

Paleoenvironment of deposition of Miocene succession in well BK-10 of Bengal Basin using electrofacies and lithofacies modeling approaches

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Abstract Integrating well log and core samples data were applied to interpret paleoenvironment of deposition of Miocene succession for understanding of reservoir facies model from a well Bakhrabad (BK)-10 of Bengal Basin. Miocene succession was subdivided into two depositional sequences/models which contain 9 para sequence sets and 35 para sequences. Detailed examination of well log data, based on considering GR (gamma ray) log shapes, size, lithologic variations permit a subdivision into five electrofacies models, e.g., bell, funnel, cylindrical, egg/bow and linear shape models. The succession consists of alternating shales, shaly sand, silts and sandstones, with minor mudstones. The study revealed eight distinct lithofacies models namely, shale dominated facies, heterolithic sandstone facies, cross bedding facies, parallel laminated shale with alternate sand/silt facies, ripple-lamination facies, bioturbation facies, wavy bedded facies and laminated shale facies. The depositional models for the Miocene sediments encountered in the studied well BK-10 inferred to be that of delta-front setting and fluvio-deltaic to shallow marine environments. Based

on lithofacies and electrofacies models associations, Miocene succession interpreted as a coarsening upward deltaic progradation; although more repetitive marine transgression and regression sedimentary processes might have an impact on the architecture of reservoir facies model.

Keywords Paleoenvironments · Miocene succession · Electrofacies model · Lithofacies model and reservoir facies model

Introduction

Wireline log is an important tool to study the sub-surface sedimentary geology. This tool has been used to reconstruct the paleoenvironment of deposition of a particular basin. Subsurface sediments in various paleoenvironmental setting demonstrate a distinct characteristic log shapes/models. This log can be used to delineate the reservoir facies model in any area (Prensky 1989; Bischke 1994). The term “electrofacies” model is defined as a set of log responses that characterizes a bed and permits it to be distinguished from the others (Serra and Abbot 1980). Moreover, electrofacies model is widely used for interpreting paleoenvironment of subsurface sedimentary geology in many parts of the world including Bangladesh (Serra and Sulpice 1975; Reading 1978; Galloway and Hobday 1983; Serra 1985; Van Tassell 1987; Van Wagoner et al. 1988; Chow et al. 2005; Mondal et al. 2009; Habib and Islam 2014; Sen et al. 2016). This model represents major and minor facies cycle, which can provide information regarding paleoenvironments of deposition of the sedimentary succession in the well bore. Electrofacies analysis is mainly done on the basis of different log signatures (Gamma and SP). GR (Gamma Ray)

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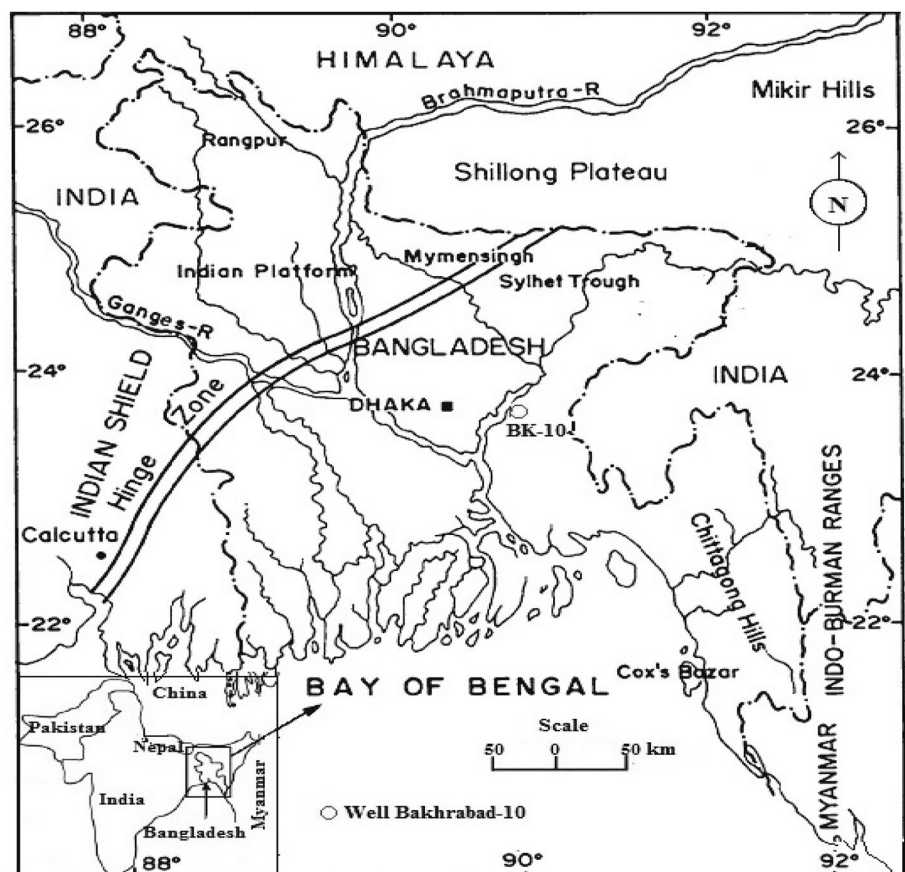
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log shapes or motifs are correlated with lithology and depositional units of sediment, which provide the useful clue to the different depositional sequences. The shape of GR log could be interpreted as grain size trend. Increase GR value indicates decrease in grain size while higher grain size related to lower GR value. In the electrofacies model analysis, para-sequence sets (first-order cycles) are composed of bed sets i.e. electrofacies model associations and para-sequences (second-order cycles) are composed of lamina set beds i.e. electrofacies model within the sequences (Mondal et al. 2009). However, GR log interpretation is not only limited to an assessment of hydrocarbon reserves; but also a powerful tool to provide a clue for paleoenvironments of deposition (Murkute 2001; Chow et al. 2005). In addition, lithofacies modeling is a way for the better understanding of sedimentary depositional environments and their probable sources. For example, in the well Bakhrabad (BK)-10, due to paucity of field exposures of Bhuban and Bokabil Formation of Bengal Basin, such kind of study is dependent on the subsurface well log and drilled core samples data. Illustration of a depositional lithofacies model using detailed of core samples, thus, allows quantitative analysis of sedimentary features with electrofacies model of the drilled well BK-10. Such analysis is widely applied

to reconstruct more realistic sedimentary depositional model for better understanding of the reservoir facies.

The well BK-10 is situated to northeast by Sylhet Trough, and Chitagong-Tripura Folded Belt to the south-east, to the west by Hinge zone and open to the south and southeast of the Bengal Basin (Fig. 1). Several attempts have been made in order to reconstruct the paleoenvironment of deposition of the Bengal Basin (Alam 1995a, b; Sultana and Alam 2000; Alam et al. 2003; Hossain et al. 2003; Devices et al. 2003; Gani and Alam 2003). According to Mondal et al. (2009), Neogene sequence of well Shahbazpur-1 of the Bengal Basin was deposited in a fluvio-deltaic to deep marine environment. Rahman et al. (2009) interpreted that Surma Group sediments representing as deposits of tide-dominated deltaic depositional setting. Gomes et al. (2010) reported that Neogene Surma sequence of the southeastern Bengal Basin represents an overall basin-ward progradation from deep marine through shallow marine to fluvial environments. Islam et al. (2014a) suggested that Miocene sequence of the well Bakhrabad-09, Bengal Basin was deposited lower deltaic plain to marginal marine setting environments. According to Habib and Islam (2014), Miocene Surma succession of well Rashidpur-4 of the Bengal Basin was deposited under prograding deltaic system and coarsening upward in nature. These

Fig. 1 Map shows the major tectonic elements surrounding the Bengal Basin. Map also represent the location of the well BK-10 of the Bengal Basin



studies have been motivated by the fact that Bengal Basin is a young prolific basin in the world. This paper focuses on detailed lithofacies models associated with electrofacies models pertaining to the paleoenvironment of deposition for the Miocene succession encountered in well BK-10 of the Bengal Basin (Fig. 1). So far, gas bearing horizons are thought to have been generated from and trapped within this Miocene succession. Therefore, paleoenvironment of the Miocene succession need to be assessed in order to show the architecture of reservoir facies model. This paper builds on the previous work of the well BK-09 of the Bengal Basin by adding more cores data in detailed with electrofacies models. This research work has been attempted to link up electrofacies models with sedimentological aspect of lithofacies models of the Miocene succession in the well BK-10 of the Bengal Basin. The objective of this paper was to reconstruct the paleoenvironments of deposition of Miocene succession for better delineating of the reservoir facies model in the well BK-10 of the Bengal Basin from integrated wireline log and limited core samples data.

