Bengal Basins. In the Assam Basin, the continental crust is exposed in the Shillong Plateau, Mikir Hills, and various other small isolated outcrops (Fig. 2). These are the northeastern extension of the Indian Peninsular complex. The Shillong Plateau, which is a major geomorphic feature in the region, was uplifted to its present height in the Pliocene (Johnson and Nur Alam, 1991). The southern edge of the plateau is bounded by the Dauki Fault (Fig. 2) (Johnson and Nur Alam, 1991).

The Bengal Basin, further downstream of the River Brahmaputra, has two broad tectonic provinces: the shallower Precambrian Indian platform (adjacent to the Indian Shield) to the northwest and west, and the deeper part to the south and east (Uddin and Lundberg, 1998a, b). A northeast-trending hinge zone separates these two provinces (Fig. 2). The Bengal foredeep is a zone of extremely thick sedimentary successions overlying deeply subsided basement (Paul and Lian, 1975). Thick successions of the foredeep basin fill have been uplifted strongly along the northern and eastern margins of the Sylhet Trough, in northeastern Bangladesh, and also along the Chittagong fold belts of eastern Bangladesh. The Sylhet Trough, also known as the Surma Basin, is an important tectonic element that holds abundant hydrocarbon reserves (Johnson and Nur Alam, 1991). The Chittagong fold belts comprise tight NNW-trending folds along the eastern edge of the foredeep. The Kohima-Patkai synclinorium is developed in the southern and southeastern parts of the Schuppen Belt and includes the folded belt of the Sylhet Trough and Chittagong Hills (Fig. 2) (Dasgupta, 1984). The fold belts of the Chittagong Hills and Sylhet Trough represent a series of north-south trending anticlinal ridges and synclinal valleys, an arcuate belt that is convex towards the west. The fold belt shows an increase in structural complexity towards the east, into the Arakan Yoma Chin Hill and the Indo-Burman Ranges (Fig. 2). The Indo-Burman Ranges are bounded by two north-south trending right lateral faults, Sagaing to the east and Kaladan to the west, adjacent to the Bengal Basin (Uddin and Lundberg, 2004). These large-scale, regional folds of the eastern Bengal Basin and the imbricate thrust belt of the Naga Thrust developed through compression during subduction (Fig. 2) (Saikia, 1999).

## 3. STRATIGRAPHY

The stratigraphy of the Assam and Bengal Basins was established initially by work on outcrops, augmenting it with the results of exploratory drilling in the 1890s in Assam, and in the 1930s in the Bengal Basin (Khan and Muminullah, 1980). The Cenozoic stratigraphy of the Bengal Basin has long been based on lithostratigraphic correlations to previously studied strata in Assam (Evans, 1964; Holtrop and Keizer, 1970; Khan and Muminullah, 1980). Lithofacies and petrologic research, however, questions the similarity of these neighbouring foreland basin successions in the eastern Himalayas. The present stratigraphic framework of these basins has been refined by subsequent studies of palynology (e.g., Baksi, 1972; Reimann, 1993), micropalaeontology (Rangarao, 1983; Banerji, 1984) and seismic stratigraphy (Salt et al., 1986; Lindsay et al., 1991).

Palaeogene successions are much thicker in Assam (Table 1). The Eocene Disang strata ( > 3 km thick) in the Assam Basin are almost non-existent in the Bengal Basin. The Disang Group is considered as the deep-marine facies in upper Assam, equivalent to the Sylhet and Kopili Formations of Eocene age to the south in the lower Assam and the Bengal Basin (Table 2) (Rangarao, 1983). The Disang sediments are fine-grained, much indurated, and represents deep marine deposits in an arc-trench system (Uddin et al., 1999). The thick Oligocene Barail strata are more prominent in the Assam Basin compared to the Bengal Basin. The predominantly arenaceous Barail unit is subdivided into three formations (Naogaon, Baragolai, and Tikak Parbat Formations) in Assam, with abundant coaly material in the youngest, Tikak Parbat Formation. The Barail unit of the Bengal Basin is also predominantly arenaceous, consisting mostly of quartzose sandstones (Uddin and Lundberg, 1998b). The Palaeogene sediments are highly deformed and weakly metamorphosed in Assam, whereas deformation is very limited in the Bengal Basin. Depositional successions in Assam suffered syn- and post-tectonic deformation resulting in NW-verging thrusts that resulted in migration of depositional lobes (Rangarao, 1983). An important widespread unconformity occurs at the top of the Barail unit in the Assam-Bengal Basin (Evans, 1964). The unconformity is identified by an abrupt change in bed thickness and the presence of a conglomerate between the Barail and Surma units in Assam, and by a laterite bed in the Bengal Basin. This widespread unconformity is marked as the Oligocene/Miocene boundary (Rangarao, 1983). The

Table 1. General stratigraphy of the Assam Basin (modified after Bhandari et al., 1973; Rangarao, 1983)

| Chronostratigraphy | Unit | | Thickness (m) | Brief lithology |
|---|---|---|---|---|
| Pleistocene | Moran Group | Dihing Formation | > 500 | Sandstones with coarse carbonaceous shale |
| Pliocene | | Namsang Formation | > 1000 | Sandstones and clays with thin bands of coal seam |
| *Unconformity* | | | | |
| Mio-Pliocene | Tipam Group | Girujan Clay | 2300 | Clay with siltstone and sandstone "alterations" |
| | | Tipam Sandstone | 2300 | Sandstones with a few thin clay bands |
| | Surma Group | Boka Bil Formation | 400 | Grey shale, associated with sandstone |
| | | Upper Bhuban Formation | 400 | Fine-grained sandstone, silt, shale, and mudstone |
| | | Lower Bhuban Formation | > 450 | Sandy shale, mudstone, and siltstone |
| *Unconformity* | | | | |
| Oligocene to Eocene | Barail Group | Tikak Parbat Formation | 700 | Sandstones, thin-bedded grey sandy siltstone |
| | | Baragolai Formation | 2700 | Predominantly shale with subordinate thin sandstone beds and prominent coal seams |
| | | Naogaon Formation | 1040 | Thinly bedded sandstone, thin subordinate shale |
| Eocene | Disang | Upper Disang Formation | > 1000 | Dark-grey splintery shale rich in carbonaceous matter and massive siltstone with concretions |
| | | Lower Disang Formation (not exposed) | > 1000 | Fine-grained sandstone with subordinate shale |
| *Unconformity* | | | | |
| Pre-Eocene | Deragaon Formation (not exposed) | | ~250 | Inferred to be fine grained sandstones and argillites |

