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Paleoenvironment of the Boka Bil Formation in the Barogang-Hari river section near Lalakhal, Jaintiapur, Sylhet, Bangladesh

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Abstract

Eleven facies (S_t, S_p, S_h, S_r, S_w, S_l, S_f, F_{sl}, F_l, F_m, and F_b) have been identified in a section of the Boka Bil Formation of Bangladesh. These facies have been grouped into three facies associations; (i) sandstone facies association of tidal channel and estuarine environments (SFTE), (ii) heterolithic facies association of tidal flat environments (HFTF) and (iii) shale facies association of deep-sea environments (SFDS). The SFTE includes facies S_t, S_p, S_h and/or S_r, whereas HFTF contains facies S_r, S_w, S_l, S_f, F_{sl} and F_m. The SFDS includes facies F_b only. The SFTE association indicates deposition under tidal action in tidal channels and estuarine tidal creeks where maximum water depth was about 7 m. Paleocurrents from the facies S_t, S_p and S_r show strong bi-directional, bi-polar of tidal action. Facies association HFTF suggests a mixed and mud-dominated tidal flat, where maximum water depth was about 33 cm. The association of SFDS with laminated greenish gray to black shale facies containing both calcareous and non-calcareous embodied ripple laminated siltstone (T_c division) and parallel laminated siltstone (T_d division), indicate deposition both above and below the CCD in deep marine environments. Overall, the Boka Bil Formation was deposited in tidal flat, tidal channel and estuarine to deep marine environments.

Key words: Paleoenvironment, Boka Bil Formation, Facies, Lalakhal, Bangladesh.

Introduction

The Boka Bil Formation is well exposed along a section of the Barogang, a tributary of the Hari river near the confluence of the Barogang and Hari rivers in the Lalakhal area, Jaintiapur Upazilla, Sylhet district, NE Bangladesh. The present field area lies within 25°7′0″ to 25°7′15″N in latitude and 92°10′3″ to 92°11′15″E in longitude (Fig. 1). Considerable controversy surrounds some aspects of the sedimentology and environments of deposition of the Boka Bil Formation of the Sylhet Trough. Although the Tertiary sequence of the basin and surrounding areas has been widely studied (Mathur and Evans, 1964; Holtrop and Keizer, 1970; Ganguly, 1983; Roy, 1986; Johnson and Alam, 1991; Shamsuddin and Abdullah, 1997; Gani and Alam, 1999; Mannan, 2002; Roy et al., 2007), detailed sedimentological study of the Boka Bil Formation of Sylhet Trough is very limited. Sandstones in the Formation form one of the reservoir rocks for the natural gas of the country. Absence of detailed study already created problems in exploration and exploitable of gas from the formation. The objective of study is to construct the facies sequence of the formation to interpret its paleoenvironments of deposition and the paleogeography during its deposition.

Methodology

The section studied was closely examined (in cm scale) to identify lithology, color, texture, internal sedimentary structures, and boundary conditions to identify the individual facies and the facies sequence and associations. Standard practices were followed by Allen (1968), Williams and Rust (1969), Casshyap and Tewari (1984), Cant and Walker (1976), Miall (1978), Rust (1978) and Reading (1986). Each facies is defined on the basis of the dominant lithology and sedimentary structures present and is coded following the schemes of Miall (1978) and Rust (1978). Finally, the environments of deposition and paleogeography have been interpreted from the facies sequence and associations. Paleocurrents and water depths were calculated from the direction and thickness of foresets of planar cross-stratified sandstone (S_p), plunge of trough, ripple marks and other structures following Pettijohn et al. (1987), Allen (1964) and Yalin (1977).

Geological Setting

The studied area covers the northeastern folded part of the Sylhet Trough/Surma Basin along the southern foothills of the Khasia-Jaintia Hill Range in Megha-

