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Article

Reservoir Heterogeneity in the Fluvio-Deltaic Deposits: A Case Study from the Surma Group Succession Exposed in the North-Eastern Surma Basin, Bangladesh

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Abstract: Well-exposed fluvio-deltaic Surma Group successions of the northeastern Surma Basin provide a direct analogue to its equivalent subsurface successions—the main hydrocarbon reservoirs in Bangladesh. The various levels of lateral and vertical heterogeneities lead to changes in the subsurface sandbody distributions and their reservoir qualities across fields. The present study aims to identify the heterogeneities in the fluvio-deltaic Surma Group successions by detailed sedimentological analysis of the Mio-Pliocene-aged Surma Group successions. Eleven lithofacies have been identified and based on the recurring pattern of these facies within the Surma Group, five facies associations have been identified. The facies associations indicate that these deposits originated from diverse depositional settings, ranging from the prodelta to the alluvial to delta plain. As a whole, they represent a progressive shallowing upward succession with two transgressive events in the upper and lower parts of the Surma Group. Five levels of heterogeneities such as prodelta mud (HL-I), tidal heterolithic deposits (HL-II & III), interbedded mud units in delta front (HL-IV), and intercalated mud laminae, drapes (HL-V) have been identified in the fluvio-deltaic Surma Group. The study suggests that the various levels of reservoir heterogeneities are controlled by the occurrence and distribution of various facies associations.

Keywords: facies analysis; fluvio-deltaic deposits**;** heterogeneity; hydrocarbon reservoir; Surma Group

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1. Introduction

Worldwide, fluvio-deltaic sandstones are significant petroleum reservoirs [1–6]. Although the reservoirs host a significant amount of hydrocarbon, heterogeneity is a major challenge [7]. Heterogeneity occurs at different scales ranging from megascopic to microscopic [7–9] that pose different uncertainties in the reservoir parameters such as its porosity, permeability, lateral and vertical continuity, architecture, etc. [1–6]. According to Jordan & Pryor [8], heterogeneity can occur at six different hierarchical scales designated as levels 1–6 where the uppermost level in the hierarchy is "Heterogeneity level 1" composed of stacked channel sandbodies and clay plugs above abandoned channels and the lowermost level is "Heterogeneity level 6" comprises sand laminae with alternating thin mud-silt laminae.

As the heterogeneity occurs in the formation at different scales, therefore, it cannot be studied through a single method due to the presence of limitations in the resolution of different data sets such as well log or seismic. Well data provide high vertical resolution but sparse lateral information, whereas seismic data provide large aerial coverage but lack vertical resolution [10,11]. Generally, outcrop data are used as an additional source to overcome these shortcomings [12–14]. Outcrop analogs play an important role in understanding the various levels of reservoir heterogeneity in the subsurface reservoirs and have been used routinely in the petroleum industries [9]. The main objective of using an outcrop analogue is to understand the detailed architecture and the internal heterogeneity of a sand-body reservoir [10].

The Bengal Basin is the world's largest fluvio-deltaic basin with a huge sedimentary thickness of about 20 km [15]. In the stratigraphic succession of the Bengal Basin, the Miocene-aged Surma Group successions comprise a major portion that is about 5 km thick [16–18]. The Surma Group is divided into two formations namely the Bhuban and Boka Bil formations which act as main hydrocarbon reservoirs [17]. As it is a fluvio-deltaic basin, therefore, like all other fluvio-deltaic basins, it has all the uncertainties related to heterogeneity, and these uncertainties such as complex reservoir geometry, variations in internal architecture over a short distance with rapid lateral and vertical changes in lithology, facies, and petrophysical properties: porosity and permeability which pose a challenge for hydrocarbon exploration and production in the petroleum industries frequently [19,20]. Exploration activities in the basin often encounter challenges and there are some examples of unsuccessful petroleum exploration and production history in the country due to a lack of clear understanding of the reservoir distribution such as Srikail-1, Begumganj-2, and Rashidpur-6 wells.