Table 2. Generalised Cenozoic stratigraphic units of the Bengal Basin (modified after Uddin and Lundberg, 1998a)

| Chronostratigraphy | Unit | | Thickness (m) | Brief lithology |
|---|---|---|---|---|
| Pliocene to Pleistocene | Dupi Tila Sandstone | | 300–500 | Medium to coarse grained, massive to cross-bedded, variously coloured sand(stone) with pebbles and clay galls |
| Late Miocene to Pliocene | Tipam Group | Girujan Clay | 70–1000 | Brown to blue mottled clay with calcareous nodules |
| | | Tipam Sandstone | 80–1100 | Yellow-brown to orange, medium to coarse grained, massive and cross-bedded, sand(stone) with pebbles and coal fragments |
| *Unconformity* | | | | |
| Middle to Late Miocene | Surma Group | Boka Bil Formation | 300–1400 | Alternation of bedded and rippled mudstone, siltstone and sandstone with calcareous concretions; top is marked by the ‘‘upper marine shale’’ |
| Early to Middle Miocene | | Bhuban Formation | 250–1700 | Light grey to light yellow bedded siltstone, sandstone and sandy mud in top unit; blue to yellowish grey silty and sandy mudstone in the middle unit; bedded siltstone, sandstone and sandy mud in the lower unit |
| *Unconformity* | | | | |
| Oligocene | Barail Formation | | 45–1600 | Pink, massive, medium- to coarse-grained sand(stone) |
| Late Eocene | Kopili Formation | | 7–150 | Thinly bedded, fossiliferous mudstone |
| Middle Eocene | Sylhet Limestone | | 90–240 | Nummulitic limestone |

magnitude of this unconformity decreases basinward to the south, in step with the presence of successive formations of the Surma Group (Rangarao, 1983).

Neogene strata, deposited in both the Assam and the Bengal Basin, are relatively similar in composition compared to the compositional difference in the Palaeogene deposits between the two basins. Depocentres shifted throughout the early Miocene in Assam, mostly toward the south thus resulting in deposition of thicker units (Surma Group, including the Bhuban and Boka Bil Formations) in the Bengal Basin. In the late Miocene to Pliocene, the units (Tipam Group, including Tipam Sandstone and Girujan Clay) deposited in the Schuppen Belt are thicker, however, compared to the Bengal Basin. This is due to channel shifting in the locally under-filled Assam Basin, resulting from tectonics within the thrust belts (Fig. 2). Depocentres shifted again (Pliocene-Pleistocene) toward the south as a result of encroaching mountain fronts close to the Assam Basin, resulting in the deposition of the Moran sediments. The Moran-equivalent unit in the Bengal Basin is known as the Dupi Tila Formation (Table 2). Compositionally, Neogene sediments in both the Assam and Bengal Basins are quartzolithic to quartzofeldspathic, presumably because of provenance from the approaching orogenic fronts (Uddin and Lundberg, 1998b; Kumar, 2004).

## 4. METHODS

Approximately 150 g of each sample were crushed to disaggregate the sandstone into discrete mineral grains. In order to evaluate the general grain-size distribution of heavy minerals and to assess the optimum size fractions for analyses, sediments were sieved at 1 phi intervals from 0 to 4 phi (1 to 0.063 mm). Resulting analysis showed that the 2–3 phi (0.250–0.125 mm) and 3–4 phi (0.125–0.063 mm) fractions of Assam Basin sediments generally contain the highest concentration of heavy minerals. For heavy-mineral grain counting the 2–3 phi fractions were used because the grains were easier to identify under the petrographic microscope. The 2–3 phi fractions were separated using a magnetic separator into 0.4, 0.8, and 1.2-A magnetic fractions based on mass magnetic susceptibility. By grouping the heavy minerals into different fractions based on magnetic susceptibility, their identification was facilitated. The 0.4-A magnetic group at slide slope 20° separates out ilmenite, garnet, olivine, chromite, and chloritoid. The 0.8-A group at slide slope 20° separates out hornblende, hypersthene, augite, actinolite, staurolite, epidote, biotite, chlorite, and tourmaline (dark). The 1.2-A group at slide slope 20° separates out diopside, tremolite, enstatite, spinel, staurolite (light), muscovite, zoisite, clinozoisite, and tourmaline (light). At the slide slope of 5°, the magnetic fraction at 1.2-A separates out sphene, leucoxene, apatite, andalusite, monazite, and xenotime. The non-magnetic fraction includes zircon, rutile, anatase, brookite, pyrite, corundum, topaz, fluorite, kyanite, sillimanite, anhydrite, and beryl (Hess, 1966).

Slide mounts were then made of each magnetically defined heavy mineral subfraction by sprinkling mineral grains (usually more than 300) onto a slide in a drop of mineral oil with a refractive index of 1.550. Mineral identification was carried out with a petrographic microscope using a modification of the Fleet method (Fleet, 1926), in which nearly all identifiable grains (more than 300) on each microscope slide were counted. Grains identified from each magnetically separated fraction were then added together to calculate the frequency percentage of heavy minerals present in 2–3 phi size fraction of a sample. Twenty-five different heavy-mineral species were identified, including opaque minerals as a single group.

