Heavy mineral composition of the Neogene sandstones and beach sands across the Inani-Dakhin Nhila area, Southeast Bangladesh: Implications for provenance

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The present research work mainly deals with the qualitative and quantitative analysis of heavy minerals of the Neogene sandstones (Plio-Miocene) and beach sands of the Inani-Dakhin Nhila area and also deals with preliminary approach on chemical composition of garnets and ilmenites to infer the provenance. The Neogene sandstones of the Inani-Dakhin Nhila hill ranges contain about 2% heavy minerals whereas the beach sands of the Inani-Dakhin Nhila area contain about 8% heavy minerals.

The heavy mineral assemblages of the sands/sandstones of the Inani-Dakhin Nhila area are characterized by clear predominance of opaque minerals (with abundant ilmenite), epidote, garnet, staurolite followed by hornblende and tourmaline, lesser amounts of zircon, rutile and kyanite and by minor to trace amounts of apatite, sillimanite, monazite and sphene. The heavy mineral data suggest a wide range of metamorphic as well as granitoid source areas. The heavy mineral suites reflect that the probable sources of the clastics which have contributed to the study area of interest is located in the north, northwest and east-northeastern part of Bangladesh. These detrital grains could have been derived from crystalline and sedimentary deposits of the Himalayas, Rajmahal hills, Shillong Plateau and Indo-Burman ranges.

Key words: Inani-Dakhin Nhila area, Neogene sandstones, Paleobeach, Beach sands, Heavy minerals

Introduction

Heavy minerals are particularly useful in studies of sedimentation related to tectonic uplift of orogenic belts, as the evolution and unroofing episodes are reflected in their foreland sediments (Mange and Maurer, 1992). Heavy mineral studies provide useful informations about the provenance and the nature of the source rock complexes, particularly about the specific rock types, such as ophiolites and high-pressure rocks (Faupl et al., 1998). Morton and Hallsworth (1999) have re-evaluated the effects of physical sorting, mechanical abrasion and dissolution operating at several stages during the sedimentary cycle on heavy mineral assemblages that can modify an original provenance signal. In spite of these constraints,

heavy mineral suites retain important provenance information.

The major concentration of the heavy mineral studies in Bangladesh is in the beach area.

Many authors (e.g., Schmidt and Asad, 1962; Biswas and Khozainov, 1974; Biswas, 1976, 1977, 1978, 1979, 1981, 1983, 1999; Samad, 1978; Mitra and Ahmed, 1990; Mitra et al., 1992; Ahmed and Islam, 2001), studied beach sands with different objectives. Their studies were mainly concentrated on exploitation and development of some economic mineral sand deposits, mechanism of heavy mineral concentration, distribution and textural characteristics of heavy minerals, and on evaluation of certain mineral like, zircon, monazite, ilmenite, and magnetite.

Some heavy mineral studies have also been carried out on the Neogene sediments in the Bengal Basin, Bangladesh towards provenance analysis (e.g., Samad and Hassan, 1982; Samad and Chowdhury, 1987; Uddin and Lundberg, 1998b; Rahman, 1999).

In the present research work an attempt has been made

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to provide qualitative and quantitative heavy mineral analysis of the Neogene sandstones and beach sands, collected from different locations across two different anticlinal structures (Inani and Dakhin Nhila) and their adjacent beaches (Fig. 1 and 2) in understanding distribution and abundance of heavy minerals. Beach sands as well as sands from Tertiary hills of adjacent beaches have been considered together to find relation if any between them in terms of heavy mineral composition in order to infer the nature of rock complexes forming the source area and to determine possible sources.

Geology and Tectonic Setting

The Bengal Basin lies in the eastern part of the Indian plate and occupies most of Bangladesh and the Indian State of West Bengal as well as part of the Bay of Bengal (Fig. 1). The Basin had its origin during the collision of Indian plate with the Eurasian and Burmese plates, building the extensive Himalayan and Indo-Burman ranges, and thereby loading the lithosphere to form flanking sedimentary basins (Uddin and Lundberg, 1998a). Tectonically the Inani-Dakhin Nhila hill ranges are located in the southern most part of the Chittagong-Tripura folded zone and forming asymmetrical anticlines of plunging in nature having a general NNW-SSE trend. Steeper western flank and a gentler eastern flank are resulted from east-west compression due to relative motions of the Indian and Burmese plates (Bakhtine, 1966; Guha, 1978). A fault has been recognized in the western flank of the Dakhin Nhila anticline, whereas the entire western flank and southernmost pitch of the Inani anticline have been eroded by the sea (BAPEX, 1980, 1981) (Fig. 2). The molasse sediments of the study area are of Neogene age, comprising alternating shales and sandstones in varying proportion. It is filled mainly by orogenic sediments derived from the eastern Himalayas to the north and the Indo-Burman ranges to the east (Uddin and Lundberg, 1999) (Fig. 1). These deposits record uplift and exhumation of mountain belts formed by the ongoing India-Eurasia collision (Uddin and Lundberg, 1999). The lithostratigraphic succession has been subdivided into Surma Group (Bhuban and Boka Bil Formations), Tipam and Dupi Tila Formations (after Evans, 1932). The deposits of the Inani Anticline have been divided into Middle and Upper Boka Bil, Tipam Sandstone, Girujan Clay and Dupi Tila Formations (BAPEX, 1980) (Table 1a), on the other hand those of the Dakhin Nhila Anticline have been divided into Upper Bhuban, Lower, Middle and Upper Boka Bil and Tipam Sandstone Formations (BAPEX,

Fig. 1 Location map of the study area and adjoining areas in the eastern part of the Indian Subcontinent (Bengal Basin).