Heterogeneity poses challenges in flow zone identification and prediction of hydrocarbon saturation in reservoirs [20–25]. Pore characteristics reflect the distribution of hydraulic flow units within the reservoir that control reservoir performance and flow dynamics of hydrocarbon [26,27] and these pore characteristics including geometry, distribution, connectivity, and structure are affected by reservoir heterogeneity [26,28,29]. It is reported in the South Caspian Basin that heterogeneity controls sandbody connectivity and flow path tortuosity in connected sandbodies, i.e., heterogeneity controls the oil-gas recovery, and sweep efficiency [2]. Heterogeneity also controls the vertical segregation of hydrocarbon and the vertical-to-horizontal permeability ratio [2]. In Niger Delta Basin, heterogeneity poses challenges in accurate reservoir modeling and hydrocarbon reserve estimation [71]. Hence, a better understanding of the various levels of reservoir heterogeneity is crucial to evaluate the reservoirs more precisely and to maximize the hydrocarbon production from them [7]. Several workers studied the tectonic evolution, basin-fill sedimentology, diagenesis, and hydrocarbon prospects in the Bengal Basin [16,30–37]. No work has been done yet to assess the various levels of reservoir heterogeneity of the fluvio-deltaic successions in the basin. The research aims to study the exposed reservoir analogues to improve understanding of the subsurface reservoir heterogeneity of the Surma Group successions in Bangladesh to avoid unexpected errors in petroleum exploration, reservoir modelling, performance prediction, and hydrocarbon reserve estimation and recovery.

2. Study Area

As most of the gas fields of Bangladesh are located in the Surma Basin, therefore, the basin is selected as the study area. The field investigation was carried out along the selected well-exposed road- and stream-cut sections in Jaintapur, located in the Surma Basin, where the whole Tertiary Succession of the Bengal Basin is exposed (Figure 1). The studied sections are the Tetulghat Section, the East and West Bank sections of the Shari River, and the Naya Gang Section (Figure 1). Jaintapur is an upazila in the Sylhet district of Bangladesh. It is located about 45km northeast of Sylhet town near the Bangladesh-India International Border at the foot of the Jaintia Hill of Meghalaya. Its geographical position is between 25°05' N to 25°11' N latitudes and 92°00' E to 92°14' E longitudes.

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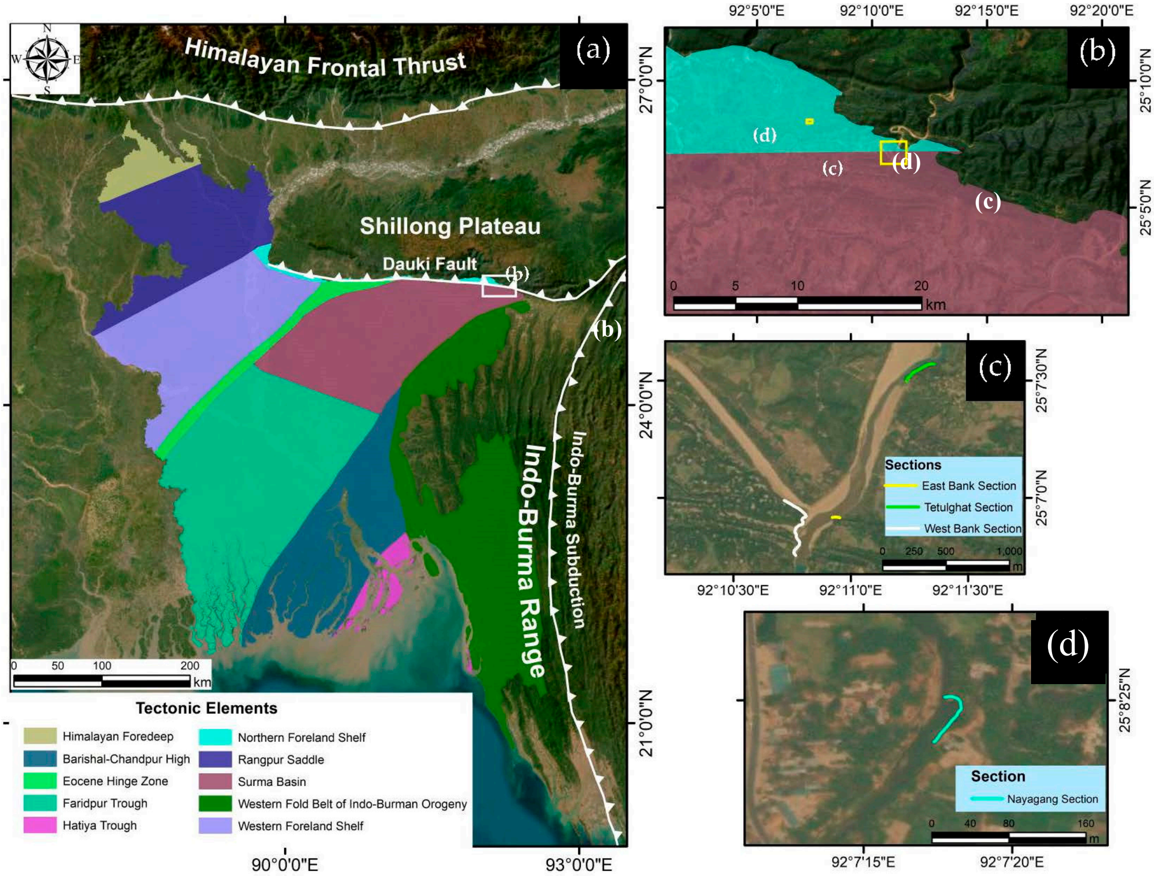