## 5. RESULTS

### *5.1. Assam Basin*

Semi-quantitative point-counting results for heavy minerals from the Assam Basin sediments are presented in Table 3. Total heavy mineral contents in the Oligocene sandstone from Assam range from 1.5 weight percent, to sometimes as low as 0.1%. Heavy mineral weight percentages in various units in the study area in Assam, from old to young, are 1.55 (Barail Group), 0.73 (Surma Group), 1.86 (Tipam Group), and 2.47% (Moran Group) (Fig. 3). Heavy mineral assemblages show variations through time and are most diverse in the Miocene and younger formations.

The most common particle size for the Assam Basin heavy minerals is 2–3 phi (fine sand), with 41–66% of the heavy fraction falling into this interval. Most of the remaining heavy fraction is roughly evenly spread between the 1–2 and 3–4 phi intervals. The 0–1 phi fraction comprises generally less than 1% of total heavy minerals. Heavy mineral weight percentages in the Oligocene and post-Oligocene samples from Assam range from negligible to ~1.5%, and from <1 to 3.5%, respectively. Opaque minerals dominate over the non-opaque varieties in the whole Cenozoic succession of Assam (Fig. 3).

The non-opaque minerals identified in the Oligocene succession of Assam are zircon, rutile, tourmaline, biotite, chloritoid, epidote, garnet, hornblende, kyanite, staurolite, zoisite, apatite, pumpellyite, and spinel (Fig. 4). Heavy minerals present in the Neogene formations are garnet, chloritoid, topaz, zircon, tourmaline, apatite, zoisite, epidote, staurolite, rutile, pyroxenes, tremolite-actinolite, chlorite, and aluminosilicates (Table 3; Fig. 4). The assemblages are generally dominated by opaque minerals (88%). The ZTR (zircon-tourmaline-rutile; Hubert, 1962) index decreases from the Oligocene to the younger units (Table 3). The ZTR in the Barail, Surma, Tipam, and Moran groups is 32.52, 14.22, 13.10, and 10.47%, respectively. Miocene and younger sands and sandstones have lower amounts of opaque minerals (~25% of the total heavy minerals), and correspondingly higher percentages of diverse non-opaque assemblages (Table 3; Fig. 4).

Of the ultra-stable heavy minerals, tourmaline is much more abundant than zircon and rutile throughout the succession. Tourmaline grains are mainly iron- and magnesium-bearing, assessed from their strong pleochroism and absorption (Mange and Maurer, 1992). Although garnets are present in Oligocene samples, they are more abundant in the younger units (Fig. 4). Heavy mineral assemblages of Miocene sands and sandstones are dominated by chlorite/chloritoid and garnets. All other groups are less dominant. Most garnets are almandine, with some compositions approaching grossular; pyrope contents rarely exceed 35% (Kumar, 2004). Aluminosilicate minerals as a group (i.e., sillimanite, kyanite, and andalusite) are sparse

Table 3. Normalised abundances of heavy minerals, Assam Basin, India

| Number of samples | Oligocene | Miocene | Miocene-Pliocene | Pliocene-Pleistocene |
|---|---|---|---|---|
| | Barail Group | Surma Group | Tipam Group | Moran Group |
| | $N = 4$ | $N = 5$ | $N = 3$ | $N = 4$ |
| Total heavy minerals (wt% of total framework grains) | 1.55 | 0.73 | 1.86 | 2.47 |
| Total opaque minerals (as % of total heavy minerals) | 68.0 | 35.0 | 24.0 | 22.0 |
| Zircon | 6.3 | 1.9 | 2.4 | 1.4 |
| Tourmaline | 14.6 | 7.2 | 6.4 | 5.8 |
| Rutile | 17.5 | 5.1 | 4.3 | 3.3 |
| ZTR index* | 38.6 | 14.2 | 13.1 | 10.5 |
| Sillimanite | 0.0 | 3.8 | 1.0 | 1.9 |
| Kyanite | 3.3 | 3.5 | 4.0 | 3.6 |
| Andalusite | 1.6 | 1.4 | 1.0 | 1.7 |
| Staurolite | 8.1 | 3.7 | 6.4 | 4.7 |
| Epidote | 2.0 | 1.4 | 2.9 | 3.3 |
| Zoisite and clinozoisite | 1.2 | 3.5 | 1.0 | 1.1 |
| Pyroxene | 6.5 | 2.8 | 5.5 | 2.2 |
| Garnet | 18.7 | 11.4 | 36.1 | 43.0 |
| Chlorite and chloritoid | 1.6 | 28.9 | 23.3 | 18.5 |
| Hornblende | 3.3 | 5.6 | 1.3 | 6.9 |
| Tremolite and actinolite | 4.8 | 7.0 | 1.1 | 0.6 |
| Glaucophane | 0.0 | 1.4 | 0.0 | 0.0 |
| Biotite and muscovite | 2.0 | 5.6 | 2.1 | 0.6 |
| Prehnite and pumpellyite | 2.4 | 2.8 | 0.5 | 0.0 |
| Apatite | 5.7 | 6.3 | 1.3 | 1.7 |

*ZTR = zircon + tourmaline + rutile.

in Oligocene sandstones, comprising only 4.3% of the non-opaque heavy minerals, but are relatively common in younger units, making up 5–6% of the heavy minerals in the Miocene to Pleistocene formations (Fig. 4). Sillimanite appears in appreciable amounts only in the Miocene sediments, with persistent appearance in the Girujan Clay of the Tipam Group. Minerals of the epidote group (epidote, zoisite, and clinozoisite) do not show any perceptible changes and are relatively low in abundance throughout the stratigraphic section in the Assam Basin sands and