1981) (Table 1b). The Surma Group sediments were deposited under the strong influence of tidal currents in a delta system and the Tipam and Dupi Tila sediments were deposited under fluvial environment. The Neogene sandstones of the Inani-Dakhin Nhila hill ranges are characterized by fine to very fine grained, well to poorly sorted, coarse to strongly fine skewed. The paleobeach sands are characteristically fine grained, well to moderately well sorted, fine skewed to near symmetrical and mesokurtic to leptokurtic. On the other hand beach sands correspond to the fine grained, well sorted, fine skewed to near symmetrical (Bari *et al.*, 2003).

The Himalayas were uplifted to a higher degree during the Miocene (Fairbridge, 1983). During this Period, a large delta complex was developed on the northeastern side of the Bengal Basin (Alam, 1989). The sediments were funneled by turbidity currents to the deeper part of the Bengal Basin mostly from the northeast (Alam, 1989). Einsele *et al.* (1996) suggested that a north-south-oriented transverse drainage system must have existed in Pre-

Fig. 2 Sample location map of the study area.

Miocene time which has documented terrigenous sediments from the northern sources in the Himalayan Fore-deep and other basins since the Eocene. The Bengal Basin with its subaerial delta and prodelta was formed by the seaward progradation of the Ganges-Brahmaputra river systems (Einsele et al., 1996). The Ganges River drains much of the southern slope of the Himalayas, while the Brahmaputra River drains much of the northern slope of the Himalayas (Curry and Moore, 1974).

Beach forming processes of the Inani-Dakhin Nhila area are related with the evolving stages of the coast through time, and consequent fluctuation of energy level of the coast, directly influenced by sea-level changes and

tectonic movements of the region. The shoreline of the Bay of Bengal at about 18,000 years BP. was hundred kilometers southward from the present coast. At the end of the last glaciation, eustatic sea level started rapidly rising and the shoreline of the Bay of Bengal started shifting northward (Monsur and Kamal, 1994). At about 5,500 years BP., the sea level rose at its highest level (more than 5 m from the present mean sea level). At this sea level, the unconsolidated rock sediments were washed out by the wave action and then only the concretions remained on the shoreline and in the continental shelf. At that period the sea level reached at near to the foot of the present hills. After 5,500 years BP., the sea level started

Table 1 The stratigraphic succession of the Inani hill range (a) (BAPEX, 1980) and Dakhin Nhila hill range (b) (BAPEX, 1981)

Age	Formation	Lithological description
Mio-Pliocene?	Dupi Tila (DT)	Sandstone: Light, brownish, yellowish and whitish grey in color, medium to coarse grained, massive, ill sorted, highly porous, loose and friable, sedimentary pebbles like quartzite, siltstone etc. common.
Late Miocene?	Girujan Clay (GC)	Bluish, earthy and whitish grey, soft and sticky;
Middle Miocene?	Tipam Sandstone (TS)	Light brownish, brownish and sometimes bluish grey, fine to medium grained, cross-bedded, ripple marked, moderately sorted and consolidated
Early Miocene?	Upper Boka Bil (BB)	Shale: Bluish to earthy grey, thinly well laminated, moderately hard and compact, occasionally calcareous siltstone tabular concretion common.
	Middle Boka Bil (BB)	Alternating beds of sandstone and shale. Sandstone: Bluish to brownish grey, fine grained to very fine grained, massive and cross-bedded, moderately consolidated, calcareous conglomeratic (occasionally fossiliferous) bed present. Shale: Bluish grey to grey, thinly well laminated, moderately hard and compact

(a)

Age	Formation	Lithological description
Middle To Late Miocene?	Tipam Sandstone	Light brownish grey to brownish grey, fine to medium grained, massive, loosely consolidated, and highly porous
Early Miocene?	Upper Boka Bil	Mostly composed of shales with subordinate sandstone. Shale: Bluish grey to grey, well laminated, moderately hard and compact, calcareous concretion of siltstone. Sandstone: Bluish grey, fine to medium grained, massive
	Middle Boka Bil	Alternating beds of shale, sandstone, silty sandstone and siltstone.
	Lower Boka Bil	Mostly composed of shale/silty shale with very subordinate siltstone and sandstone
	Upper Bhuban	Composed of sandstone (20%), shale (65%), siltstone (10%) and silty sandstone (15%). Sandstone: Light brownish grey, occasionally light grey, fine grained, massive bedded Shale: Grey, dark grey, laminated occasionally silty, hard and compact, tabular calcareous concretion common. Siltstone: Grey to dark grey, hard and compact, massive

(b)

to move down and the supra-tidal or salt marsh area became exposed. The existence of supra-tidal flat worldwide is the result of the high stand sea level of 6,000–5,000 years BP. (Fairbridge, 1961). The existence of concretions was under the beach sand of the supra-tidal flat from Cox's Bazar to Teknaf indicates a Paleobeach of the high stand Holocene sea level. Eventually the beach forming phase is attaining now with the evidences of dune, strand plain and sand flat formation through the entire coast and leaving behind the eroded remnants of the Tertiary hills in the beach area (Kibria et al., 2000).