Geological setting

The Bengal Basin contains a succession of thick (± 16 km) sediments, however, Miocene succession of Bengal Basin reaches up to 6 km thick deltaic deposits. Bengal Basin is located in the north-eastern part of the Indian subcontinent, between the Indian Shield to the west and north, and the Indo-Burmese Ranges to the east, and occupies most of Bangladesh, parts of West Bengal and Tripura states of India and the Bay of Bengal (Alam et al. 2003). The Bengal Basin of Bangladesh includes one of the largest delta complexes in the world, covering an area of more than 200,000 km² and 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). The basin was characterized by three distinct geotectonic provinces: namely, the stable shelf province, the central deep basin province and the Chittagong-Tripura fold belt province (Alam et al. 2003). The Greater Bakhrabad structure lies on the central deep basinal part of Bengal Basin. The well BK-10 of Belabo structure is one of the parts of Greater Bakhrabad structure which is randomly directed egg like shaped anticline whose run slightly longer N-S axis (BOGMC 1990). Miocene succession reaches up to 6 km thick deltaic sedimentation. It contains the early to middle Bhuban Formation and the middle to late BokaBil Formation making up thick accumulations of sandstones and alternating shale with siltstones. The sediment started intensifying during Early Miocene and its apex development took place probably during Late Miocene sedimentation and finished in Pliocene time and was deposited during repeated transgressions and regressions regimes.

The subsurface stratigraphy of the study area was established on the basis of drilling, well log, seismic data and also correlated with neighboring established wells (BOGMC 1991). Stratigraphy succession of the well BK-10 is represented in Fig. 2. Stratigraphic correlation of studied well BK-10 with well BK-09 and well BK-01 are displayed in Fig. 3.

Data and methods

The well log data (GR, SP log) of the well BK-10 was collected from the Data Centre, Petrobangla. The limited core samples were obtained from Bangladesh Petroleum Exploration & Production Company Limited (BAPEX), Petrobangla. The present study was accomplished from the usage of GR log shapes/motifs. The GR log of the well BK-10 was qualitatively analyzed at first. The qualitative analysis was employed for the identification of electrofacies, sequences, cycles and associations and correlating prominent features as well as sharp contact on electrofacies models with the similar features on the lithofacies models for interpreting paleoenvironment of Miocene succession. The uninterrupted core samples represent the subsurface sedimentary layer which penetrated in the studied well BK-10 were observed and described based on color of rock samples, grain size, textural variation, lithological constituent and sedimentary structure features. Eight core samples from the well BK-10 of the Bengal Basin (depth range 1680–1681 m, 1975–1976 m, 2245–2246 m, 2360–2361 m, 2390–2391 m, 2904–2905 m, 3171–3172 m and 3430–3431 m) have been used in present study. Both electrofacies and lithofacies models provide an insight the sedimentation history, processes of paleodepositional environments of the study well. The core samples data were matched with depth wise with respect to GR log shapes at the erosive base step by step on the well bore. Prediction of depositional environments can be made based on lithology, grain size characteristics and GR log shapes (Morris and Biggs 1990). MS-Excel 2007 and ArcGIS (10.2 version) software were used for generating map and electrofacies and lithofacies models for the present study. The flowchart is shown in the Fig. 4 which adopted for this study.

Results

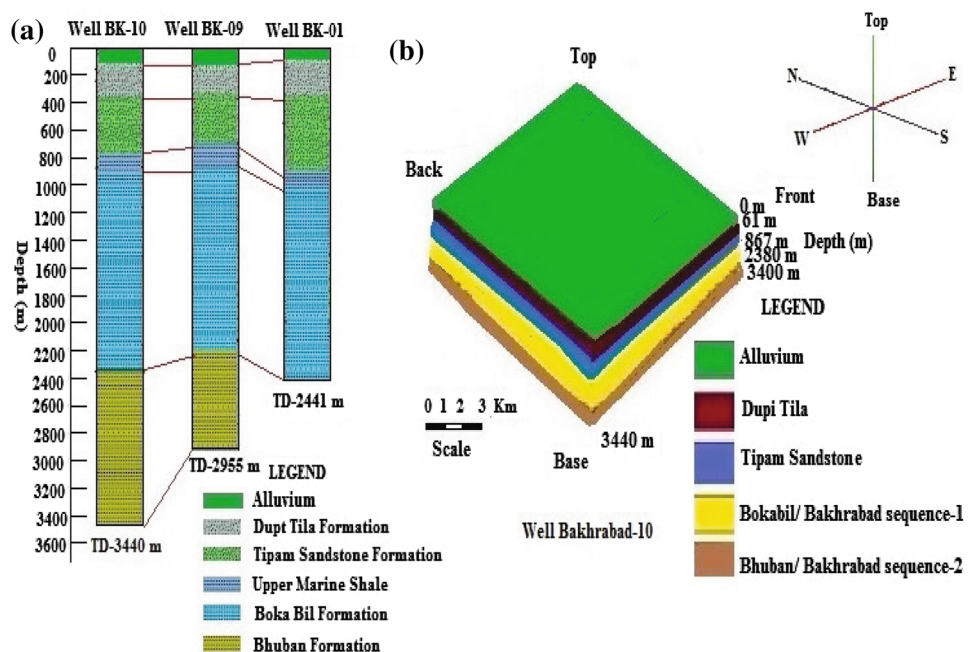
Descriptions of electrofacies model

Based on available GR (gamma ray) log shapes, size, lithologic variations permit a subdivision of five major electrofacies models. Typical GR log shapes and motifs were identified in the study well bore (Fig. 5).

Fig. 2 Stratigraphic succession with photographical representations of the major lithological units of the study area

Age	Group	Formation	Litholog	Lithological features/descriptions	Thickness approx. (m)	Gas shows	
Recent		Alluvium		Sand, silt and clay	161		
Upper Mio-Pliocene	Dupi Tila	Upper		Shale with interbedded sandstone	110 (?)		
		Lower		Light color sandstone			
Middle Miocene	Tipam	Girujan Clay		Black to dark grey shale	696+		
		Tipam Sandstone		Light grey sandstone			
Lower Miocene	Surma	Bokabil		Grey thick shale with sandstone	1517+		
			Bhuban	Upper		Light grey sandstone with interbedded shale	1096+
		Middle			Light grey sandstone with interbedded shale		
		Lower		Light grey sandstone with interbedded shale			

Fig. 3 a Geological correlation of the well BK-10 with well BK-09 and well BK-01 (After modified from Farhaduzzaman et al. 2014; Islam et al. 2014); **b** 3-D stratigraphic view of studied well BK-10



Electrofacies model 1: funnel shape

Funnel shape showed a coarsening upward sequence where GR values and shale content decreases upward and sandstone lead at top portion. This shaped indicated an increasing hydrodynamic energy condition upward at deposition

time. It indicated prograding delta or crevasses splays deposition (Selley 1998 and; Chow et al. 2005). Serrated funnel shape electrofacies was identified at depth ranges of 1193–1425 m, 2555–2644 m (Fig. 5a), 2840–2905 m and also funnel shapes of 2140–2225 m and 2245–2285 m, 2290–2314 m depth intervals in the study well BK-10.