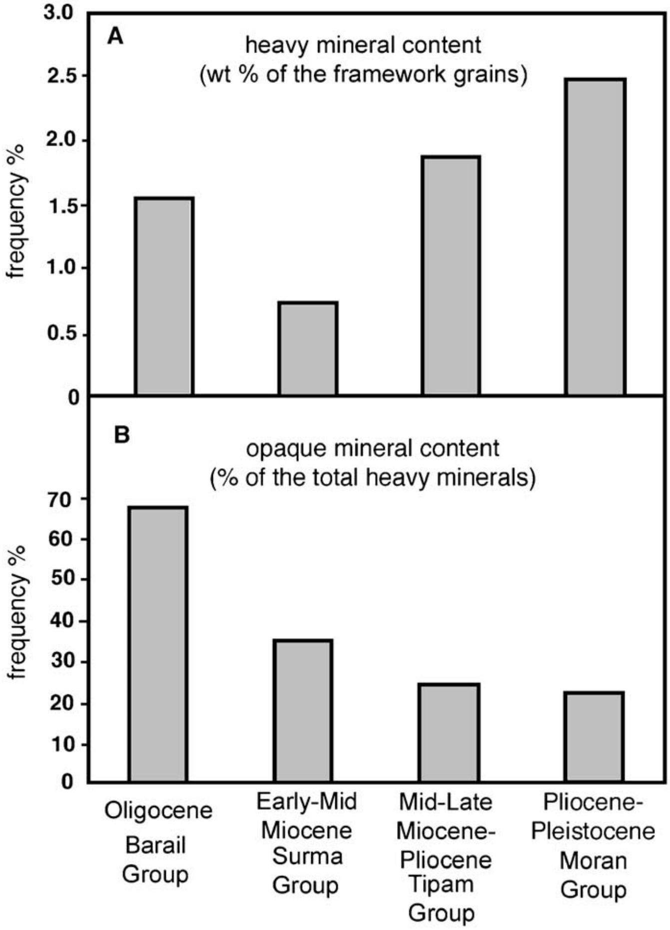

Fig. 3. Total heavy mineral content of Cenozoic successions from Assam, shown as weight percentage of total framework grains (A), and opaque mineral content, indicated as percentage of total heavy minerals (B). Note that the Oligocene Barail unit contains more opaque minerals than the younger units.

sandstones (Table 3). The abundance of blue-green hornblende is generally low but varies irregularly with stratigraphy. Significant amounts of blue-green hornblende appear in the Surma and Tipam Group sandstones. Tremolite and actinolite are present in Oligocene but are less abundant in the Miocene and younger successions. Mica is present in small amounts throughout the sequence, but is more abundant in the Neogene sediments. Although relatively uncommon, orthopyroxene is most common in the Oligocene Barail Group sediments (5%) and constitutes less than 1% of the non-opaque heavy minerals in the younger sediments (Fig. 4). The opaque fraction includes magnetite, pyrite, ilmenite, and hematite. Chromite is present in traces. In the Pliocene-Pleistocene Moran Group, the heavy mineral suites include garnet, staurolite, chlorite-chloritoid, epidote, kyanite, as well as

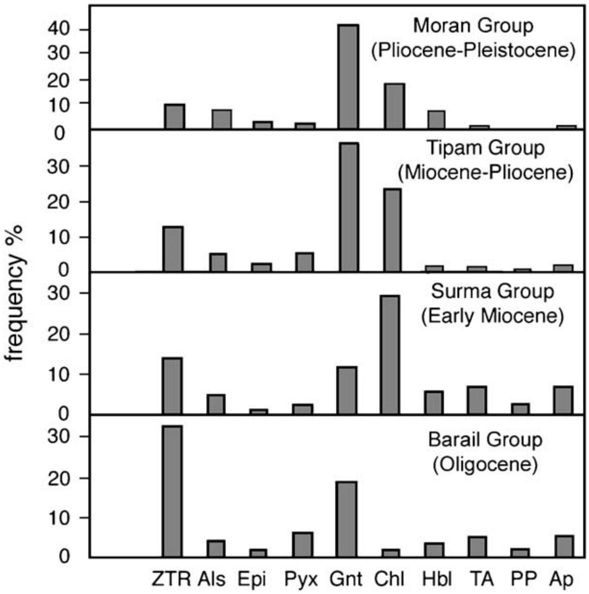

Fig. 4. Abundance of heavy minerals in four groups of different age in the Cenozoic successions of the Digboi-Mergherita area of Assam, shown as percentages of non-opaque heavy minerals. ZTR = sum of zircon, tourmaline, and rutile; Als = aluminosilicate minerals (andalusite, kyanite, and sillimanite); Epi = epidote group; Pyx = pyroxene group; Gnt = garnet group; Chl = chlorite and chloritoid; Hbl = hornblendes; TA = tremolite and actinolite; PP = prehnite and pumpellyite; Ap = apatite.
Note: ZTR percentages decrease through time, whereas garnet increases in the upper sections.

sillimanite, andalusite, zircon, tourmaline, rutile, monazite, hornblende, tremolite, and actinolite.

## *5.2. Bengal Basin*

Similar to the Assam successions, the 2–3 phi size fractions contain most of the heavy minerals in the Bengal Basin sediments (Table 4) (Uddin and Lundberg, 1998a). Quartzose sandstones of the Palaeogene from the Bengal Basin contain only 0.2% heavy minerals, comprising abundant opaque and only stable minerals such as tourmaline, garnet, rutile, and zircon (Figs. 5 and 6) (Uddin and Lundberg, 1998a). By contrast, the Neogene sandstones contain more abundant and more diverse heavy mineral assemblages. These include, in addition to abundant opaque grains, garnet (mostly almandine), and moderate to minor amounts of tourmaline, kyanite, zircon, tremolite, rutile, chlorite, zoisite, staurolite, epidote, sillimanite, and clinopyroxene. The Mio-Pliocene successions along with the above minerals also contain abundant blue-green hornblende, orthopyroxene, and sparse chromite. Heavy mineral assemblages of the sands and sandstones of the Plio-Pleistocene units are similar to those of the underlying Miocene sandstones, but they comprise larger amounts of high-grade mineral phases.