The Bay of Bengal near the study area possesses a swift clockwise circulation of surface water during spring at the south and southeast directions but a lesser-speed anticlockwise reversal during autumn (La Fond, 1966). The condition of the coastline between the monsoon and dry season in the Cox's Bazar area was studied and found that the coast is aggraded during the monsoon (Biswas, 1988). The funnel shape of the bay, uniform shoaling of its bottom and a record average value of yearly seasonal sea-level change (1.22 m at Chittagong) causes high tides and internal waves of varying times and lengths, which all facilitated the suspension of sediments contributed by the Ganges, Brahmaputra and Meghna river systems and played a vital role in their littoral drift (Rahman et al., 1994).

Materials and Methods

The field investigation and sample collections were carried out in the Cox's Bazar and Teknaf areas covering a distance of about 115 km. The locations of sampling points are shown in the Fig. 2. For systematic study of the area, GPS as well as traversing and spot location methods were used. Samples were collected along the stream sections, where the Neogene (Mio-Pliocene) sandstones were well exposed. On the other hand samples were collected from the beach near the shore line from a depth of about 1 m and from the paleobeach between foot-hill and shore line with a depth ranging from 1 to 3 m from the surface. Sampling along the beach was done with the help of an auger.

A total of 25 sands/sandstones samples from the Inani-Dakhin Nhila hill ranges and their adjacent beach were investigated for the heavy mineral study. Following the procedure mentioned in Faupl et al. (1998), heavy minerals were separated from both loose sand samples (for beach and paleobeach) and crushed sandstone samples (for Neogene sandstones). 25 g (for beach and paleobeach) and 30 g (for Neogene sandstones) were taken

from each sample for heavy mineral analysis. Carbonate minerals were dissolved in acetic acid. Gravitational heavy liquid separation of the sieve fraction 0.5–0.063 mm was carried out using bromoform as heavy liquid (density 2.89 g/cm³). After mounting the grains in Canada balsam, the grains were examined under the polarizing microscope. More than 450 translucent grains of each sample were counted with the ribbon count method. Several minerals, such as biotite, chlorite and glauconite were excluded from qualitative examinations. Non-parametric Spearman Rank correlation was used for calculating a correlation matrix between the minerals, and SPSS statistical programme was followed for a cluster analysis.

The chemical composition of core part of garnets and ilmenites was analyzed using an electron probe micro-analyzer with three spectrometers (JEOL JXA-733) at Okayama university, Japan with an accelerating voltage of 15 kV and a sample current of 0.01–0.02 μ A. Standards used were natural or synthetic oxides and silicates. The matrix correlations employed followed the procedures of Bence and Albee (1968), using alpha factors of Nakamura and Kushiro (1970).

Results

The framework grains of the Neogene sandstones of the Dakhin Nhila structure are very much similar to the framework grains of their adjacent beach sands. The sands/sandstones of the Inani-Dakhin Nhila hill ranges and their adjacent beaches have quartzolithic composition and a more quartzose one with abundant sedimentary and low grade metamorphic lithics and low content of feldspar. Rock fragments make up 5 to 16% of the total framework grains. Sedimentary lithic grains are chiefly chert, shale fragments and metamorphic rock fragments are dominated by fine-grained mica schist, quartz-mica schist and phyllites, partly graphite-bearing, along with a few volcanic rock fragments.

Heavy mineral composition

The Neogene sandstones of the Inani-Dakhin Nhila anticlines contain about 2 wt.% heavy minerals whereas the beach sands of the Inani-Dakhin Nhila area contain about 8 wt.% heavy minerals.