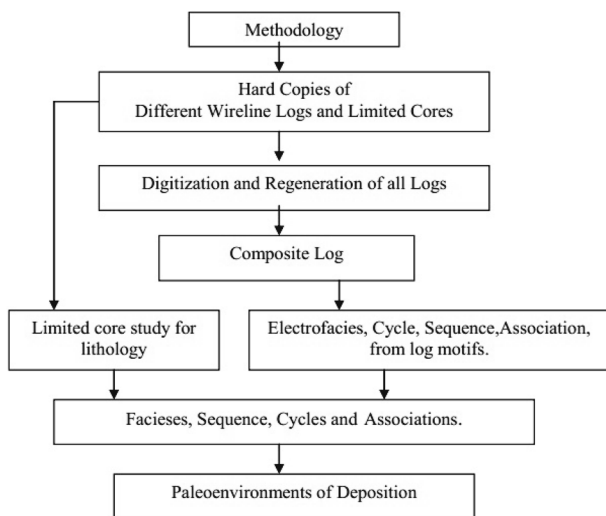


Fig. 4 Flowchart adopted for the present study (After modified from Mondal et al. 2009)

Funnel shape electrofacies model suggested that prograding channel, alluvial fan system and regressive shallow marine sub-environments of deposition.

Electrofacies model 2: bell shape

Bell shape electrofacies showed a fining upward sequence where GR log values increase and decrease in grain size upwards. Bell shape represented retrograding distributary channel floodplain, inter-distributary channel, mud flat and fluvial channel sub-environment of deposition. The electrofacies suggests retrograding distributary channel and tidal channel (Nelson and James 2000). Bell shape also showed a decreasing hydrodynamic energy condition upward sequences at deposition time. The bell shaped found in almost whole succession at varying depth (Fig. 5b). The serrated bell shaped electrofacies (2740–2804 m) was

identified in the study well bore (Fig. 5c). This electrofacies model showed a thick homogeneous sediment bounded by channel-fill sediments with sand dominating sequence.

Electrofacies model 3: cylindrical

Cylindrical shape electrofacies model indicated that aggrading fluvial channel and distributaries channel and tidal sand flat sub-environments condition. The electrofacies was observed at depth ranges of 1730–1795 m, 1840–1875 m (Fig. 5d), 2225–2245 m, 2285–2300 m, 2420–2555m and 975–1112 m were serrated cylindrical shape in nature. This model suggested the slope and fan channel environments (Shell 1982).

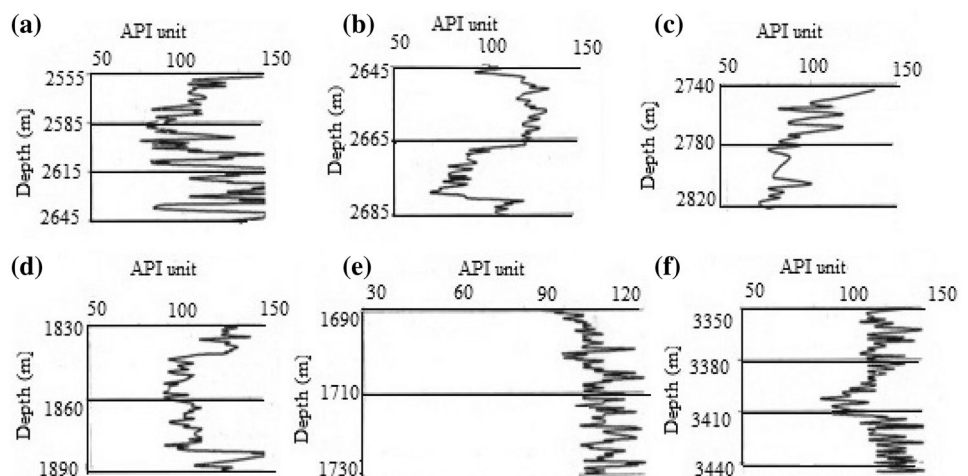
Electrofacies model 4: linear shape

Linear shape is generally non-deviating shape and shale dominant sequence, inter-bedded with siltstone. Linear shape electrofacies model suggested uniform depositional sequence either of coarse grained or fine grained sediment. The electrofacies inferred that inter-distributary bay, delta fringes and marsh sub-environments of deposition. It also reflected shallow marine environments with possible transgression event (Pongpandin 2013). It was observed at the depth ranges of 910–970 m, 1690–1730 m (Fig. 5e), 2020–2140 m, 2380–2420 m, 3190–3350 m and serrated linear shapes of 1112–1193 m, 1425–1555 m depth interval.

Electrofacies model 5: egg/bow shape

The egg shape electrofacies model indicated both the coarsening and then fining upward or vice versa of sequences. The serrated egg shape electrofacies having both the coarsening upward and fining upward sequence, indicating aggradation of shale or silt (Emery and Myers 1996).

Fig. 5 Electrofacies model (GR) shapes of the Miocene succession in the studied well bore, **a** serrated funnel shape; **b** bell shape; **c** serrated bell shape; **d** cylindrical shape; **e** linear shape; **f** egg/bow shape



According to Coleman and Prior (1980), environments of deposition are channel floodplain, sub-tidal channel, inter-tidal sand flat and mud flat etc. The egg shape electrofacies reflected aggradational environment in channel-floodplain, sub-tidal flat of mud rich fan system. The egg/bow shape electrofacies was observed at the depth interval of 3350–3440 m (Fig. 5f) and serrated egg shaped electrofacies was found in 1875–2020 m, 2804–2840 m depth ranges in the study.

Electrofacies model associations

The Bakhrabad sequence-2 (3440–2380 m) consists of 3 para sequence sets and 14 para sequences which were identified on the basis of GR log responses and limited core study (Fig. 6a). The lower para-sequence set-1 showed the depth ranges of 3440–2684 m, having thickness of 756 m indicated coarsening then fining upward para sequences. The BKS2-1 consists of one fining-coarsening para sequence at bottom part, seven fining para sequences at top most part, one coarsening upward sequence at middle part of the para sequence set-1. The egg/bow, serrated bell and serrated funnel shape electrofacies associations were observed in para sequence set-1. The middle para sequence set-2 was found within the depth ranges of 2680–2555 m, having thickness of 125 m represented coarsening upward para sequences with minor fluctuations. It consists of one fining para sequence at lower portion and one coarsening para sequence at upper portion of the para sequence set-2 indicated that deltaic retrograding and prograding phase of deposition. The upper para sequence set-3 was identified within the depth range of 2555–2380 m having thickness of 165 m showed fining upward para sequences and also minor fluctuations.

The Bakhrabad sequence-1 (900–2380 m) was the uppermost part of the well BK-10. This sequence comprises 6 para sequence sets and 21 para sequences (Fig. 6b). The lower para sequence set-1 was occupying the depth ranges of 2384–2020 m, having thickness of 364 m shown fining upward para sequence. This para sequence set-1 consists of 8 para sequences and serrated bell, cylindrical, serrated funnel and serrated linear shape in nature form electrofacies associations were observed within this para sequence set-1. The para sequence set-2 was identified within the depth ranges of 2020–1675 m, having thickness of 345 m exhibited fining upward para sequence. This para sequence set-2 consists of three fining upward para sequences at bottom and two coarsening upward para sequences at top part. The para-sequence set-3 was occupying within the depth range of 1675–1193 m, having thickness of 375 m represented fining-coarsening upward sequences. The para-sequence set-3 consists of two coarsening upward para sequences at top part and three fining upward para sequences at bottom

part of that para sequence set-3. The para-sequence set-4 was identified within the depth ranges of 1193–1112 m, having thickness of 81 m displayed almost fining upward para sequence. The para-sequence set-5 was found within the depth ranges of 1112–975 m having thickness of 137 m indicated homogenous para sequence. The upper most para sequence set-6 contains depth ranges of 975–900 m represented 75 m thickness, fining upward para sequence. The last phase of marine transgression is known as “Upper Marine Shale” unit (Holtrop and Keizer 1970) which was identified by linear shape electrofacies model within the para sequence set-6.