Table 4. Normalised abundances of heavy minerals, Bengal Basin (modified after Uddin and Lundberg, 1998a)

| Number of samples | Eo-Oligocene | Early-Mid Miocene | Mid-Late Miocene | Late Miocene-Pliocene | Pliocene-Pleistocene |
|---|---|---|---|---|---|
| | Kopili & Barail Fms | Bhuban Formation | Boka Bil Formation | Tipam Group | Dupi Tila Sandstone |
| | $N = 4$ | $N = 7$ | $N = 8$ | $N = 9$ | $N = 6$ |
| Total heavy minerals (wt% of total framework grains) | 0.21 | 0.50 | 0.98 | 1.92 | 2.90 |
| Total opaque minerals (as % of total heavy minerals) | 54.0 | 17.2 | 14.8 | 13.6 | 11.4 |
| Non-opaque heavy minerals: (as % of non-opaque heavy minerals) | | | | | |
| Zircon | 5.0 | 7.0 | 2.0 | 3.0 | 5.0 |
| Tourmaline | 41.2 | 11.9 | 13.4 | 12.6 | 11.7 |
| Rutile | 5.0 | 7.0 | 4.0 | 3.0 | 5.0 |
| ZTR index* | 51.2 | 25.9 | 19.4 | 18.6 | 21.7 |
| Sillimanite | 0.0 | 1.0 | 1.0 | 1.6 | 8.1 |
| Kyanite | 1.5 | 4.7 | 3.3 | 11.3 | 10.0 |
| Andalusite | 2.6 | 1.3 | 3.0 | 2.1 | 2.7 |
| Staurolite | 0.3 | 2.2 | 2.9 | 3.0 | 3.1 |
| Epidote | 1.0 | 6.8 | 8.7 | 10.0 | 11.1 |
| Zoisite and clinozoisite | 0.3 | 1.6 | 1.8 | 2.1 | 3.7 |
| Orthopyroxene | 0.0 | 0.6 | 0.7 | 1.3 | 3.9 |
| Clinopyroxene | 1.4 | 1.0 | 1.0 | 1.0 | 1.5 |
| Garnet | 6.0 | 31.0 | 27.0 | 12.0 | 9.0 |
| Chlorite and chloritoid | 0.0 | 4.1 | 5.8 | 6.9 | 2.2 |
| Hornblende | 0.9 | 3.3 | 4.0 | 14.8 | 4.6 |
| Tremolite and actinolite | 2.0 | 1.3 | 1.0 | 2.3 | 2.1 |
| Glaucophane | 0.0 | 1.5 | 0.3 | 0.1 | 1.4 |
| Biotite and muscovite | 5.5 | 7.4 | 11.1 | 6.0 | 3.2 |
| Prehnite and pumpellyite | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 |
| Apatite | 3.4 | 2.5 | 1.9 | 1.2 | 2.9 |

*ZTR = zircon + tourmaline + rutile.

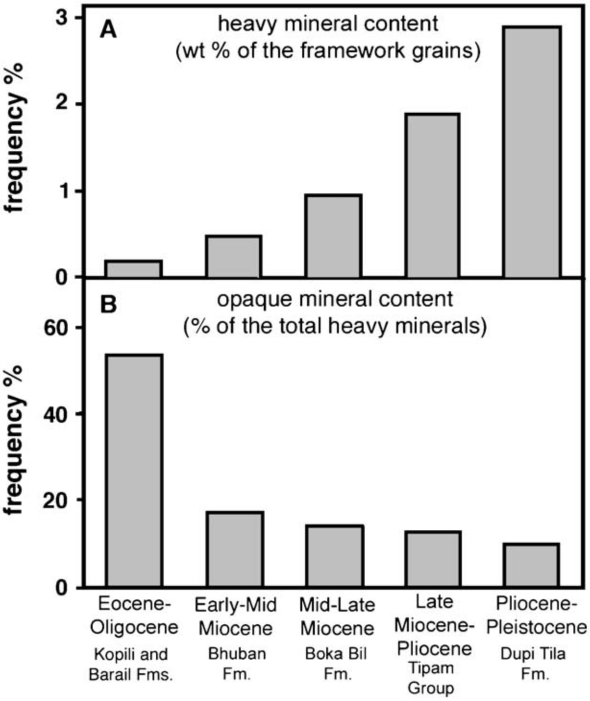

Fig. 5. Total heavy mineral content of Cenozoic successions studied from the Bengal Basin, expressed as weight percentage of total framework grains (A), and opaque mineral content, shown as percentage of total heavy minerals (B). Note that the Eocene-Oligocene Kopili and Barail Formations have the least amount of heavy minerals, and that most of them are opaque (modified after Uddin and Lundberg, 1998b).

## 6. PROVENANCE HISTORY

### 6.1. Assam Basin

Semi-quantitative grain counts of heavy mineral assemblages from the Assam Basin sediments illustrate relationships between individual mineral species, and the assemblages in which they are found as detrital grains, and provide information on the source rocks from which they are derived. In the Oligocene Barail Group, abundant opaque grains, low-diversity heavy mineral assemblages, a relatively high ZTR index, poor preservation, and moderate grain rounding indicate intense weathering in the source areas and/or diagenetic dissolution of the unstable components.

Sinha and Sastri (1973) studied heavy minerals from the Eocene Disang Group of sediments further south of the study area, which show an impoverished suite dominated by very abundant opaque minerals (nearly 88%; mostly pyrite) and traces of garnet, tourmaline, zircon, rutile, and monazite. The heavy mineral suites of the Disang and Oligocene Barail are similar and differ only quantitatively (Sinha and Sastri, 1973; Kumar, 2004). The Disang Group consists of shale, siltstone, and fine-grained sandstone, whereas the Barail Group is mostly represented by fine- to