Figure 1. **(a)** Map represents the tectonic settings, different tectonic features, and elements of Bangladesh and surrounding regions with the location of the study area (white rectangular box); **(b)** zoomed-in view of the part of the Surma Basin focusing the study area, rectangles in the map represent the location of studied sections; **(c)** map shows the locations of different stream-cut sections along the Shari River including East Bank, West Bank, and Tetulghat sections; **(d)** map shows the location of Nayagang Section.

3. Regional Geology

3.1. Tectonic Settings

Bengal Basin is a foreland basin, evolved from a remnant ocean basin, that developed at the junction of the Indian Plate and the Burma Plate during the Cretaceous to Holocene time [38,39]. The basin started to develop about 127 Ma ago during the Early Cretaceous by rifting of the Indian Plate from Antarctica. About 90 Ma ago, the Indian plate started to move northward and collided with the Eurasian plate between ca. 55 and 40 Ma [34,39,40]. With time the Indian plate subducted beneath the Burma plate along the Indo-Burman Subduction Zone on the eastern boundary of the basin. The Bengal Basin has gone through a complex evolution process and transformed from a remnant ocean basin to a foreland basin on the margins of the Indo-Burman ranges and the Himalayas [34,39,40]. The basin can be subdivided into two major parts: stable platform and deep basin, separated by a paleocontinental slope or hinge zone. The deep basin part comprises different tectonic elements, where the Surma Basin is one of those elements (Figure 1). It is a sub-basin located in the northeastern part of the Bengal Basin. Its boundary is delineated by the Shillong Plateau on the north, by the Chittagong-Tripura Fold Belt on the east, by the Stable Shelf on the west, and by the Madhupur-Tripura Threshold on the south [30]. The Sylhet Basin is underthrusting the Shillong Plateau along the Dauki Fault on the north [32–36] (Figure 1).

3.2. Stratigraphy

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The stratigraphy of the Bengal Basin can be divided into two subdivisions one for the stable part and another for the deep basin area. The deep basin part comprises mainly Tertiary to Recent succession and the stable part consists of succession ranging from Precambrian Basement complex to recent deposits [17]. The generalized stratigraphic succession of the deep basin part of Bangladesh is given in Table 1 based on Reimann and Hiller [18], Holtrop and Keiser [16], and Imam [17]. The deep basin consists of more than 20km thick sedimentary succession ranging from the Oligocene to Pleistocene age. In the Surma Basin, the stratigraphic succession begins with the Jaintia Group of Paleocene–Eocene time. The Jaintia Group comprises three formations namely Paleocene–Lower Eocene aged 170–360m thick Tura Sandstone Formation, Middle Eocene aged 250m thick Sylhet Limestone Formation, and Upper Eocene aged 40–90m thick Kopili Shale Formation [15,31]. The Jaintia Group is overlain by the Barail Group of Oligocene age which is 800m to 1600m thick [31,34,46]. The Surma Group in the Surma Basin is unconformably overlies the Barail Group and underlain by the Tipam Sandstone Formation of the Tipam Group [31,34]. The thickness of the Surma Group in the basin ranges from 2700m in the Atgram 1X well to more than 3900m in the Fenchuganj 2 well [c. 60km south of Atgram 1X well; 15]. The Surma Group comprises two formations namely, the lower, Bhuban Formation and the upper, Boka Bil Formation (Table 1). The overlying Tipam Group of about 3500m thickness comprises two formations including the Middle Pliocene-aged Tipam Sandstone Formation and Girujan Clay Formation [15,31,34]. Among the Tertiary stratigraphic units, the Miocene Surma Group deserves special attention because of its hydrocarbon reserve in the Bengal Basin [17].