Lithofacies model descriptions

Mainly eight core lithofacies models were recognized in the well BK-10 on the basis of color, composition, texture and sedimentary structures (Table 1).

Facies model 1: shale dominated facies

The cored interval (3430–3431 m) consists of bluish grey color of shale dominated facies interbedded with sandstone/siltstone (Fig. 7a). The sandstone was very fine to fine grained while the laminated shale was composed of clay and silt. Based on the sand/shale ratios and internal sedimentary structure, this facies was divided into sand/silt-streaked shales and lenticular bedding. The sandy streaks are thick parallel lamination with flat to slightly undulation upper and lower contacts and sometimes discontinuous. The lenticular bedding shows micro cross-lamination with thick ripples. This lithofacies model lies in between the channel sandstones in multistoried cycle, indicating the top of each fining upward sequence. The foreset laminae depicted vertically adjacent rippled lenses, showing their deposition by current reversal. Worm burrows occurred at this core intervals. Laminated shales (Fig. 7) form an important part of the whole sequence.

Facies model 2: heterolithic sandstone facies

The heterolithic facies showed high sand-to-shale ratio. The core interval (2904–2905 m) contains light greyish brown sandstone with predominant lags of mud clasts, which commonly show a platy to rounded shapes (Fig. 7b). Fine-grained, moderate to well sorted and low angle of cross bedded sandstone. The heterolithic facies was apparently massive at this intervals but internal stratification was traced specially by the oriented lags of mud probably along the foreset laminae. Sandstones generally exhibit well sorted ripple cross laminations with inter-bedded shale. This ripple cross laminations are marked by ferruginous particles, as also occasionally by carbonaceous matters.

Fig. 6 a GR log responses, para sequence sets, log shapes, lithologic description and electrofacies associations of the Bakhrabad sequences-2 in the well BK-10, **b** GR log responses, para sequence sets, log shapes, lithologic description and electrofacies associations of the Bakhrabad Sequences-1 in the well Bakhrabad-10

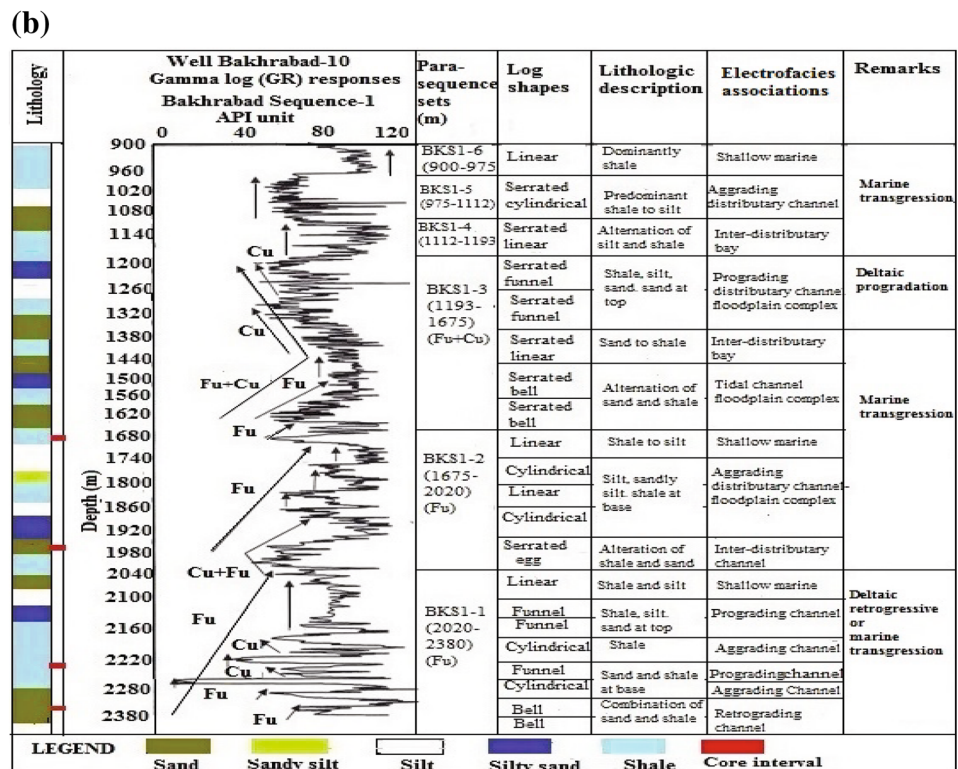
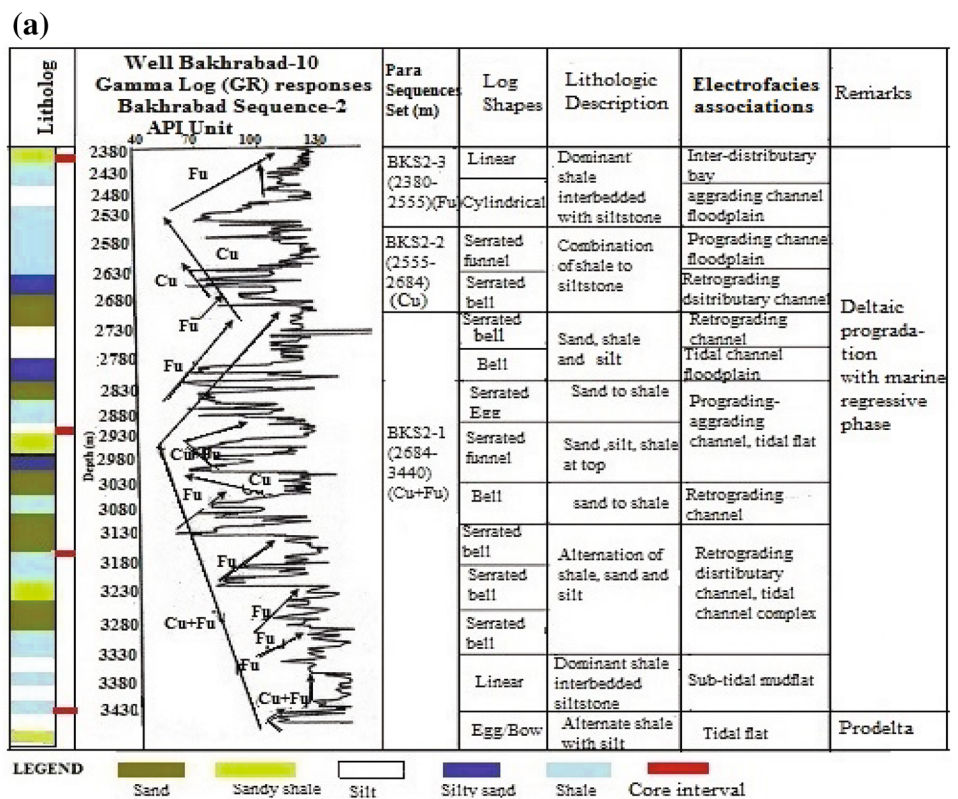
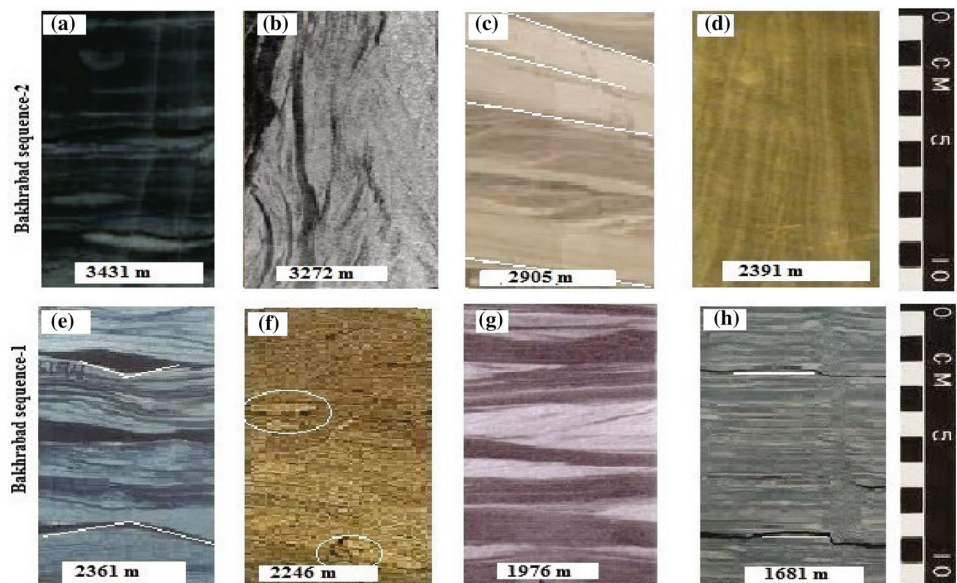