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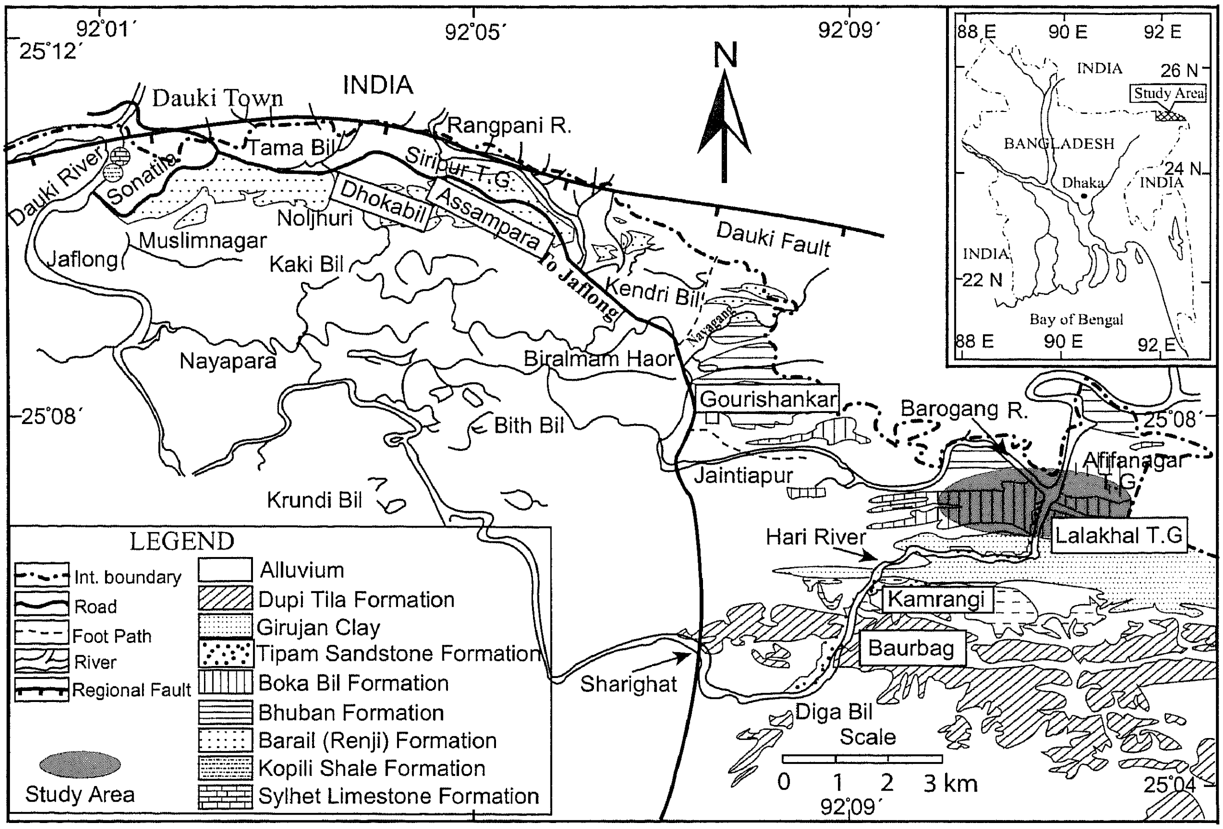

Fig. 1 Geological map of the study area showing the exposed Tertiary rock sequence.

laya (Hiller and Elahi, 1984). The Dauki fault system lies just north of the area (Fig. 1). The sedimentary sequences of the area consist of a continuous sequence from Paleocene Tura Sandstone Formation to recent alluvium (Reimann, 1993; Gani and Alam, 1999; Mannan, 2002). The Sylhet Trough/Surma Basin is a sub-basin of the Bengal Basin situated in the northeastern part of Bangladesh. The basin is bounded on the north by the Shillong plateau, to the east and southeast by the Chittagong-Tripura fold belt of the Indo-Burman ranges, and to the west by the Indian Shield platform. The Sylhet Trough/Surma Basin is open to the main part of the Bengal Basin to the south and southwest (Mathur and Evans, 1964; Hiller and Elahi, 1984). The study area forms a homoclinal fold having strike towards N 82°W–S82°E and dipping 17°–58° towards SW.

The stratigraphy of the Surma Basin has been established on the basis of extensive geophysical survey, drilling, and the exposed rock sequence in different areas (Khan, 1978; Johnson and Alam, 1991; Reimann, 1993; Mannan, 2002; Roy et al., 2007). The sedimentary sequences of the area consist of the Jaintia, Barail, Surma, Tipam, Dupi Tila, and Dihing Groups, and alluvium of Paleocene to recent ages (Reimann, 1993) (Table 1). The stratigraphic unit at the top of the Middle Miocene succession in the Bengal Basin was designated as the Boka Bil Stage (Evans, 1932). In Sylhet Trough, the thickness of the Boka Bil Formation ranges from a few hundred meters to about 1740 m (Khan, 1978). Fairly good sections of the Boka Bil Formation are exposed along the southern bank of the Barogang river and both banks of the Hari river near Lalakhal Tea Garden (Fig. 1).

Boka Bil Formation

The Boka Bil Formation conformably overlies the Bhuban Formation and is unconformably overlain by the Tipam Sandstone Formation (Table 1). It chiefly consists of silty shale/shale, siltstone, and sandstone. The average strike is N 82°W, dipping 58° to the SW. The silty shale is gray to bluish in color, laminated to thinly bedded, moderately hard, compact, and highly jointed. At some sites starved ripples with micro-cross-lamination are present within the shale. The shale is greenish gray to bluish gray, very thinly to thickly laminated, and intercalated with silty shale. The siltstone is bluish gray to yellowish gray, moderately hard and compact, and laminated to thinly bedded, and shows

Table 1. Stratigraphy of the study area in and around Lalakhal, Sylhet.

Age	Group	Formation		Lithologic description
Middle-Upper Miocene	Tipam	Tipam Sandstone		Light to dark yellowish brown coarse to fine-grained cross-bedded sandstone and siltstone with shale; abundant clay gall present.
				Unconformity
Lower-Middle Miocene	Surma	Boka Bil	Upper	Black, dark gray to bluish gray shale with a few micro-cross laminated lenses of siltstone.
			Middle	Medium to fine-grained, ripple laminated sandstone with wavy and flaser laminated rippled, very fine-grained sandstone alternating with parallel to wavy laminated shale.
			Lower	Gray to yellowish gray trough and planar cross-bedded, parallel and ripple-laminated medium to fine-grained sandstone and siltstone with impersistant clay and subordinate laminated shale.
		Bhuban		Bluish gray to black laminated shale, occasionally calcareous, ripple and wavy laminated siltstone and sandstone
				Unconformity

a few ripple marks. The sandstone is light gray to yellowish gray, moderately hard and compact, thin to thick bedded, and medium- to fine-grained. The sandstone is commonly trough, and planar cross-bedded with abundant flaser lamination.