The qualitative and quantitative results of heavy mineral study of sands/sandstones samples from the Inani-Dakhin Nhila hill ranges and their adjacent beach are shown in Table 2. The correlation coefficients of heavy minerals are shown in Table 3. For each area the average heavy mineral concentrations are presented in phi diagrams Fig. 3. The heavy mineral composition of the

Table 2 Heavy mineral composition of the Neogene sandstones (Plio-Miocene) of the Inani-Dakhin Nhila hill ranges and sands of their adjacent beach (grain %).
 Apa = Apatite, Epi = Epidote, Gar = Garnet, Hor = Hornblende, Kya = Kyanite, Mon = Monazite, Opa = Opaque, Pyr = Pyroxene, Rut = Rutile, Sil = Sillimanite, Sph = Sphene, Sta = Staurolite, Tou = Tourmaline, Zir = Zircon

Sample	Apa	Epi	Gar	Hor	Inani hill range (Tertiary)					Sil	Sph	Sta	Tou	Zir	Dakhin Nhila hill range (Tertiary)												
					Kya	Mon	Opa	Rut	Zir						Sample	Apa	Epi	Gar	Hor	Kya	Mon	Opa	Rut	Sil	Sph	Sta	Tou
SKP-2	1.4	19.8	21.2	3.3	1.6	0.2	27.7	3.3	0.0	0.0	8.6	7.2	5.8	NL-5	0.7	23.5	22.8	1.8	1.8	0.2	29.8	2.7	0.0	0.2	8.4	3.2	5.0
KB-3	0.2	22.3	17.5	10.6	5.1	0.0	16.1	0.7	0.9	0.0	10.1	15.9	0.7	RG-9	0.7	17.1	10.8	5.4	4.3	0.5	36.0	3.8	0.5	0.2	6.3	5.0	8.8
BC	0.2	19.2	25.3	9.4	1.6	0.0	18.4	1.6	0.4	0.0	10.0	13.1	0.8	RC-5	0.9	21.3	38.8	1.5	0.7	0.2	23.3	2.8	0.0	0.4	5.0	1.7	3.0
SHC-1	1.0	23.0	21.6	5.7	1.0	0.0	18.3	1.4	0.4	0.4	10.0	13.2	3.5	NY-4	0.6	15.5	6.4	23.9	1.8	0.2	28.8	2.6	0.6	0.2	8.2	7.0	4.0
Average	0.7	21.1	21.4	7.2	2.3	0.1	20.1	1.8	0.4	0.1	9.7	12.3	2.7	Average	0.7	19.4	19.7	8.1	2.1	0.3	29.5	3.0	0.3	0.3	6.9	4.2	5.2
Dakhin Nhila paleobeach																											
SB-2	0.4	21.9	25.1	4.5	1.3	0.4	19.4	1.5	0.0	0.0	11.9	11.5	1.9	MK-4	0.4	18.9	13.8	6.6	3.4	0.2	28.7	4.7	0.9	0.4	10.6	4.9	5.3
BV	0.2	18.5	22.1	4.6	1.6	0.0	30.9	1.6	0.4	0.2	8.8	7.1	3.8	SSK-2	1.2	22.2	20.3	9.3	2.3	0.0	17.4	2.5	0.0	0.0	13.5	7.5	2.7
NR-2	1.1	20.1	15.2	7.8	3.6	0.0	22.8	2.1	0.2	0.2	14.6	7.6	4.4	BD-2	0.2	22.6	21.6	8.3	2.3	0.2	20.5	4.0	0.0	0.0	11.6	6.3	2.3
SP-2	0.4	16.7	21.9	3.6	1.5	0.4	31.7	3.8	0.0	0.2	7.5	5.4	6.7	TK-2	0.5	21.7	15.8	15.4	2.5	0.2	17.7	1.4	0.5	0.2	11.3	10.0	1.8
MSB-2	0.0	11.2	18.4	2.1	0.5	0.2	43.5	2.6	0.2	0.0	9.3	3.0	9.1	Average	0.6	21.4	17.9	9.9	2.6	0.2	21.1	3.1	0.3	0.2	11.8	7.2	3.0
Average	0.4	17.7	20.5	4.5	1.7	0.2	29.7	2.3	0.2	0.1	10.4	6.9	5.2														
Dakhin Nhila present beach																											
BHC-1	0.7	26.4	15.6	7.9	3.4	0.2	19.9	1.6	0.2	0.0	15.6	4.5	2.9	MK-1	0.4	25.2	14.6	6.2	###	0.0	19.1	1.5	0.4	0.0	15.0	4.6	0.6
SR-1	0.2	21.8	19.4	5.3	2.5	0.0	25.1	4.0	0.0	0.0	12.9	5.1	3.8	NL-1	0.6	27.5	18.8	3.2	1.9	0.2	27.7	3.2	0.2	0.6	11.2	2.3	2.3
RP-1	1.3	24.2	17.2	8.6	3.5	0.2	17.0	1.1	0.4	0.2	15.0	7.7	2.6	RC-1	0.4	26.9	21.3	7.2	3.7	0.0	18.0	2.6	1.1	0.2	14.1	2.6	1.5
Average	0.7	24.2	17.4	7.3	3.1	0.2	20.6	2.2	0.2	0.1	14.5	5.8	3.1	TK-1	0.9	26.0	19.8	5.0	5.8	0.3	19.5	2.3	0.3	0.0	14.0	2.3	3.2
														BM-2	0.4	27.0	16.7	1.5	0.8	0.0	37.7	1.3	0.2	0.2	6.3	1.3	6.5
														Average	0.5	26.5	18.2	4.6	4.8	0.1	24.4	2.2	0.4	0.2	12.1	2.6	2.8

Table 3 Rank correlation coefficient of heavy minerals of sands/sandstones of the Inani-Dakhin Nhila area (n=25).