Table 1 Facies, lithofacies models associations of identified limited core interval of Miocene Surma succession in the well BK-10 of Bengal Basin

S/N	Facies model	Description	Lithofacies model associations	Comments
1	Shale dominated facies	Bluish gray laminated shale, sometimes silty, minor mudstone; occasionally bioturbation	Tidal flat (FA1)	Mud rich delta system Tidal influenced; prodelta
2	Heterolithic sandstone facies	Light gray shaley sandstone; fine to medium grained sandstone separated by thin layers of shale. There is an occasional hummocky cross	Tidal channel floodplain complex (FA2)	Deposit associated with suspension settling to low flow condition, possibly in tidal channel or semidiurnal tidal rhythmicity
3	Cross bedded sandstone facies	Stratification; zero bioturbation Light gray to gray shaley sandstone as well as curved foresets; mostly fine-grained; mud laminae and mud clasts along foresets	Prograding aggrading channel (FA3)	Small scale 2D/3D Sand waves, mostly subtidal to channel setting; high-energy flow regime
4	Parallel laminated shale-alternating sand/silt facies	Dark to light gray sandy shale; fine-grained; mostly horizontal upper plain bed laminated structure	Inter-distributary bay (FA4)	Upper flow regime condition
5	Ripple laminated sandstone with flaser bedded facies	Ripple laminated gray sandy shale; Fine to very fine-grained; ripples are asymmetrical in nature	Retrograding channel (FA5)	Small scale 2D/3D ripple in lower flow regime condition
6	Bioturbation sandstone facies	Fine to medium grained sand stone, moderately to well sorted with sparse fossils; Intensely to complete bioturbated	Prograding channel (LA6)	Medium to low energy conditions; periodic rapid deposition of thick sediments
7	Wavy bedded sand/silt with shale facies	Dark gray thin laminated shale with sand alternating straight to slightly wavy intercalations	Inter-distributary channel (FA7)	Deposit into inter distributary channel areas
8	Laminated shale facies	Bluish gray laminated shale; occasionally silt, and rarely bioturbation	Shallow marine (FA8)	Product of no bed movement in calm and quiet water condition

Fig. 7 Core interval photographs represent lithofacies model of the well BK-10, **a** shale dominating facies in core 8; **b** heterolithic sandstone facies in core 7; **c** cross bedding facies in core 6; **d** parallel laminated shale with alternating sand/silt facies in core 5; **e** ripple lamination facies in core 4; **f** bioturbation facies in core 3; **g** wavy bedding facies in core 2; **h** laminated shale facies in core 1. *Shale* indicates dark to grey color and *sand* indicates light grey color and siltstone shows moderately grey color symbols



Facies model 3: cross bedded sandstone facies

The core interval (3171–3172 m) contains very fine grain sandstone with alteration of shale and siltstone in fining upward sequences (Fig. 7c). The sandstones are dominated by asymmetrical cross lamination with mineralogical as well as textural variations in foreset laminae. The planar cross-bedded sandstones are much more abundant than the tangential cross-bedded sandstones. The cross-bedded sandstone are highlighted by the presence of thin mud laminae, and sometimes carbonaceous detritus is also present along the foresets laminae.

Facies model 4: parallel laminated shale with alternating sand/silt facies

The core interval (2390–2391 m) comprises dark to light gray color shale and alternating with fine sand and silt which is characterized by both a textural and mineralogical composition of horizontal, typical upper plane bed lamination (Fig. 7d). The shale layers occurred as continuous shades forming parallel laminated structure. Bioturbation was moderated in nature. Sedimentary structures at the top part of this facies have been locally deformed by soft sediment, indicating a convolute lamination, water escape structures.

Facies model 5: ripple laminated sandstone with flaser bedded facies

The core interval (2360–2361 m) consists of ripple laminated fine to medium grained sand with thin shale (Fig. 7e). The color was mainly light brown to brownish gray

sandstone and silty sandstone. The ripples were asymmetrical in nature with occasional bundle structure, while symmetrical natures were rarely form in the cores studied. Flaser mud usually occurred on the ripple lamination and sometimes continue on the bottom part of the ripple laminae. Vertically, there was high shale/sand ratio and flaser bedded facies. Bioturbation was zero percent in the core interval of well Bakhrabad-10.

Facies model 6: bioturbation facies

The facies (2245–2246 m) consists of a very fine-to-fine grained, moderately to well sorted and greyish brown sandstone and interbedded with shale layer (Fig. 7f). Wave ripple cross lamination and parallel laminations were sometimes present. The bioturbation facies was medium sand-to-shale ratio with high presence of bioturbation. Bioturbation sandstone facies was characterized by graded bedding, flat bedding, ripple cross lamination with occasionally parallel lamination from base to top, which are embedded as channels of different size and shape within shale. Sandstone bodies were sharp base and tend to grade upward into finer silt and mud. Within the sandstone bodies combination of graded bedding, ripple cross lamination and occasionally parallel lamination were identified in core interval.

Facies model 7: wavy bedded sand/silt with shale facies

The core interval (1975–1976 m) comprises wavy-bedded dark gray to light shale with sand ranged from 50 to 80% of the lithology (Fig. 7g). The sandy intervals were very well sorted. Sands were characterized by wavy ripple cross

lamination. The sands were usually ripple-laminated and mud-draped. The wavy ripples were generally asymmetrical in nature, indicating deposition under bidirectional currents. Burrows structures, particularly small-scale load structures were encountered at cores intervals. Bioturbation was moderately intense in nature.

Facies model 8: laminated shale facies

The interval of this facies (1680–1681 m) consists of laminated dark gray shale (Fig. 7h). Laminations were present due to very fine to fine grain size differences in this part. Sometimes, small pod like structures were present. The very high shale/sand fraction and very low levels of bioturbation ranging from rare to absent characterized by the shale facies. Parallel laminations are manifest by either ferruginous or carbonaceous material. Shales are micaceous at some places and commonly fossiliferous. Burrows identified from the shale facies tops of the fining upward sequences, show a gap.