Lithofacies Analysis

Eleven distinct sedimentary facies have been recognized in the studied section of the Boka Bil Formation. The facies scheme is summarized in Table 2. The individual facies are described below.

1. Trough cross-stratified sandstone facies (S_t)

This facies consists of yellowish gray to yellowish brown, moderately sorted, medium- to fine-grained sandstone with few siltstone layers. Width and depth of the trough varies from 2.9 to 3.9 m and 0.59 to 0.9 m, respectively. Both troughs and grain sizes are diminished upward in the succession. Clays, pebbles and mud blades occur along some of the foresets and bases of troughs. In places, intrasets of cross-strata dipping in opposite direction to the main trough sets are present. The facies occurs mainly in the lower part of the sequence and at the base of most channel deposits. The channel feature in the outcrop shows 15–20 m and 1.2 –3.6 m in width and depth, respectively.

2. Planar cross-stratified sandstone facies (S_p)

This is one of the dominant facies in the Boka Bil Formation. This facies occurs as sets or co-sets of gray, medium to very fine-grained sandstone with siltstone and occasionally overlies facies S_t, being finer grained than the facies S_t. The sandstones are moderately to well sorted within the individual cross-strata.

The changes in geometrical feature from angular through tangential and concave to sigmoid shape are found. Lateral accretion is well documented by changes of dip (low to higher angle of dip, ending in lower angle again) and grain size. Laminae sets of angular, tangential, concave and sigmoid morphological unit are sometimes mud draped (Koshick and Terwindt, 1981). On the basis of height, the planar cross-stratified sandstone facies (S_p) are classified into large scale and small scale sets or cosets. In general, the foresets varies from 0.2 to 45 cm in thickness, and from 5° to 6° in dip. From field study it is to be noted that the planar sets cross-strata dipping towards the north have comparatively smaller set height, lower dip angle, and finer grain size with respect to those dipping towards the south (Table 2). Locally, the immediately overlying and underlying sets show bi-directional paleocurrent pattern. The facies is designated as herringbone planar cross-stratified sandstone facies (S_{ph}) when bi-directional and bipolar paleocurrent pattern is recorded.

The thickness of foreset type was measured perpendicular to foreset alignment midway between the upper and lower boundaries. The grain sizes also are coarsening in the full vortex structure of concave foresets compared to that of prevortex angular and tangential and post vortex sigmoid foresets. Heights of foresets vary from 0.5 to 5 cm, averaging of 1.2 cm. This facies might have mainly formed by migration of straight-crested (D) dunes and ripples (Jopling, 1967; Reineck and Singh, 1980; Harms et al., 1982; Dalrymple, 1984; Boggs, 1995).

3. Horizontal stratified sandstone facies (S_h)

This facies generally overlies the facies S_p. It consists of light yellowish gray to gray, medium- to fine-grained sandstone strata including little siltstone layers. The individual laminaes of this facies are horizontal to sub-horizontal with very low degree of inclination, i.e. nearly flat without any signature of parting lineation. This horizontal laminated facies indicates the formation under lower flow regime conditions (Allen, 1980; Terwindt, 1981).

Table 2. Facies schemes for the Boka Bil Formation in the study area.

Facies code	Lithofacies	Texture	Sedimentary structure	Contact	Thickness of bed/laminae (cm)	Occurrence	Interpretation
F_h	Laminated black shale	Shale	Parallel lamination	Sharp	0.02 to 0.1	Bathyal and abyssal	Deep marine environment
F_m	Mudstone	Clay	Massive, occasional root traces, leaf impression, bioturbation	Gradational	0.03 to 0.2	Bar top deposit or may be intertidal flat.	Product of no bed movement in slack water stage of tidal environment
F_l	Parallel laminated silty shale-shale	Silty shale to shale	Parallel lamination	Sharp/ Gradational	0.04 to 0.3	Upper most part of channel fill or tidal flat.	Product of lowest flow condition in lower flow regime of tidal environment
F_{sl}	Lenticular laminated sandstone-siltstone	Very fine-grained sand to silt within clay	Lenticular lamination	Sharp	0.1 to 0.7	Starved ripple in a mud dominated environment.	Product of ripple movement alternating with mud deposition in lowest lower flow regime condition of tidal flat environment
S_f	Flaser laminated sandstone-siltstone	Very fine-grained sand to silt with few clay	Flaser lamination	Sharp	0.2 to 1.5	Clay as flaser, mostly within the trough of ripple.	Deposition standstill phase and current activity in tidal environment.
S_w	Wavy laminated very fine sandstone-siltstone	Very fine-grained sand to silt	Wavy lamination	Sharp	0.3 to 1.2	Tidal flat	Product of ripple movement in lowest lower flow regime with slack water condition for mud deposition between two tides, flood and ebb.
S_r	Ripple laminated sandstone-siltstone	Fine to very fine-grained sand and silt	Ripple lamination	Sharp	0.3 to 2.5	Small scale 2-D and 3-D ripple	In abandoned part of channel, shallow and crevasse channel, tidal flat at shallow water intertidal environment
S_l	Parallel laminated sandstone-siltstone	Fine-grained sand to silt	Parallel lamination	Sharp	0.4 to 9.2	Parallel lamination in tidal flat	Lower flow regime plain beds in bar tops or shallowest parting tidal channels.
S_h	Planar stratified sandstone	Medium to very fine-grained sand with occasionally silt	Plane stratification	Sharp	3 to 20	Plain bed in bar tops, inter-tidal flat	Lower flow regime plain bed in estuarine and shallow marine environment
S_p	Planar cross-stratified sandstone	Medium to fine-grained sand with occasional silt	Planar cross-stratification	Erosive	0.2 to 45	Sub-aqueous 2-D ripple or occasionally sand wave	Product of migration of sub aqueous 2-D ripple is shallow water part of tidal channel
S_t	Trough cross-stratified sandstone	Medium to very fine-grained sand and silt	Trough cross-stratification		50 to 260	Sub aqueous 3D dune in the deepest part of thalweg of channels, small to medium.	Deposition in the deeper part of tidal channel