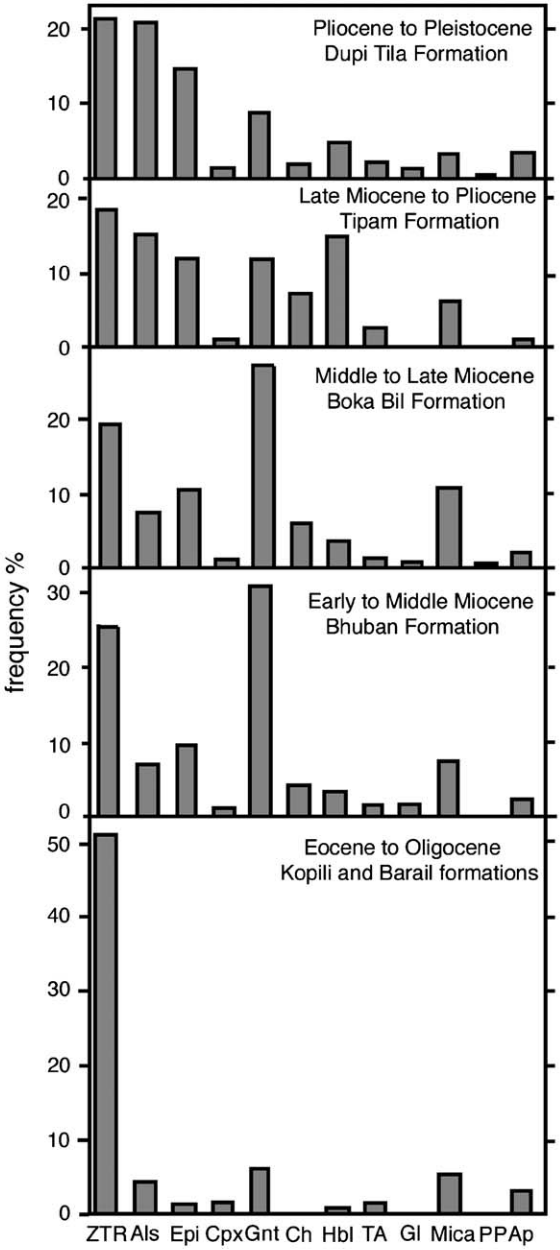

Fig. 6. Content of key heavy minerals in five formations of different age in the Cenozoic successions of the Bengal Basin, shown as percentages of non-opaque heavy minerals. Key as in Fig. 4.

Note: ZTR percentages decrease through time, whereas garnet increases in the Miocene (modified after Uddin and Lundberg, 1998a).

medium-grained sandstones. The Palaeogene sandstones from the Assam Basin (Disang and Barail Groups) are quartzolithic in composition and the heavy mineral assemblages show very little variation. The Disang sediments were deposited in deep-marine environments close to an arc-trench system during the Eocene (Kumar, 2004). During the Cretaceous-Eocene, ophiolites of the ophiolite belts were obducted onto the continent close to the Assam Basin in the Indo-Burman Ranges (Saikia, 1999). Thus, the occurrence of a few mafic rock fragments such as those present in the Disang sandstone (Saikia, 1999) may have derived from the ophiolite belts in the Indo-Burman orogen (Fig. 2). These ophiolites are thrust over the Disang rocks at a high-angle reverse fault, suggesting tectonic contacts.

During the initial deposition of the Oligocene Barail Group sediments, the depositional environment changed from deep marine to deltaic. With delta progradation, the growing delta plains were incised by a number of distributary channels in which coal-bearing sediments were deposited (Rangarao, 1983). The presence of radiolarian chert fragments in the basal conglomerates may indicate a contribution from the eastern ophiolite belt of the Indo-Burman Ranges.

The Neogene Surma Group sediments that unconformably overly the Oligocene sandstones comprise diverse heavy mineral assemblages, and are in stark contrast with the Oligocene Barail Group. They contain a very high percentage of chlorite, chloritoid, and epidote, and are also enriched in garnet and ZTR compared to the underlying Barail Group, indicating derivation from low- to medium-grade metamorphic terranes.

The Tipam Group bulk suite is very diverse, consisting of almost all the heavy mineral species found in the underlying Surma Group, but also contains enstatite, sillimanite, and andalusite. Opaque minerals are less abundant than in the underlying Barail and Surma groups. All these heavy mineral species suggest an orogenic source, with input from additional source terranes of diverse lithologies, ranging from high-grade contact metamorphic rocks to igneous rocks. Blue-green amphiboles in Miocene sediments have been reported from the Bengal Basin (Uddin and Lundberg, 1998a) and further south from the Bengal Fan (Amano and Taira, 1992). Cerveny et al. (1989) also found similar mineral species in the Siwaliks from the western Himalayas. The blue-green amphiboles present in the Tipam Group of the study area suggest simultaneous unroofing along the complete strike of the Himalayas. The Girujan Clay contains thin arenaceous bands that also yield diverse heavy mineral assemblages. The suite is similar to that of the Tipam Group, except that it contains more abundant enstatite, sillimanite, and andalusite.

The Pliocene-Pleistocene Moran Group sediments (Namsang and Dihing Formations) are characterised by diverse heavy minerals. They suggest derivation from different rock complexes in the adjacent orogenic belts similar to those in the eastern Himalayas and Indo-Burman Ranges.

### 6.2. Bengal Basin

The record of the Himalayan collisional orogen in the Himalayan foreland basin sediments reveals that the Eocene to Oligocene pre-collisional to syn-collisional sediments in the Bengal Basin are overwhelmingly quartzose and contain only small amounts of heavy minerals (mainly ultra-stable species of ZTR) of which about 60%

are opaque varieties (Table 4; Figs. 5 and 6) (Uddin and Lundberg, 1998a). The low diversity of heavy minerals indicates intense weathering during deposition of the Palaeogene sandstones of the Bengal Basin, because the basin was located close to the equator (Lindsay et al., 1991). The subangular nature of the Palaeogene detrital grains suggests a short transport distance along a pathway of low relief. Compositional and textural characteristics of these pre-Miocene sandstones signal that these were derived from the Indian craton immediately to the west. Streams currently draining the Himalayan and Indo-Burman orogenic fronts were a long distance away during that time, and their depocentres were farther upstream, possibly more proximal to the orogenic fronts, as in the basins preserved in Assam. Garnets are not abundant in the Oligocene sandstones of the Bengal Basin (6%) compared with the much higher garnet quantities in the Assam Basin (with 18.7% garnets).