Lithofacies model associations

The core lithofacies of Miocene Surma succession revealed rhythmic or alternating shales and sandstones bedded as depicted from cores (Fig. 8) and well logs data sets (Fig. 6). The coarsening then fining upward sequences were observed in the cores (5–8) of Bakhrabad sequences-2 with shale dominated facies, sandstone heterolithic facies and cross bedded facies passing then into parallel laminated shale-alternate sand/silt facies (Fig. 8). The shale

dominating facies showed that the calm and quite energy condition. This facies indicated a fining upward sequence and reflected the decreasing wave action from the subtidal zone to tidal flat. The shale lithofacies model shows a vertical accretion through interruption the sequence. In fluvio-deltaic setting, this relates to deposition in flood plain environment. The sandy shale unit of this core was interpreted as a prodelta shale that underlies sub-tidal mudflats. The sandstone heterolithic facies exhibited an active but lower energy condition which inferred tidal channel complex. Cross lamination and herringbone suggested a tidal influence environment of deposition. The alternation of cross beddings facies interpreted as a product of marked fluctuation between normal sedimentation and periods of greater energy. It inferred low to moderate energy condition with variable current velocity in prograding aggrading channel sub-environment setting. The parallel laminated shale interbedded with sand/silt facies suggests inter distributary bay or delta fringe sub-environments of deposition prevailing during that time. The core lithofacies was matched with the different the electrofacies within the Bakhrabad sequence-2 on the basis of GR log shapes and trends to represent facies associations (Fig. 9a). All these indicated that upper part of the sequence was deposited in deltaic progradation with marine regressive phase of depositional environments.

The overall fining upward sequences started with ripple laminated partly flaser bedded facies, bioturbation facies, wavy bedded sand/silt with shale facies and finally passing into laminated shaly facies in cores (1–4) of the Bakhrabad sequence-1 (Fig. 8). The ripple laminated with flaser bedded facies represented alternation of high and low energy

Fig. 8 Lithologs with characteristic of sedimentary structures of core-1 to 8 of the Miocene succession encountered in the well BK-10 of the Bengal Basin

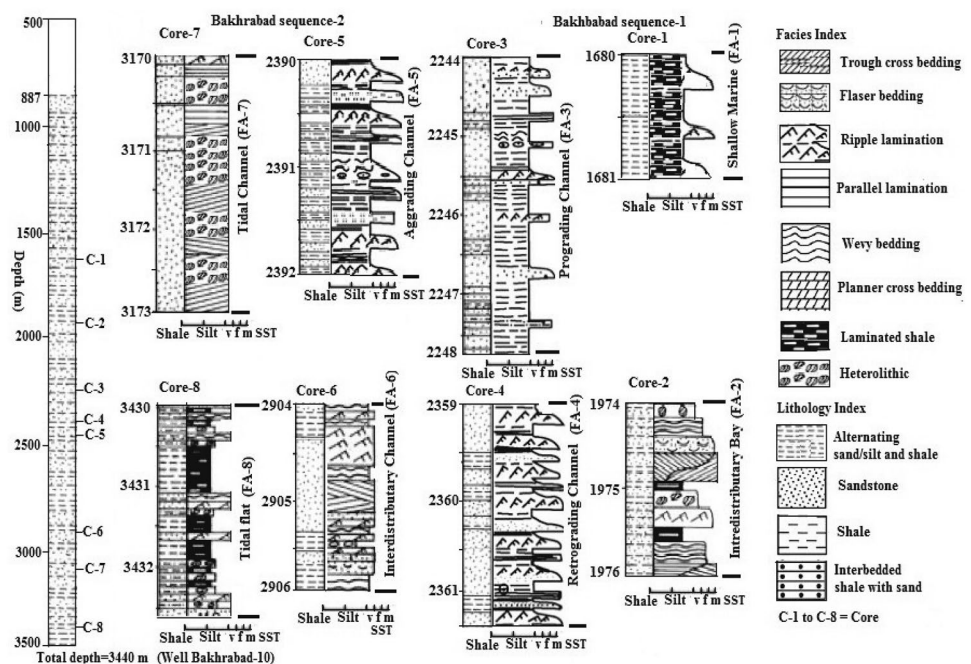
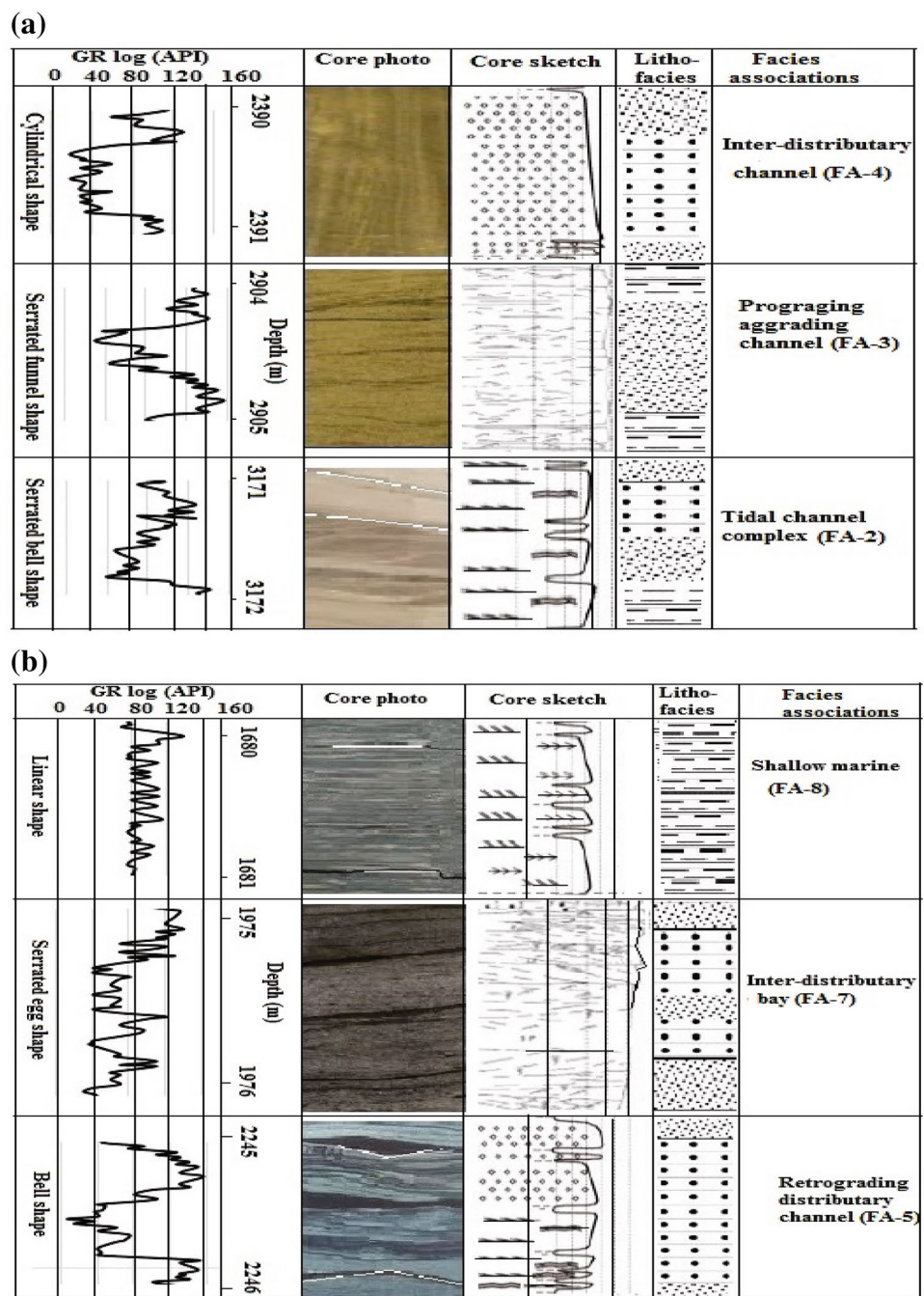