	Apatite	Epidote	Garnet	Hornblende	Kyanite	Monazite	Opakes	Pyroxene	Rutile	Sillimanite	Sphene	Staurolite	Tourmaline	Zircon
Apatite	1.000	0.182	-0.100	-0.010	0.130	0.265	-0.223	0.397*	-0.088	-0.161	0.293	0.109	0.089	0.121
Epidote		1.000	0.022	-0.059	0.311	-0.205	-0.415*	0.055	-0.327	-0.052	-0.058	0.497*	-0.306	-0.482*
Garnet			1.000	-0.382	-0.537**	0.030	-0.092	-0.503*	0.075	-0.510**	-0.044	0.221	0.087	-0.165
Hornblende				1.000	0.514**	-0.308	-0.637**	0.471*	-0.273	0.535**	-0.221	0.461*	0.612**	-0.505**
Kyanite					1.000	-0.078	-0.434*	0.489*	-0.041	0.489*	-0.139	0.607**	0.040	-0.369
Monazite						1.000	0.296	0.180	0.274	-0.222	0.095	-0.197	-0.177	0.334
Opakes							1.000	-0.309	0.499*	-0.240	0.240	-0.642**	-0.534**	0.821**
Pyroxene								1.000	-0.232	0.493*	0.159	0.427*	0.146	-0.101
Rutile									1.000	-0.315	0.145	-0.267	-0.389	0.432*
Sillimanite										1.000	0.202	0.125	0.162	-0.243
Sphene											1.000	-0.384	-0.165	0.234
Staurolite												1.000	0.152	-0.558**
Tourmaline													1.000	-0.307
Zircon														1.000

* Correlation is significant at the .05 level (2-tailed).

** Correlation is significant at the .01 level (2-tailed).

sands/sandstones of the Inani and Dakhin Nhila areas (beach, paleobeach and Tertiary hill ranges) are characterized by predominance of opaque minerals (~25%) (with abundant both unaltered and altered ilmenites) as well as epidote group (~22%), garnets (~19%), staurolite (~11%), hornblende (~7%) and tourmaline (~6%), followed by lesser amounts of zircon (~4%), kyanite (~4%), rutile (~2%) and by minor to trace amounts of apatite, sillimanite, monazite and sphene. Around half of the samples show clear predominance of epidote group minerals (~19%–~28%). The stable mineral group- zircon, tourmaline, rutile (ZTR) show an average of 13% with a range between 7% and 18%. Amphiboles are mainly calcic variety, which are mostly bluish green hornblendes. In compare to northeastern parts of the Bengal Basin, the heavy mineral composition of the sands/sandstones of the Inani and Dakhin Nhila areas (beach, paleobeach and Tertiary hill ranges) contain high proportion of opaque minerals, epidote group minerals and amphiboles.

Chemical characterization

Provenance attributes have been emphasized using garnet and ilmenite populations.

The preliminary results of chemical analyses of detrital garnets (n=31) and ilmenites (n=8) from beach sands are shown in Table 4. The garnets are rich in FeO* contents (20.11–36.66 wt.%, average 30.21 wt.%) and poor in Cr₂O₃ (less than 0.90 wt.%) and TiO₂ contents (less

than 1.00 wt.%). The MgO contents range from 0.83–8.19 wt.% (average 3.88 wt.%). MnO contents vary from 0.36–17.69 wt.% (average 2.81 wt.%). CaO contents range from 0.79–13.09 wt.% (average 4.60 wt.%). Compositional data for garnets are summarized in Fig. 4. Detrital garnet analyzed in this study is almandine-rich (44 mol.% to 82 mol.%) (Fig. 4). The average content of pyrope and grossular is 15 mol.% and mol. 14% respectively. Spessartine content is very low (av. mol. 6%). The chemical character of detrital garnet from beach sands is similar to that of from Neogene sands of the Surma Group in the northeastern Bengal Basin (Rahman et al., 2006).

Majority of the almandine garnet is a solid solution with pyrope > 10% (up to 31%); and grossular < 10%; some Fe-garnets have solid solution with grossular > 10% (up to 34%); and pyrope < 10%; almandine garnets with pyrope and grossular both > 10%; few minor almandine garnets have solid solution with spessartine > 10% (up to 39%); and pyrope and grossular < 10%.

The detrital ilmenite is characterized by high TiO₂ contents (37.9–57.27 wt.%; average 50.25 wt.%) which is in good agreement with that of ilmenites from other part of coastal area (Cox's Bazar) in southern Bangladesh (Mitra et al., 1992). The MnO contents are generally erratic (0.56 wt.%–11.41 wt.% with an average 3.56 wt.%). The Al₂O₃ contents are low (average 0.08 wt.%). The MgO contents are also generally low and range from 0.04 to 1.66 wt.% (~0.36 wt.%).

Fig. 3 Average heavy mineral composition of the Neogene sandstones (Plio-Miocene) in Inani and Dakhin Nhila anticlines and adjacent paleobeach and present beach of the Inani-Dakhin Nhila area

Fig. 4 Chemical composition of detrital garnets ($n=31$) from beach sands.