Contrasting with the Oligocene, the Neogene strata from the Bengal Basin contain abundant and diverse heavy mineral assemblages (Figs. 5 and 6) and suggest derivation from orogenic fronts that may have moved by then close to the Bengal Basin. Modal analysis of sandstones from these successions reveals that significant amounts of feldspars and lithic fragments first appeared at about the same time, roughly at the Oligocene/Miocene boundary (Uddin and Lundberg, 1998b), providing further evidence for the dramatic shift to an orogenic sediment source for Bengal Basin detritus. The youngest stratigraphic units, the Tipam Sandstone and the Dupi Tila Formation, contain heavy mineral assemblages that are even more abundant and more diverse than those of the underlying strata (Figs. 5 and 6). These observations suggest the emergence of additional source terranes with complex lithologies, ranging from high-grade contact metamorphic rocks to various igneous bodies. Aluminosilicates and related minerals throughout the Bengal Basin successions also reflect systematic exhumation of progressively deeper crustal levels in the eastern Himalayas (Uddin and Lundberg, 1998a). Similar trends have been observed in heavy mineral assemblages of Siwalik successions in the western Himalayas (e.g., Chaudhri, 1972; Gill, 1984). Modal analysis also indicates unroofing of progressively deeper crustal levels in the source area through the Neogene, as revealed by the appearance of systematically higher grade metamorphic lithic fragments in the sandstones (Johnson and Nur Alam, 1991; Uddin and Lundberg, 1998b). Mineralogical evidence shows that orogenic activity in the eastern Himalayas and the Indo-Burman Ranges was significant during the Neogene and Pleistocene, and that modern drainage patterns were well developed by then.

Blue-green amphiboles appear first in the late Miocene Boka Bil Formation and are found abundantly in the Mio-Pliocene Tipam Sandstone (Uddin and Lundberg, 1998b). The presence of blue-green amphiboles and the initial appearance of sparse chromites signal unroofing of arc and ophiolitic rocks from suture zones of the Himalayas and/or the Indo-Burman Ranges (Fig. 1). Blue-green amphiboles are also present in strata of similar ages in the Siwalik sandstones on the Potwar Plateau of the Pakistan Himalaya (Johnson et al., 1985; Cerveny et al., 1989); successions in Assam (Kumar, 2004) and in cores from Ocean drilling programme (ODP) Leg 116 sites on the distal Bengal Fan (Yokoyama et al., 1990; Amano and Taira, 1992) suggest sediment dispersal to the southern Himalayan basins from erosion of similar rocks from the entire Himalayas. Similarly, orthopyroxenes, particularly hypersthene, first appear in the Bengal Basin in the early to middle Miocene Bhuban Formation, and become relatively abundant in the Plio-Pleistocene Dupi Tila Sandstone. This increase in orthopyroxene content provides further evidence for continued orogenic unroofing, and along with the small amounts of chromites, also indicates erosion of ophiolitic rocks (Uddin and Lundberg, 1998a).

It is probable during the Miocene that a major fluvial system, similar to the present-day Brahmaputra River, developed or migrated toward the remnant ocean basin, represented by the Bengal Basin of that time. This paleo-Brahmaputra system apparently drained through the upper Assam valley and reached the eastern part of the Sylhet Trough to enter the Bengal Basin (Uddin and Lundberg, 1999), and—with its distributaries—may have formed the first major delta in the Bengal Basin. This major drainage, caught between the southward-advancing Himalayan belt and the westward-advancing Indo-Burman Ranges, shifted westward in the northern part of the Bengal Basin during the Pliocene, because of uplift of the Shillong Plateau (Johnson and Nur Alam, 1991). The Arakan-Yoma hills of the Indo-Burman Ranges probably contributed sediment to the Chittagong area via a second sediment plume (*palaeo-Karnafuli?*), most probably a submarine one. However, the major sediment source for Miocene sediments of the Bengal Basin was the early uplifted range of the eastern Himalayas (Uddin and Lundberg, 1999). This suggestion is also supported by the existence of a third major stream (*palaeo-Ganges?*) in the northwestern Bengal Basin, where long-term sediment accumulation was restricted by very limited subsidence in the Indian Platform (Uddin and Lundberg, 2004). These Miocene deltas in Bangladesh migrated from east to west and from north to south, toward the Bay of Bengal, as under-thrusting of India beneath southeast Asia along the Sunda Trench and its northern extension continued during the post-Palaeogene (Uddin and Lundberg, 2004). Subsidence of the deltaic deposits continued from at least the Miocene, with subsidence near the mountain belts accelerated by loading of the advancing orogens.

Although the Assam Basin sediments signal orogenic provenance, compared with the Bengal Basin their heavy mineral compositions do not show the obvious trend observed in the Bengal Basin. There is no evidence for a systematic and progressive unroofing of an orogenic belt, and medium- and low-grade minerals are equally distributed in all Cenozoic sections. Several regional and local thrust faults and the close proximity to the eastern syntaxis of the Himalayas have apparently resulted in homogenisation of the heavy mineral distribution in the Cenozoic successions of Assam.

## 7. REGIONAL TECTONIC IMPLICATIONS

The Oligocene heavy mineral assemblages from Assam contrast strongly with coeval units from the Bengal Basin, indicating distinct provenance histories for these two eastern Himalayan foreland basins. The presence of chrome-spinel in Oligocene sediments of Assam suggests provenance from ophiolitic rocks from the orogenic belts (Kumar, 2004). This finding is consistent with the modal analysis from Assam (Uddin et al., 1999; Kumar, 2004). Palaeogene sandstones from the Digboi-Margherita area of northeastern Assam show a strongly orogenic derivation, being compositionally and texturally immature with quartz (both mono- and polycrystalline), plagioclase and lithic fragments of both sedimentary and low-grade metamorphic origin. Late Oligocene units in this area also show significant amounts of volcanic and higher grade metamorphic detritus.