Fig. 9 a Correlation of different electrofacies, lithofacies models and core photographs on the basis of GR log shapes and trends analysis in the Bakhrabad sequence-2 of the well BK-10, **b** correlation of different electrofacies, lithofacies and core photographs on the basis of GR log shapes and trends analysis in the Bakhrabad sequence-1 of the well BK-10



condition. The upward decreased in bed thickness and sand/shale ratio indicated retrogradation processes. This facies associated with sediment fallout to low flow regime, possibly in retrograding channel setting deposition. The bioturbation facies indicated a low stressed marine and slow current depositional environment allow to prograding as well as aggrading channel sub-environment setting. The sediment structures such as wave ripple cross lamination suggests a low channel influenced settings. The wavy bedded sand/silt with mud facies indicated low energy environment. The grey to dark color shown high organic

matter. The inter-distributary channel started with erosive base cross-bedded sandstone, followed by wavy laminated sandstone overlain by shale. Coal fragment and detritus woody materials indicated fluvial marine origin, which were identified in this sequences. The overall fining upward sequences reflected decrease in energy flow condition. The neritic type of trace fossils indicated the offshore marine facies. It can be inferred that this facies only reflected low depositional calm energy condition and particular in shallow marine environment. Identical electrofacies model was correlated to the core lithofacies within the Bakhrabad

sequence-1 from the well Bakhrabad-10 to show facies associations (Fig. 9b). Lithofacies model associations suggested that frequent cyclic marine regression and transgression of deposition inferred to be affected architecture of reservoir facies within this sequence.

Interpretation and discussions

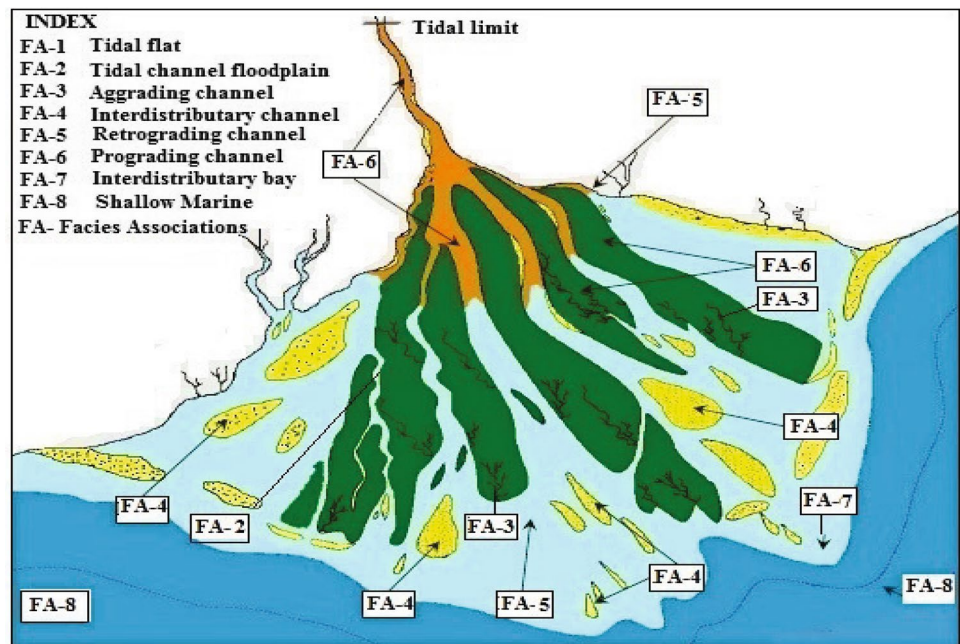
The paleoenvironment of deposition of the Miocene sediments were carried out based on the well log and limited core data. Miocene Surma succession consists of alternating shale, sandstone and sandy shale, indicative of repetitive deposition from delta, delta front and paralic facies with partially marine facies (Holtrop and Keizer 1970; Mannan 2002). Uddin and Lundberg (1999) observed that sand thickness and percentages of Miocene deltaic sediments are consistently higher in the eastern part of the Sylhet Trough than other parts of Bengal Basin. On the basis of electrofacies, lithofacies, sequences, cycles and associations of sedimentary succession, 9 para-sequence sets and 35 Parasequences were identified in the well BK-10. All the cycles are either fining or coarsening upward sequences based on cylindrical, bell, funnel, linear and egg/bow shape electrofacies models.

The Bakhrabad sequence-2 comprises of 3 para-sequence sets. The lower para sequence sets-1 contains depth interval of 3440–2684 m having 90, 160, 95, 105, 45, 30, 65, 36, 64 and 54 m thickness (Fig. 6a). Thickness of the lower para-sequence set-1 varied from bottom to top portion. The maximum thickness was observed in para-sequences sets-2 was about 160 m thick of which sand/shale ratio was about 35:65 (3190–3350 m) whereas minimum thickness was perceived in para-sequences set-6 is about 30 m (2905–2935 m). Identified electrofacies was the egg/bow, serrated egg, linear, bell, serrated bell and serrated funnel shape in nature. The middle para-sequence set-2 contains depth of 2555 to 2684 m having 129 m thickness demonstrate one fining and one coarsening upward para sequences. Upper para-sequence set-3 at depth interval of 2380 to 2555 m having 175 m thick reflects one fining upward para sequence and one linear para sequence. The sand/shale ratio of the Bakhrabad sequence-2 was about 55:45. Overall trends of the Bakhrabad sequence-2 exhibited fining upward cycles on the basis of GR log responses. At least three phases of retrograding distributary channel and two phases of prograding channel floodplain with aggrading channel floodplain and tidal channel, sub-tidal mudflat and inter-distributary channel were identified in the Bakhrabad sequence-2 by using electrofacies model associations (Fig. 6a). The associations of these facies are commonly identified in the cores (5–8) of the Bakhrabad sequence-2 were thought to be diagnostic of tidal influenced

environments (Fig. 8). This is consistent with the study of Sitakunda anticline of eastern Bengal Basin and northeastern Sylhet Trough of the Bengal Basin (Alam 1995a; Rahman et al. 2009). Islam (2012) revealed that Neogene reservoir succession of Bengal Basin was contributed by a large fluvial system with strong evidence of tide dominated depositional processes. Herringbone cross-bedding is common in tidal flat sub-environments (Singh and Singh 1995). The parallel laminated sandstone facies is believed to be formed under upper flow regime condition in shallow tidal channel, or develop as deposits of high velocity highly turbulent flows (Terwindt 1971). The correlation of cores lithofacies with the different the electrofacies within this sequences depicted tidal channel complex, prograding aggrading channel and inter-distributary bay sub-environment of deposition (Fig. 9a). This finding is in good agreement with study of well Bakhrabad-09 of Bengal Basin (Islam et al. 2014). From the conceptual depositional models for Miocene succession suggested shale dominated facies thought to be deposited in the prodelta setting while sandstones heterolithic and cross bedded facies inferred to be deposited within tidal channels floodplain complex sub-environments (Fig. 10). The Bakhrabad sequences-2 was characterized by the lower deltaic plain typically overlies delta front and prodelta deposits. The Bakhrabad sequence-2 presumed to be deposited under prodelta to delta-front condition within lower delta plain by the influences of sea level changes and low rate of sedimentations.