The Bhuban Formation can be divided into the Upper, Middle, and Lower parts where the Upper and Lower Bhuban are sandier than the Middle Bhuban which is more shally [18]. This formation unconformably overlies the Renji Formation of the Barail Group and is conformably underlain by the Boka Bil Formation with a transitional contact [18]. The Bhuban Formation mainly consists of repetitive sandstones and well-laminated silty shales and siltstones [18]. The sandstones are fine to very fine-grained, bedded to massive-bedded in nature, the siltstones are mostly calcareous, hard, and compact, and the shales are fissile [18]. The formation shows gradational contact with the overlying Boka Bil Formation and the thickness of the formation decreases toward the northeastern margin of the Surma Basin [18].

The Boka Bil Formation is unconformably overlain by the Tipam Formation in the marginal part but conformably in the deeper part and is unconformably overlain by the Dupi Tila Formation in the Atgram Anticlinal area [18]. The formation is more argillaceous in its upper and lower parts and arenaceous in its middle part [18,47]. It consists of shales, sandstones, siltstones, and little conglomerates. The top of the unit is made up of a predominantly shaly sequence, which was designated as the Upper Marine shale equivalent unit [16].

Table 1. Stratigraphic succession of the deep basin part of Bangladesh [16–18].

Age	Group	Formation	Thickness (meter)	Rock Types
Pleistocene		Madhupur Clay	30	Reddish clay
Plio-Pleistocene	Tipam	Dupitila	2500	Predominantly sandstone with shale and clay beds.
		Girujan Clay	1000	Mainly Shales
Pliocene		Tipam Sandstone	2500	Predominantly sandstone with minor shale and clay beds.

Mio-Pliocene	Surma	Upper Marine Shale Boka Bil	1500	Alternating dark-grey shale, sandy shale, and sandstone with minor siltstone.
Miocene		Bhuban	3500	Alternating and repetitive sandstone, pebbly sandstone at the top, and sandy shale with minor conglomerate and siltstone at the bottom.
Oligocene	Barail	Renji	700	Predominantly shale with minor shale.
		Jenum	240+	Predominantly shale with minor siltstone and sandstone.
Base not encountered				

4. Materials and Methods

It is an outcrop analogue study where sedimentological data were collected through direct field observations. Sedimentological data comprises lithology(colour, grain size, sorting, and composition), sedimentary structures, contact types, the geometry of rock units, etc. Sedimentological data were collected by recording continuous sedimentary logs in different outcrop sections. These data were analyzed through different methods described in the following sections.

4.1. Facies Analysis

To identify facies in the studied succession facies scheme developed by Miall [40] was used where every single rock unit with a characteristic lithology, sedimentary structure, geometry, and textural properties such as grain size, sorting, etc. that represent a certain depositional condition is considered as a single facies. Facies that show genetic relationships are grouped into a single facies association that represents a particular depositional feature formed in a specific depositional setting. Several facies associations are combined to depict the depositional history and to interpret the depositional environment of the Surma Group successions.

4.2. Heterogeneity Analysis

In analyzing the various levels of heterogeneity, we adopted the approach described by Jordan & Pryor [8] and Keogh et al. [7]. According to Jordan & Pryor [8] and Keogh et al. [7], six levels of heterogeneity encompass all reservoir heterogeneity ranging from megascopic to microscopic (Figure 2). Heterogeneity level 1 comprises the entire system and it is the largest unit. It is hundreds of meters thick, tens of kilometers wide, and tens of kilometers long. It is composed of many sand bodies. Floodplain mud acts as a laterally extensive regional barrier to fluids in the system [8]. Heterogeneity level 2 comprises a single sand body within a system. It is generally separated from other sand bodies within the system by clay plugs. It is tens of meters thick and several kilometers wide [8]. Heterogeneity level 3 comprises the channel bar and crevasse-splay sand bodies where the main barriers are thin sheets and lenses of mud. This level is tens of meters thick, hundreds of meters wide, and several kilometers long [8]. Heterogeneity level 4 includes bundles of sequentially stacked bedding units within a bar. Each bundle is separated from overlying and underlying bundles by thick sheets of mud and silt. This unit may be several meters thick and hundreds of meters wide [8]. Heterogeneity level 5 comprises individual beds within a bundle of stacked bedding units. They are cm to meter-scale thick, several meters wide, and tens of kilometers long. Permeable bedding unit is

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separated by mud or silt layers such as cross-bedded sand units are separated by horizontal and inclined mud or silt layers along the bed-sets boundaries and reactivation surfaces. Low-permeability mud or silt layers impede the vertical and lateral fluid flow. Although their lateral extension is limited they can make the flow path tortuous. Mud layers may be absent in bed boundaries but infiltrated mud and grain size differences make these boundaries flow-barriers [8]. Heterogeneity level 6 comprises individual lamination that constitutes the sand body and is the smallest unit. This horizontal or inclined lamination is a few centimeters thick, a few centimeters to several meters long, and a few centimeters to many meters wide. Laminae are often separated from each other by textural variations and very thin mud laminae. Flow in this level is inter-particle flow [8].