Prp: Pyrope, Alm: Almandine, Sps: Spessertine, Grs: Grossular

Discussion

The heavy mineral assemblages of the Inani paleobeach

and Dakhin Nhila anticline and those of Inani anticline, Inani beach, Dakhin Nhila paleobeach and Dakhin Nhila beach show little differences. The heavy mineral

composition of the Inani paleobeach and Dakhin Nhila anticline are characterized by opaques (~30%)-garnet (~20%)-epidote (~18%)-assemblages with high content of zircon (~5.2%), whereas the samples from Inani anticline, Inani beach, Dakhin Nhila paleobeach and Dakhine Nhila beach are relatively rich in epidote (~23.4%) followed by opaque (~21.8%) and garnet (~18.8%) and have low content of zircon (~2.9%). This slight compositional difference might be caused by hydraulic sorting of the grains, sedimentary processes (e.g. long shore currents and wave action) as well as mixing influence from different source materials.

Source rock lithology

A broad range of metamorphic source rocks was reflected from the characteristic heavy mineral composition, e.g. garnet, staurolite, kyanite, epidote, hornblende (Fig. 3). Significant positive correlation between kyanite and staurolite ($r=0.61$); and sillimanite ($r=0.49$); epidote and staurolite ($r=0.50$); between hornblende and kyanite ($r=0.51$), sillimanite ($r=0.54$), staurolite ($r=0.46$), tourmaline ($r=0.61$) supports this inference.

The possible sources of garnet and staurolite are mica schist complexes (Faupl et al., 1988). Garnets are mostly almandine type (Fig. 4) which is typical of garnetiferous schist and gneisses resulting from the regional metamorphism of argillaceous sediments (Deer et al., 1982).

Almandine garnets from the beach sands contain diverse amounts of pyrope. Generally, almandine garnets with pyrope contents from 10 to 40 mol.% occur in epidote-amphibolite to granulite facies gneisses (Miyashiro, 1953; Coleman et al., 1965). The pyrope-almandine garnets with subsidiary amounts of grossular are likely to have been derived from metamorphosed Ca-poor argillaceous rocks of epidote—amphibolite to granulite facies. Garnets from peridotites and associated eclogites can be excluded as possible source rocks due to the low (<50 mol.%) pyrope component (Coleman et al., 1965; Deer et al., 1992). Grossular is characteristically found in both thermally and regionally metamorphosed impure calcareous rocks, and also occurs in rocks which have undergone calcium metasomatism (Deer et al., 1992). Garnets with appreciable grossular contents are unlikely to be derived from igneous rocks. Significant amounts of spessertine garnets may occur in almandines from acidic igneous rocks e.g. granitic pegmatites and calc-alkaline granites and from contact metamorphic aureoles. In metamorphic rocks, spessartine garnets are known from low-grade regional metamorphosed rocks. Some spessartine-rich almandine garnets in the beach sands were presumably derived from thermally metamorphosed of low grade

metamorphic rocks, such as metapelites, metacherts and blueschists.

The preliminary compositional data of ilmenites from beach sands (Table 4) indicate that they were likely derived from mixed metamorphic and igneous (dominated by felsic) rocks (Grisby, 1992; Basu and Molinaroli, 1991). Grisby (1992) has indicated that ilmenites from igneous rocks have TiO_2 contents mostly between 40 and 52 wt.%. Grisby (1992) showed that ilmenite grains with $\text{MnO} > 2.0$ wt.% are most prevalent in sands from felsic igneous rocks and those with $\text{MgO} > 1.5$ wt.% are in sands of intermediate and mafic sources. In comparison, Basu and Molinaroli (1991) have mentioned that ilmenite grains with TiO_2 contents between 50 and 60 wt.% are more prevalent in metamorphic rocks. They indicated that TiO_2 contents of ilmenite in igneous rocks mostly range from 40 to 50 wt.%.

According to Heinrich (1956), the presence of tourmaline and epidote is suggestive of derivation of the sediments from low to medium grade metamorphic provenance. Staurolites point to medium grade metamorphism. Presence of zircon indicates the source as intrusive acid igneous rocks (Biswas, 1983; Biswas and Kundu, 1985; Ahmed and Islam, 2001). Some rounded zircons are also noticed indicating sedimentary source. The gneisses and granitoid rocks are possible sources of stable minerals such as zircon, tourmaline, rutile and apatite. Very strong positive correlation between opaques and zircon ($r=0.81$), significant positive correlation between opaques and rutile ($r=0.50$); rutile and zircon ($r=0.43$) may point to indication of granitoid rocks as another significant source rocks.

Tourmaline is also known from low-grade metamorphic complexes. It was noted that tourmaline is the predominant mineral among the ZTR suites. Uddin and Lundberg (1998 b) and Rahman (1999) also found the clear predominance of garnet and tourmaline (among ZTR index) along with the presence of some sillimanite for the Neogene Surma Group sediments of the Bengal Basin. Apatite is believed to be derived from biotite-rich rocks (Faupl et al., 1998).