The Bakhrabad sequence-1 consists of 6 para-sequence sets having at least five coarsening, four fining and 1 coarsening-fining upward para sequences were identified within the well BK-10 (Fig. 6b). The para-sequence set-1 sequence with depth interval of 2020–2389 m having 269 m thick contain two fining upward, three coarsening upward para sequences. The para-sequence set-2 of depth ranges of 1675–2020 m having 345 m thick reflects one coarsening-fining upward para sequences, two linear and two cylindrical sequences. The para-sequence set-3 of depth ranges of 1193–1675 m having 382 m thick consists of two fining upward, two coarsening upward and one linear para sequences. The para-sequence set-4 with depth ranges of 1112–1193 m having 79 m thick while the para-sequence set-5 of 975 to 1112 m depth with 137 m thickness. The upper most para-sequence set-6 of the depth interval of 900–975 m having 75 m thickness. The overall, sand/shale ratio was about 45: 55. Thickness of sand/shale ratio indicated that thickness was gradually increasing in upper part than lower part of this Bakhrabad sequence-1. As a whole, GR log responses suggested coarsening upward cycles within the Bakhrabad sequences-1. At least four phases of aggrading channel and three phases of prograding distributary channel with retrograding distributary channel and tidal mudflat, tidal sandflat, inter-distributary

Fig. 10 Schematic conceptual depositional models in the study area (after modified from Pongpandin 2013)



bay/delta fringe to shallow marine regimes were identified in the Bakhrabad sequence-1 using electrofacies associations (Fig. 6b). In fact, all the para sequence sets and para sequences were characterized by lower phase of deltaic retrogressive, middle phase of deltaic progradation and upper phase of marine transgression. Ripple laminated sandstones with flaser bedded facies were probably deposited in retrograding distributary channel sub-environment setting whereas laminated shale facies has been assumed to deposited under shallow marine regime (Fig. 9b). Typical electrofacies associations were correlated to the cores lithofacies within this sequence advocated that retrograding distributary channel, inter-distributary channel and shallow marine environment of deposition (Fig. 8). The Bakhrabad sequence-1 assumed to be deposited under two phases of deltaic condition; one deltaic progradation phase and another deltaic retrogradation phase. This observation is in agreement with the results of Habib and Islam (2014) for the well Rashidpur-04 of Surma Basin, Bangladesh using log facies interpretation. Depositional environments were between the sub-tidal to intertidal estuarine setup in the lower part of the Boka Bil formation within Miocene Surma Group (Hossain et al. 2008). Haque et al. (2010) pointed out that the area was deposited under aggrading as well as progradational channel environment. The deltaic retrogradation rate was higher within the Bakhrabad sequence-1 than Bakhrabad sequence-2 confirmed by seismic interpretation of the well BK-10 of the Bengal Basin (BOGMC 1991). Sultana and Alam (2000) deduced that Miocene Surma succession ranging environments from shallow marine to tide-dominated coastal setting within

a cyclic transgression-regression regime. Bioturbation is not intense in the Miocene Surma Group sequences, indicating rapid deposition of the sediments (Reineck 1967; Singh and Singh 1995). The average sedimentation rate of the Miocene Surma Group and therefore the rate of delta subsidence are thus 1.2 km/my (Worm et al. 1998) which may be one of the largest sedimentation rates ever sustained for millions of years. According to the earlier literature, it seems that shale-dominated facies can be deposited between the tide dominated distributary channels within the prodelta area of the deltaic setting. This study is also consistent with the previous observation by Rahman et al. (2009), where shale dominating facies occurred within tidal influenced inter-distributary channel in the subsurface Neogene Surma succession of the Bengal Basin, Bangladesh. Thus, the enormous sediment influx, huge sedimentation rate, repeated prograding cycles depicted as tidal influences as well as characteristic sedimentary structures of the Miocene Surma successions probably indicating these sediment input could be supplied by a fluvial delta system, might be filled in well BK-10 of Bengal Basin. This finding is consistent with preservation of thick orogenic successions (Rao 1983) in Assam, northeast India.

The heterolith sandstone facies displays a weaker currents in the floodplain channel environment of deposition. The overlying shale dominating facies matches to vertical accretion through interruption in the protected regions away from the active floodplain area in fluvio-deltaic setting (Casshyap and Tewari 1984). The floodplain, along with prograding and retrograding environmental condition, which promoted the deposition of hydrocarbon

reservoir rock, though inter-distributary bay deposited clastic sediments in floodplain environment, resulting fine to medium grained sandstone/siltstone within shale dominated sequences. This finding agreed with the observation made by Islam (2012) from the study of depositional environment of Neogene reservoir succession of Bengal Basin, Bangladesh. Furthermore, various lithofacies models display a fining upward sequences, which have been deposited horizontally in alike fashion follow by Walther's Law. The whole lithofacies model succession, hence, can be recognized to a fluvio-deltaic depositional modeling (Fig. 10).

Cyclic sequences are found in everywhere within fluvial channel and distribute it over a wide range of time scales in Bhuban and Bokabil Formation of Bengal Basin. It demonstrates that the fluvio-deltaic paleoenvironment is characterized by similar processes that tend to reproduce the similar depositional consequences frequently (Catuneanu and Galloway 2011). These are characterized by an early stage of relatively high fluvial energy flow which may be noted as an erosional surface. These surfaces are followed by progressively fine-grained sediments deposition, related with the reservoir facies architecture that decrease in time scale period (Sen et al. 2016).

However, Islam et al. (2014b) was estimated shale volume from GR log index in the five gas bearing zones of Norshingdi gas field, Bangladesh. The results showed an average range of 12 to 25% of shale existed in the hydrocarbon bearing zones, indicating an evidence of sand development. Previous finding is in agreement with the present finding, where shaley dominated sandstone facies found in the well BK-10. From the analysis of subsurface lithofacies and electrofacies models associations of the Miocene succession in the studied well BK-10 represented that both sequences (BKS-1 and BKS-2) thought to be deposited in prodelta to delta-front condition and fluvio-deltaic setting to shallow marine environment in response to cyclic marine regression and transgression, basin subsidence and increase of sedimentation of different sub-environments of depositional models. The study suggested that various cyclic regressive and transgressive phase of deposition might be affected on the architecture of reservoir facies model in the well BK-10 of the Bengal Basin.

Conclusions

Electrofacies and lithofacies modeling approaches are applied to interpret paleoenvironment of deposition in the well BK-10 using integrated wireline well log and drilled core samples data, suggests a fluvio-deltaic to shallow

marine depositional model for Miocene succession of Bengal Basin, which mainly characterized by coarsening upward sequences from fluvial channel. The following conclusions can be drawn from the above study:

1. Detailed investigation of well log data from the studied well BK-10, based on gamma ray (GR) log shapes, size, lithologic variation permit recognition of five major electrofacies models, e.g., bell, funnel, cylindrical, egg/bow and linear shapes. Several electrofacies associations namely, small scale finning upward and coarsening upward sequences were identified within Miocene succession.
2. The facies and lithofacies models associations of the core samples from the studied well Bakhrabad-10 revealed that eight lithofacies grouped into eight distinct lithofacies associations based on color, composition, texture and sedimentary structures, e.g., shale dominated facies, heterolithic sandstone facies, cross bedding facies, parallel laminated shale with alternate sand/silt facies, ripple lamination facies, bioturbation facies, wavy bedded facies and laminated shale facies. Distinctive sedimentary structures suggested that heterolithic sandstone and cross bedding represented fluvial depositional environments while flaser, wavy bedding, bioturbation and ripples lamination showed tidal dominance sedimentation within the depositional environments.
3. The conceptual depositional model for the Miocene successions encountered in the well BK-10 indicated that Bakhrabad sequence-2 deduced to be deposited under prodelta to delta-front condition in prograding and retrograding deltaic setting in response to basin subsidence and high rate of sedimentation whereas Bakhrabad sequence-1 presumed to be deposited under fluvial setting to shallow marine environments.
4. The rhythmites nature of Miocene Surma succession supposed to be characterized by cyclic transgressive and regressive sedimentary processes might have impact on the architecture of reservoir facies models.
5. Further investigation is required for depositional cyclicity and patterns within the Miocene succession, both from surface and subsurface, in the study area, along with well to well correlations for stratigraphic prediction of the reservoir facies model.

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