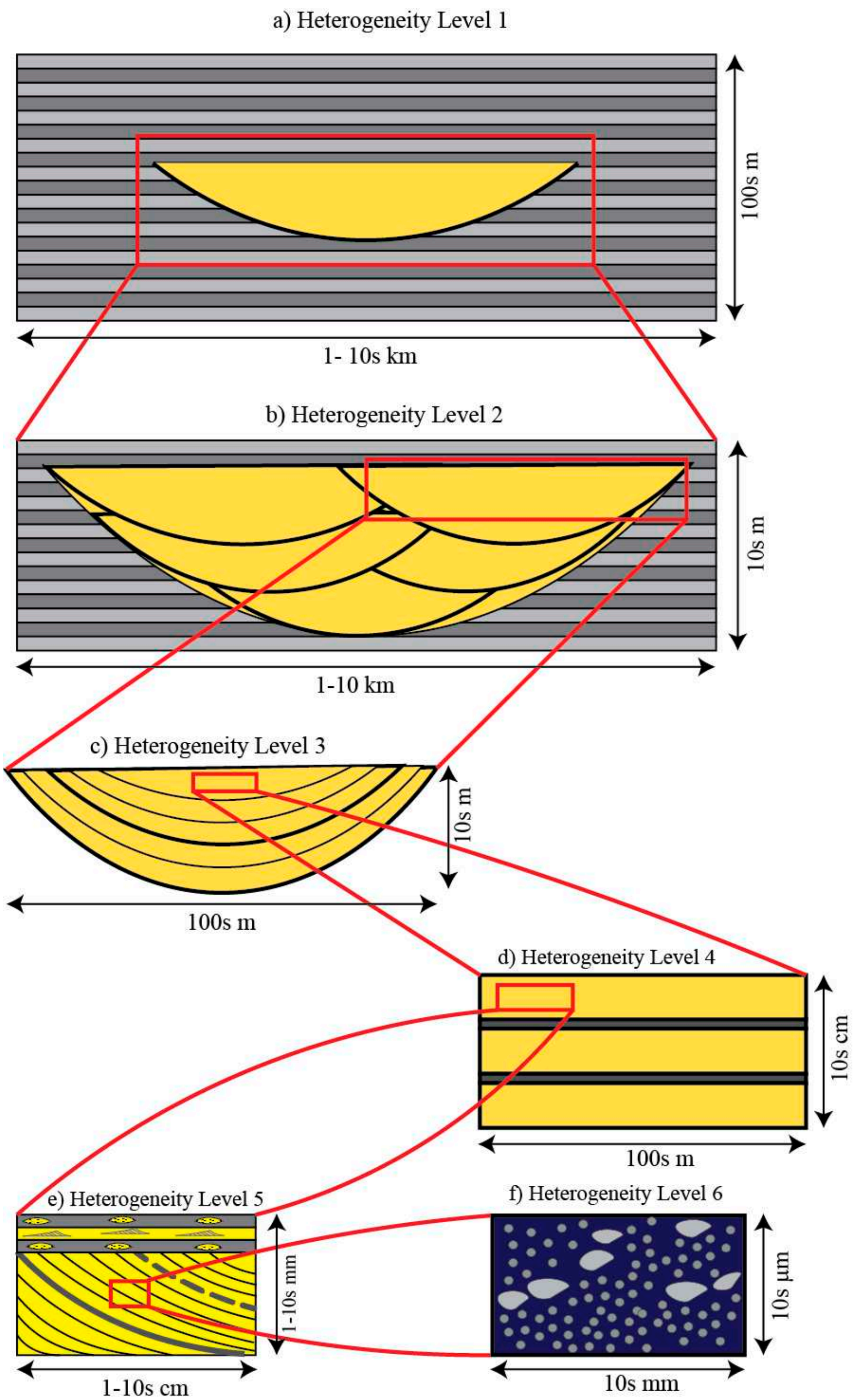

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Figure 2. Schematic view of the different scale and type of sand body heterogeneities [after 7,49–52].