Possible source areas

As revealed from the heavy mineral studies, medium to high-grade metamorphic terrains are reflected in the source area from the common occurrence of garnet, staurolite, kyanite as well as trace of sillimanite. The presence of apatite, zircon, and rutile indicates the existence of granitoid source terrain. The high Himalayan tectonic unit is composed of various metamorphic rocks. The garnet, amphibole and epidote are the major constituents in the

Table 4 Selected EPMA analyses of detrital garnets (G) and Ilmenites (Ilm) from the Beach sands.

Sample SB2																				
Wt.%	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	Ilm1	Ilm2	Ilm3	Ilm4	Ilm5
SiO ₂	38.40	37.77	36.84	38.09	38.49	37.37	38.77	37.76	37.36	37.48	37.38	38.27	37.372	37.52	37.98	0.00	0.02	0.10	0.022	0.04
TiO ₂	0.00	0.08	0.04	0.00	0.03	0.04	0.10	0.00	0.10	0.29	0.00	0.00	0.05	0.00	0.19	52.81	52.61	57.27	49.83	47.89
Al ₂ O ₃	21.80	20.99	20.65	21.52	21.50	21.11	21.89	21.25	20.86	21.01	21.05	21.74	20.89	21.16	21.22	0.03	0.02	0.22	0.02	0.03
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.06	0.00	0.05	0.04	0.02	0.06	0.03	0.05
FeO*	31.04	27.90	21.50	34.00	26.06	32.37	29.05	34.84	33.74	30.18	33.74	31.30	36.66	35.60	26.17	44.74	46.25	35.17	47.10	40.51
MnO	0.36	2.58	17.69	0.38	0.53	6.99	1.04	1.19	0.57	3.86	4.18	1.17	0.79	2.70	2.84	2.29	0.81	1.37	2.25	8.22
MgO	6.14	0.99	1.32	4.24	2.89	2.49	7.94	3.50	1.55	2.64	3.20	5.52	1.30	2.99	2.19	0.29	0.22	0.15	0.18	0.04
CaO	2.91	9.90	3.54	2.87	10.64	0.79	1.92	2.42	5.93	5.01	1.60	3.05	3.95	1.16	9.75	0.10	0.02	0.03	0.05	0.02
Na ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
K ₂ O	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
total	100.7	100.2	101.6	101.1	100.2	101.2	100.7	101.0	100.1	100.5	101.2	101.1	101.1	101.1	100.4	100.3	100.0	94.4	99.5	96.8
O=	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	3	3	3	3	3
Si	2.994	3.014	2.968	3.000	3.018	2.996	2.993	3.000	3.007	2.991	2.985	2.989	3.003	2.998	3.001	0.000	0.000	0.003	0.001	0.001
Ti	0.000	0.005	0.002	0.000	0.002	0.003	0.006	0.000	0.006	0.017	0.000	0.000	0.003	0.000	0.012	0.998	0.998	1.099	0.963	0.955
Al	2.004	1.974	1.960	1.997	1.987	1.995	1.991	1.990	1.979	1.976	1.981	2.001	1.979	1.992	1.977	0.001	0.001	0.006	0.001	0.001
Cr	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.001	0.002	0.000	0.004	0.000	0.003	0.001	0.000	0.001	0.001	0.001
Fe	2.025	1.862	1.449	2.239	1.709	2.170	1.875	2.315	2.270	2.014	2.254	2.045	2.464	2.378	1.730	0.940	0.975	0.750	1.013	0.898
Mn	0.024	0.174	1.207	0.025	0.035	0.474	0.068	0.080	0.039	0.261	0.283	0.078	0.054	0.000	0.190	0.049	0.017	0.030	0.049	0.185
Mg	0.714	0.117	0.158	0.498	0.337	0.298	0.914	0.415	0.186	0.314	0.381	0.642	0.156	0.357	0.258	0.011	0.008	0.006	0.007	0.001
Ca	0.243	0.847	0.306	0.242	0.894	0.068	0.158	0.206	0.511	0.428	0.137	0.256	0.340	0.099	0.826	0.003	0.000	0.001	0.001	0.001
Na	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
K	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Total	8.00	7.99	8.05	8.00	7.99	8.00	8.01	8.01	8.00	8.00	8.02	8.01	8.00	8.01	8.00	2.00	2.00	1.90	2.04	2.04
XMg	0.24	0.04	0.05	0.17	0.11	0.10	0.30	0.14	0.06	0.10	0.12	0.21	0.05	0.12	0.09					
XFe	0.67	0.62	0.46	0.75	0.57	0.72	0.62	0.77	0.76	0.67	0.74	0.68	0.82	0.79	0.58					
XCa	0.08	0.28	0.10	0.08	0.30	0.02	0.05	0.07	0.17	0.14	0.04	0.08	0.11	0.03	0.27					
XMn	0.01	0.06	0.39	0.01	0.01	0.16	0.02	0.03	0.01	0.09	0.09	0.03	0.02	0.06	0.06					

Table 4 Continued.