4. Ripple cross-laminated sandstone-siltstone facies (S_r)

Ripple cross-laminated sandstone-siltstone facies (S_r) is the most dominant facies in the Boka Bil Formation. It consists of gray to yellowish brown, moderately well sorted, very fine-grained sandstone and siltstone. Generally it occurs over the facies S_p, S_h and S_l. The wavelength of ripples ranges from 2.5 to 29 cm. Ripple Indices (RI) and Ripple Symmetry Indices (RSI) vary from 3 to 15.71 and 1.25 to 3.33, respectively (Table 3), suggesting that they are mostly wave-induced ripples (Boersma, 1970; De Raaf et al., 1977). This facies occurs as lenticular units parallel to flow direction. Crestal areas are sometimes truncated and internal laminations are mud draped. Internal cross lamination of this ripple type shows unidirectional cross lamination with lee sides of ripple in opposite directions.

Lateral or vertical succession of ripples commonly shows internal cross lamination with bidirectional paleocurrent. Due to reversibility of flow direction in tidal environments, the RSI values can be very similar to those of wave originated ripples (Table 2). However,

Table 3. Parameters of ripples in ripple laminated sandstone-siltstone facies (S_r).

(a) up slope (0°–90° and 271°–360°).

No.	LS (cm)	LL (cm)	λ = LS+LL	Rh = (cm)	RI = (λ/R_h)	Origin according to RI Value	RSI = LS/LL	Lee Azimuth	Origin according to RSI value
1	9.5	7	16.5	3.5	4.71	M	1.357	35°	W
2	5	3.5	8.5	1	8.5	M	1.428	25°	W
3	3.5	1.5	5	0.5	6	M	1.57	15°	W
4	10	5.5	15.5	1.8	8.61	M	1.818	15°	W
5	4	2.5	6.5	1.5	4.33	M	1.6	5°	W
6	4	1.5	5.5	0.5	11	M	2.66	32°	M
7	3.5	2	5.5	1	5.5	M	1.75	10°	W
8	15	6	21	4.5	4.66	M	2.5	27°	W
9	4.5	3	7.5	2.5	3	W	1.5	25°	W
10	5	3.5	8.5	1	8.5	M	1.428	15°	W
11	2.5	2	4.5	1	4.5	M	1.25	10°	W

(b) down slope (91°–270°)

No.	LS (cm)	LL (cm)	λ = LS+LL	Rh = (cm)	RI = (λ/R_h)	Origin according to RI Value	RSI = LS/LL	Lee Azimuth	Origin according to RSI value
1	3.5	2	5.5	1	5.5	M	1.75	195°	W
2	5.5	3.5	9	1.5	6	M	1.57	200°	W
3	3	1	4	0.4	10	M	3	196°	M
4	7	4	11	0.7	15.71	C	1.75	200°	W
5	7	5	12	2	1.4	W	6	190°	C
6	5	2	7	2	3.5	W	2.5	205°	W
7	4	2.5	6.5	1.5	4.33	M	1.6	200°	W
8	21	8	29	3.5	3.625	W	2.625	202°	M
9	4	2.5	6.5	1	6.5	M	1.6	210°	W
10	1.5	0.7	2.5	0.5	4.4	M	2.142	205°	W
11	9	5.5	14.5	2	7.25	M	1.635	195°	W

(M = Mixed, C = Current and W = Wave)

RI and RSI values indicate the presence of wave action in a tide-dominated environment. The facies is subdivided into ripple-laminated sandstone-siltstone with mud drape (S_{rm}) and bioturbated ripple laminated sandstone-siltstone facies (S_{rb}), if mud drapes and bioturbation are present, respectively (Fig. 2, Table 2).