Pre-Miocene strata of the Bengal Basin are, however, apparently not orogenic, in accord with their mature heavy mineral suites. Temporal variations between heavy mineral assemblages in the Bengal Basin and the coeval western Himalayan strata, e.g., the Murree redbeds and the Chulung La Formation near the western Himalayan syntaxis in Pakistan (Critelli and Garzanti, 1994), suggest that orogenic detritus appeared in the eastern Himalayan Basin (Bengal Basin) much later (early Miocene) than in the western Himalayan basins (Eocene) (Uddin and Lundberg, 1998b). However, the Palaeogene successions in Assam (further northeast of the Bengal Basin) suggest an orogenic source. Thus, the Himalayan convergence cannot have been as diachronous as previously assumed (Uddin and Lundberg, 1998b), with convergence in both syntaxial parts in pre-Miocene time. The Bengal Basin may have been more distant from the Assam Basin and/or was protected by a barrier from orogenic sedimentation from the Himalayas and the Indo-Burman Ranges (Uddin et al., 2002). If "distance" was the cause, then the part of the Indian continent represented by the Bengal Basin was far to the south of Asia until the Early Miocene. Movement of this part of the Indian plate relative to Southeast Asia (Indochina) was most likely along right-lateral faults, as in the north-south trending Kaladan fault, located east of the Bengal Basin (Fig. 2) (Uddin et al., 2002).

By Miocene times, major fluvial systems had developed and debouched sediments into both the Assam and the Bengal Basins (Uddin and Lundberg, 1999). Other than changes in stratigraphic thickness, Miocene and younger heavy mineral assemblages are similar in both the Assam and Bengal Basins. Study of framework components corroborates this observation where feldspars, polycrystalline quartz and sedimentary, volcanic and metamorphic lithic fragments are found in sandstones of both the Assam and Bengal Basin (Uddin and Lundberg, 1998b; Kumar, 2004). The appearance of blue-green amphiboles in both basins toward the end of the Miocene is significant, and indicates orogen-wide unroofing of arc-type material. Cerveny et al. (1989) suggest the Kohistan island arc as the source of the blue-green amphiboles in the Siwalik successions of Pakistan. Blue-green amphiboles in the Assam and Bengal basins may have derived from coeval arcs in the eastern Himalayas, Tibet, and the Indo-Burman Ranges (Srimal, 2005). The Linzizhong Formation of Tibet and the Abor Volcanics of the eastern syntaxis of the Himalayas are considered to be contemporary to the Kohistan arc of the western Himalayas (Srimal, 2005). A source of these blue-green amphiboles in the amphibolites, granites, and gneisses in the Higher Himalayas cannot be ruled out either (Amano and Taira, 1992). The Assam Basin at this time records the presence of abundant plagioclase feldspars, suggesting erosion of thrusted crystalline basement rocks and dissected magmatic arcs from the orogenic belts (Kumar, 2004). Alternatively, plagiogranite-bearing lithotectonic belt may have since been eroded from the eastern Himalayas or the Indo-Burman Ranges. While continental convergence was active in the Schuppen Belt area of Assam, subduction-related processes deposited the early Miocene Surma trench slope turbidites in the southeastern Bengal Basin (Uddin and Lundberg, 2004). These are now exposed in several sections in and around the Chittagong Hills (Fig. 2) (Akhter et al., 1998). Although the last Miocene marine transgression covered most of the Bengal Basin during the late Miocene, Assam successions were deposited mostly in fluvial and transitional environments. The younger units are much thicker in the Bengal Basin as a result of orogenic encroachment toward the basin from both north and east.

## 8. CONCLUSIONS

The Assam Basin strata show a marked variation in their heavy mineral compositions through time. The moderate to low diversity of heavy mineral assemblages in the Palaeogene sediments indicates that the source rocks were uniform and localised, and may have experienced intense weathering. In contrast, marked variations in heavy mineral distributions in Neogene sediments reflect diverse sources, including low- to medium-grade metamorphics. This also suggests unroofing of the orogenic belts in the higher areas, such as the Himalayas in the north and in the Indo-Burman Ranges to the east. Heavy mineral compositions in Assam, however, do not show a characteristic trend of progressive unroofing of an orogenic belt throughout the Cenozoic.

Palaeogene sandstones from the Bengal Basin also contain relatively few mineral species. Opaque minerals are dominant in these sandstones, with most of the non-opaque suite comprising stable minerals, and assemblages showing a high degree of compositional maturity (Uddin and Lundberg, 1998b), possibly related to intense weathering. The moderate textural maturity (e.g., moderate rounding, poor sorting) suggests relatively short transport. These assemblages indicate a cratonic source, most probably the Indian craton immediately to the west, and maybe the more distant orogenic belts in the north and east from the Bengal Basin.

Palaeogene sediments from the Assam Basin are derived from an orogenic source. Although the heavy mineral suites of the Palaeogene in the Assam and Bengal Basins are both relatively rich in ZTR, the Assam successions contain a more diverse heavy mineral assemblage than those in the Bengal Basin. Assam was more proximal to the orogenic fronts during the Palaeogene, and sedimentation most probably occurred in a trench-slope setting. This suggests input of orogenic detritus from the eastern Himalayas and the Indo-Burman Ranges.

Diagnostic and diverse minerals in the younger sediments in the Bengal Basin signal erosion from complex source lithologies, including high-grade to contact-metamorphic rocks, and silicic to ultra-mafic igneous rocks. Similar conclusions can also be drawn from coeval strata in the Assam Basin. Blue-green amphiboles are widespread, occurring in Assam, the Siwaliks in both Pakistan and northwest India, and in the Bengal Fan. They signal orogen-wide unroofing of arc-type material and/or derivation from amphibolites, granites, and gneisses of the Higher Himalayas. The upward increase in aluminosilicates in both the Assam and Bengal Basins suggests that Miocene and younger deposits of both basins were derived from orogenic terranes. Local and regional tectonism has, however, contributed toward subtle differences in composition between these younger units.

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