[illegible]

High Himalaya (review by Yokoyama *et al.*, 1990). Based on petrographical data of metamorphic and granitic rocks from the Himalayas, garnet is a common mineral in both the biotite schist and gneiss, as well as calcic amphibole in the High Himalaya is predominantly a bluish-green hornblende (review by Yokoyama *et al.*, 1990). The Lesser Himalayan crystalline basement is built up of low (chlorite) to medium (biotite + garnet + kyanite + staurolite) grade terrains. Kyanite is a typical marker of the High Himalaya Crystalline, but is also found locally in Lesser Himalaya (Pecher, 1989).

In the Indo-Burman ranges, thick Eocene to Oligocene turbidite successions and Upper Miocene to Pleistocene molasse sediments (review by Uddin and Lundberg, 1998b) are the significant rocks successions, whereas crystalline rocks are uncommon (Johnson and Alam, 1991). Uddin and Lundberg (1998a, 1999) based on sand petrography and lithofacies maps, suggested that the Miocene sediments were transported from the immediate east also, including the Indo-Burman ranges as well and yield a clear record of unroofing of the eastern Himalayan/Indo-Burman ranges. The source rocks of these sands were dominantly supracrustal rocks. The appearance of blue-green amphiboles in the Miocene units in the Bengal Basin, together with the initial appearance of sparse chrome spinels, suggests unroofing of arc and ophiolitic rocks from suture zones of the Himalayas and/or the Indo-Burman ranges (Uddin and Lundberg, 1998b). Uddin and Lundberg (1998b) also concluded that the relative abundance of various aluminum silicates and epidote minerals indicate orogenic input from the erosion of low- to high-grade metamorphic rocks in the orogenic belts and further systematic unroofing of progressively deeper level units in the eastern Himalayas.

Unfortunately, it has found difficult in the present research work to correlate the results with those of the Indo-Burman Ranges due to lack of available information. From the preceding discussions, it is obvious that the Himalayan terrain could be recognized as the principal source area for the Neogene sediments of the study area. Recycled sediment materials from the flysch successions of the Indo-Burman ranges could be mixed with the sediments of Himalayan origin within the deltaic system. The conspicuous enrichment of quartz in the Neogene sandstones of the Surma Group in the Bengal Basin may be explained by such reworking and mixing processes (Rahman, 1999).

The heavy mineral suites reflect that the probable source of the clastics which have contributed to the study area of interest is located in the north, northwest and

east-northeastern part of Bangladesh. These detrital grains could have been derived from crystalline and sedimentary deposits of the Himalayas, Rajmahal hills, Shillong Plateau and Indo-Burman ranges.

Conclusions

From the heavy mineral assemblages, it can be assumed that a broad range of metamorphic source rocks was reflected from the characteristic heavy minerals composition, e.g. garnet, staurolite, kyanite, epidote, hornblende. Metamorphic terrains comprising mica schist and other metamorphic rocks, e.g. epidote-amphibolite to granulite facies were likely present in the source area. The presence of staurolites indicates a medium-grade metamorphic source terrain. Trace of sillimanite gives evidence for existence of high-grade metamorphic terrains.

The dominance of opaque minerals and the presence of zircon, rutile and tourmaline suggest the derivation of the sediments from crystalline rocks. A granitoid source terrain was also an important feeder as reflected from common occurrence of stable minerals, especially of zircon, rutile and apatite.

It is likely that uplifted terrains of the Himalayas were the principal source area of the Neogene sandstones and beach sands of the study area. Reworking of flysch sediments of the Indo-Burman ranges and mixing with the Himalayas derived sediments within the delta system could be responsible for the relatively quartz-rich composition of the sediments. From the heavy mineral studies, it may be concluded that the Neogene sandstones of the adjacent hill ranges likely contribute to the formation of beach and paleobeach sands.

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南東バングラデシュ，イナニおよびダキンニーラ丘陵地域の新第三系砂岩と
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本研究では主にイナニおよびダキンニーラ丘陵地域の新第三系砂岩と完新統海浜砂の重鉱物組成分析を行い，それらの後背地を検討した．ざくろ石とチタン鉄鉱については予察的な化学組成の分析を行った．新第三系砂岩は約2%の，海浜の砂には約8%の重鉱物を含む．調査地域の新第三系砂岩と完新統海浜砂の重鉱物組成の特徴として，まず優勢なのは不透明鉱物（主にチタン鉄鉱），緑れん石，ざくろ石である．次いで十字石，角閃石，電気石が多く，より少量のジルコン，ルチル，藍晶石があり，さらに微量の燐灰石，珪線石，モナズ石，スフェンからなる．この組成は多様な変成岩および花崗岩質岩石の地質からもたらされたことを示している．砕屑物の供給源は，バングラデシュの北から北西および北東から東にある，ヒマラヤ山脈，ラジマハル丘陵およびシロング高原，インド・ビルマ山脈に分布する結晶質岩石や堆積層であると考えられる．

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