The presence of mud drapes within sandstone indicates slack water stages alternating with period of current activity. This is commonly observed in shallow tidal environments, possibly tidal flats. The paleocurrents also support this interpretation. Bipolar and bidirectional paleocurrents with truncated ripples and bioturbation patterns are suggestive of tidal environments (De Raaf et al., 1977; Archer et al., 1991). Water depth during deposition of the facies S_r lay in the ranges of 3.64–32.92 cm and 2.4–33.0 cm, according to the formulas of Allen (1982) and Yalin (1977), respectively (Table 3).

5. Parallel laminated sandstone-siltstone facies (Sl)

This facies normally occurs over the facies S_p and occasionally over the facies S_r, S_w and S_f. The facies is pale gray to gray, moderately sorted, and fine to very fine-grained sandstone and siltstone. The laminae is parallel with negligible dip. Thickness of laminae varies from 0.1 to 2.3 cm. Due to presence of mud drapes; this is designated as parallel laminated sandstone-siltstone with mud drape facies (S_{lm}).

6. Wavy laminated very fine-grained sandstone-siltstone facies (S_w)

This facies comprises light gray, moderately sorted, very fine-grained sandstone and siltstone. The wavy nature is probably due to the presence of underlying rippled surfaces (Reineck and Singh, 1980). This facies is common in the fine-grained upper heterolithic part of the sequence that overlies the channel bodied sand-

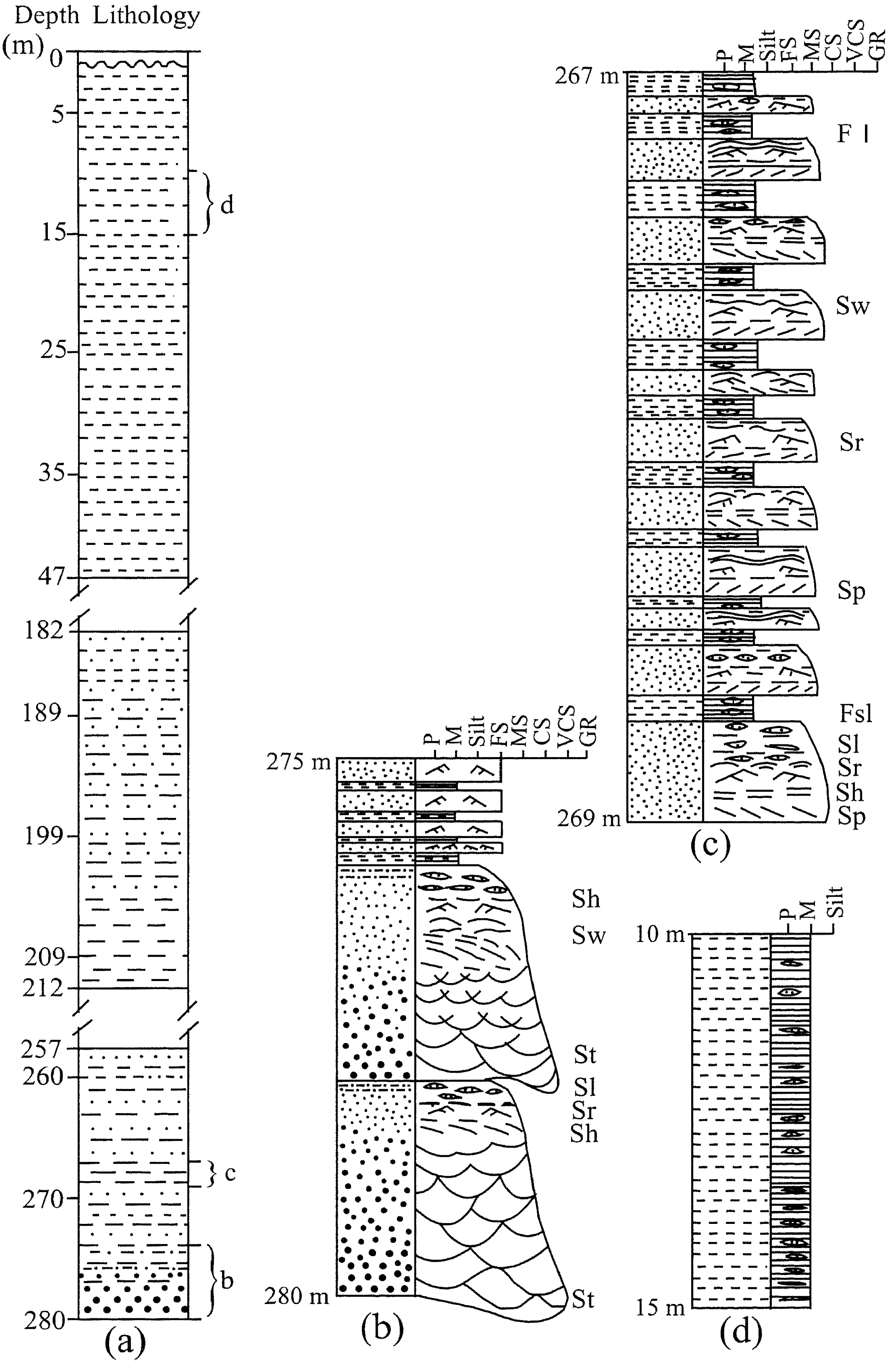

Fig. 2 (a) Summarized litholog of the Boka Bil Formation, Lalakhal, Jaintiapur, Sylhet, Bangladesh, (b), (c), (d) are the enlargement of facies logs in Fig. 2a, within the thickness range of 275 to 280 m, 267 to 269 m and 10 to 15 m, respectively. (Abbr. P, Peat; M, Mudstone/Shale; Silt, Siltstone; FS, Fine-grained sandstone; MS, Medium-grained sandstone; CS, Coarse-grained sandstone; VCS, Very coarse-grained sandstone; GR, Gravel/Pebble).

stone, with infills of planar, trough and ripple types facies (p_x, t_x and S_r). Sandstone and siltstone layers sometimes alternated upward in cyclic patterns known as vertical accreted tidal bundles, VTB (Lapido, 1988; Tessier and Gigot, 1989).

7. Flaser laminated sandstone-siltstone facies (S_f)

The coarse-grained portion of this facies is composed of light gray, very fine-grained sandstone and siltstone. The fine-grained portion is made up of brownish-gray clay sized particles, implying alternate periods of current activity for the deposition of sand and silt, with period of quiescence or standstill for the deposition of clay (Reineck and Wunderlick, 1968). The mud deposited from suspension during slack time is preserved mainly on the troughs or partly on the crests of ripples, and hence the mud is called flaser (Reineck and Wunderlick, 1968).

8. Lenticular laminated sandstone-siltstone facies (F_{sl})

Lenticular laminated sandstone-siltstone facies consists of light gray to light yellowish gray, very fine-grained sandstone and siltstone having appearance of biconvex lens embedded in shale or mud layers. The lenses are biconvex and/or starved ripples, mostly current generated and sediment supply was deficient. The length of the lenses varies from 0.05 to 0.25 cm whereas the thickness ranges from 0.1 to 0.7 cm. This facies is commonly observed in the upper, fine-grained part of heterolithic facies. This facies also indicates a larger period of quiescence during which mud was deposited, occasionally disturbed by current activity when a lens of sandstone-siltstone was deposited (Reineck and Singh, 1980).

9. Parallel laminated silty shale-shale facies (F_l)

This facies comprises grayish to bluish gray, laminated silty shale to shale with or without organic matter and mica flakes. Organic matter is a little blackish. In places leaf impressions and root traces (mostly carbonaceous) are observed. The thickness varies from 0.3 to 0.4 cm. Generally this facies is observed in the middle part of the facies cycle of F_{sl}, F_l and F_m. The parallel laminations may have originated at the lowest current velocity of the lower flow regime (Harms et al., 1975) having high suspended sediment. These are common in less energetic mud-dominated tidal flats (Reineck and Wunderlick, 1968; Tirsgaard, 1993).

10. Massive clay facies (F_m)

This facies is gray or bluish gray in color and lacks sedimentary structures, although root traces, leaf impression, burrows, and mud cracks are locally present. It forms the uppermost part of the heterolithic sequence. Generally it forms the top part of the facies cycle constituted by the facies F_{sl}, F_l and F_m. Deposition of clay requires a calm environment when flow velocity is nearly zero and suspension fallout rate was high. Presence of roots, leaves and mud cracks suggest deposition in a mangrove type forest land in the intertidal to near supratidal zone (Tirsgaard, 1993).

11. Laminated black shale facies (F_b)

The black shale facies (F_b) is a few centimeters to 1 m thick, sometimes ripple to thinly parallel laminated siltstone units of turbidite Tc and Td divisions (Fig. 2) are intercalated. This shale is locally calcareous. Black shale with thin parallel lamination denotes quiet conditions under a reducing environment. The calcareous or non-calcareous nature of the black shale suggests it was deposited above and below the carbonate compensation depth (CCD), the depth below which carbonates are completely dissolved (Hesse, 1975). These shales are in fact pelagic and hemi-pelagic mud layers, division Tc of turbidites deposited in deep-sea environments, particularly in bathyal and abyssal plains (Bouma, 1962; Hesse, 1975; Mutti, 1977). The rhythmic occurrence of fine-grained turbidite Tc/Td divisions and black shale observed in this facies can be interpreted in terms of deep-sea sedimentary sequence (Shanmugam, 1980).

Facies Association

On the basis of dominant lithology, dimensions of sedimentary structures and water depths, the facies of the study area has been grouped into three facies associations: (1) sandstone facies association of tidal channel and estuarine environments (SFTE) including facies S_t, large scale S_p and S_h, (2) heterolithic facies association of tidal-flat environments (HFTF) including small scale S_p, S_l, S_r, S_w, S_f, F_{sl}, F_l and F_m, and (3) shale facies association of deep-sea environments (SFDS), which includes laminated black shale (F_b) facies with ripple to parallel laminated sandstone-siltstone (turbidite Tc and Td divisions) (Fig. 2).

1. SFTE Association

The SFTE facies association is restricted to tidal processes in channels (large or small) and tidal creeks. Sediment thickness is greater than that of HFTF. The SFTE comprises facies of S_t, large scale S_p, and S_h where S_p is most dominant and S_h is rare. In SFTE, fluctuation of water velocity both in magnitude and direction up and down local slopes and of water depth in periodic order is regarded as tides, in response to attractions of the moon-earth-sun system.

High frequency tidal cycles include semidiurnal, diurnal, mixed, fortnight, and monthly cycle. This type of tidal cyclicity may be determined from the lateral succession of planar cross stratification of facies S_p with mud drape on foresets. This lateral succession may be called laterally accreted tidal bundles (LTB). Due to the absence of lengthy exposures and vegetation coverage, the lateral succession of LTBs could not be properly determined and documented in the Boka Bil Formation in the study area. Consequently, tidal cyclicity (whether diurnal or semidiurnal) could not be recognized. However, the association of facies S_t, S_p and S_h clearly identifies tidal action in channels, estuaries and tidal creeks of SFTE where water depths vary from 0.1 m to 7 m. Paleocurrents are dominantly bidirectional and bipolar with distinct distribution (Fig. $3b_{(i)}$).

2. HFTF Association

Vertical accreted tidal bundles (VTB), consisting of alternations of comparatively thicker laminae of sandstone-siltstone layers with apparently sharp contact and thinner mudstone layer are sometimes visible within the HFTF association. The coarse-grained fraction of the VTB (facies small-scale S_p, S_r, S_l, S_w, S_f, and F_{sl}/S_{ln}) represents high energy conditions suggestive of peak tidal velocity, and the fine-grained fraction (facies F_l and F_m) represents slack water stages of flow. According to Shji (1991) thick sand/silt-rich layer with facies small-scale S_p, S_r, S_l, S_w, S_f, F_{sl}/S_{ln} may represent spring tide periods (7–8 days), and thin mud-rich layers with facies F_l and F_m may indicate neap tidal periods (8–7 days). Paleocurrents show bipolarity (Fig. $3b_{(ii)}$). It generally constitutes top part of the SFTE or middle part of the whole sequence.

The facies sequence, association and paleocurrent pattern in this heterolithic facies association suggest its deposition in shallow marine to intertidal flat environments (De Reaf et al., 1977; Reineck and Singh, 1980; Terwindt, 1981; Tirsgaard, 1993; Dalrymple, 1992), where depth varied from 3 cm to 33 cm.

3. SFDS Association

Laminated black shale facies (F_b) with embodied ripple laminated siltstone (Tc division) and parallel laminated siltstone (Td division) constitute the SFDS facies association. It occupies the top most part of the whole sequence. The both calcareous and non-calcareous nature of the black shale indicates deposition above and below the carbonate compensation depth (CCD) in deep marine conditions. The embodied ripple (Tc division) and parallel lamination (Td division) in siltstone are indicative of distal turbidite deposition in a deep-sea environment. The occasional presence of pyrite in black shale (Reimann, 1993) further suggests reducing conditions. The SFDS is hence suggestive of a deep-marine environment in the upper part of the Boka Bil Formation in the study area, with water depth assumed to be 2000 m or more.

Facies Model and Paleoenvironments of Deposition

We obtained paleocurrent data from azimuths of foresets in (1) the planar cross-stratified sandstone-siltstone (S_p), (2) ripple cross-laminated sandstone-siltstone (S_r) and (3) axis of trough cross-stratified sandstone-siltstone (S_t) facies. Paleocurrent patterns (Fig. 3b) show bidirectional bi-polarity and a monodirectional paleocurrent in a small sector (120°–150°). Field observation revealed that paleocurrents in the lower subunit were within some channels, which were estuarine in nature. However, the middle part of the sequence was deposited in open tidal flat. These may contribute to the bipolar bidirectional paleocurrents. The monodirectional paleocurrent in the small sector (120°–150°) may have been derived from turbidity currents in the upper subunit.

From the interpretation of facies and facies association, we conclude that the lower part of the Boka Bil Formation along the Borogong-Hari River section was deposited in estuarine environments where water depth was up to 7 m. This environment shallowed upward into shallow marine to intertidal, and even to a supratidal environment during deposition of the middle part of the formation (Fig. 3c). Bidirectional paleocurrent also support a tidal environment during deposition of the middle and lower parts of the formation. The environment became deeper during deposition of the upper Boka Bil sediments into the deep-sea marine part where distal turbidites could reach. Reducing conditions are supported by the presence of pyrite and black to bluish black shale with turbidite Tc and Td divisions. Deep-sea sedimentation during the upper Boka Bil Formation may be attributed to marine transgression. These types of sediments have been reported from the top part of the Boka Bil Formation in other area of the Sylhet Trough (Reimann, 1993).

Conclusions

Sedimentary facies of trough cross-stratified sandstone facies (S_t), planar cross-stratified sandstone facies (S_p), planar stratified sandstone facies (S_h), ripple

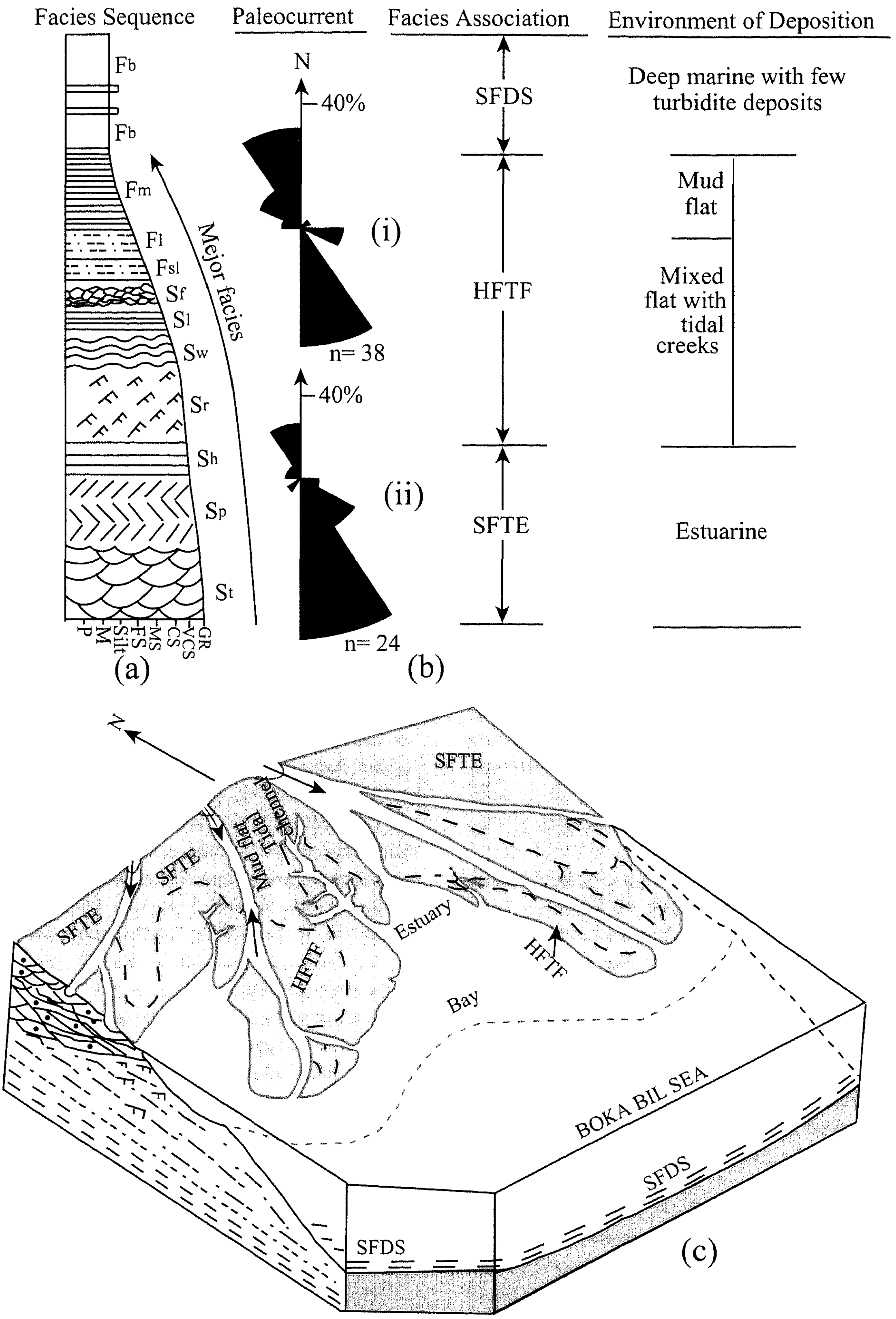

Fig. 3 Facies sequence and schematic depositional model for the Boka Bil Formation near Lalakhal, Sylhet, Bangladesh.

cross-laminated sandstone-siltstone facies (S_r), wavy laminated very fine sandstone-siltstone facies (S_w), parallel laminated sandstone-siltstone facies (S_l), flaser laminated sandstone-siltstone facies (S_f), lenticular laminated sandstone-siltstone facies (F_{sl}), parallel laminated silty shale-shale facies (F_l), massive clay facies (F_m) and laminated black shale facies (F_b) are recognized within the Boka Bil Formation in the study area. These are grouped into three facies associations. The SFTE association comprises facies S_t, large scale S_p, S_h and or S_r, interpreted as the deposition related to strong tidal effects,. The deposition of HFTF facies association is related to weaker tide and finer heterolithic grain sizes suspension nature. The HFTF consists of facies of small-scale S_p, S_r, S_w, S_l, S_f, F_{sl}, F_l and F_m. This facies association related to deep sea sedimentation (SFDS) consists of facies F_b with ripple (Tc) and parallel laminated (Td) turbidite divisions.

Paleocurrents in both the SFTE and HFTF are strongly bi-direction and bipolar, which strongly supports the influence of tidal action. Water depths ranged from 0.1 to 7 m, 0.03 to 0.33 m and 2000 m or more during the deposition of the SFTE, HFTF and SFDS associations, respectively.

The paleogeographic configuration during deposition of the Boka Bil Formation varied from estuarine channels and tidal creeks in the lower part, tidal flat for the middle part, and deep marine environment for the upper part.

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