5. Results

In the studied Surma Group succession, eleven (11) facies were identified from different sections based on their lithologic characteristics such as composition, textural properties, sedimentary structures, etc. Individual facies are described below.

5.1. Facies

5.1.1. Mm- Massive Mudstone

The massive mudstone (Mm) facies is composed of light gray to dark gray colour, structureless mudstone. This facies is present in the middle part of the Surma Group in the Tetulghat Section (Figures 3a, 5 and 10). Individual facies is 30cm to 4m thick. The facies is alternated with irregular sand units such as massive sandstone (Sm) and massive graded sandstone (Smg) facies. It is almost devoid of any silt streaks showing its massive nature in the lower part of the studied succession. This massiveness gradually changes into a heterogeneous nature with the presence of silt streaks and lenticels. The facies is thicker in the lower part of the succession but thickness gradually reduces upward in the stratigraphic succession (Figures 5 and 10).

Mud deposits from settling down of finer sediments including clay and silt from suspension in response to the slowdown of flow energy and reduction of sediment supply [53].

5.1.2. Msl- Mud with Silt Laminae

The mud with silt laminae (Msl) facies is comprised of dark gray coloured mud with light gray coloured frequent silt laminae, streaks, and lenticels (Figure 3b). The facies is present in the lower part of the studied succession in the Tetulghat Section and the upper part of the studied succession in the West Bank Section of Shari River (Figures 5, 8 and 10). Individual laminae are 3mm to 9mm thick. This facies is subjected to soft sediment deformations and different structures developed in the facies such as load structures, convolution, etc. (Figure 3l).

Mud deposits from settling down of finer sediments including clay and silt from suspension in response to the slowdown of flow energy and reduction of sediment supply [53]. The occurrence of silt streaks and lenticels within mud indicates periodic fluctuations of terrigenous sediment input and energy conditions [54].

5.1.3. Sm- Massive Sandstone

The massive sandstone (Sm) facies is composed of light gray to yellowish gray color, medium to fine grain, and structureless sandstone. This facies is observed in the middle part of the Surma Group in the Tetulghat Section (Figures 3c, 5, 6 and 10). Individual beds are 30cm to 40cm thick in the lower part and 15–30cm thick in the middle part of the Tetulghat Section and more than 7m thick in the Nayagang Section (Figures 5, 6 and 9). This facies alternates with massive mudstone (Mm) and lenticular mud (Ml) facies throughout the succession. In the cycle of lithologic alternation, this facies is replaced by normally graded sand units, ripple cross-laminated sand units in the younger direction (Figures 4b and 5).

Massive sandstone is generated in the absence of fluid-flow traction transport, because of sediment gravity flow or rapid sedimentation [53]. It is deposited from hyperpycnal flows generated at the river mouth during individual high-discharge flooding and storms [55].

5.1.4. Smg- Massive Graded Sandstone

The massive graded sandstone (Smg) facies is comprised of light gray to yellowish gray coloured, medium to fine-grained sandstone devoid of any internal sedimentary structure except gradation. It shows a normal grading from medium to fine sand. Individual units are 15cm to 40cm thick. This facies is present in the Middle part of the Surma Group in the Tetulghat Section (Figures

5, 6 and 10). These units occur less frequently in the studied succession in the Tetughat Section and (Figures 5, 6 and 10). The facies alternates with other facies present in the succession such as mud units, and are associated with ripple cross-laminated sandstone (Sr), parallel laminated sandstones (Spl), and massive sandstone (Ms) facies along with interbedded mud facies in the Tetulghat Section (Figures 5, 6 and 10).

The facies is generated by the decelerating flow of sediment-bearing waning storm currents on clastic shelves [56]. Sediments are settled down from a suspension of different-sized sediments according to size [53].

5.1.5. Sr- Ripple Cross-laminated Sandstone

The ripple cross-laminated sandstone (Sr) facies is composed of light gray to yellowish gray coloured, fine-grained sandstone. It comprises asymmetric current and wave ripples. Discontinuous mud laminae and drapes are observed along the top of ripples (Figure 3d). Individual units are 15cm to 40cm thick. This facies is found in association with other facies present in the Middle Surma succession in the Tetulghat Section and the Lower Surma succession in the Nayagang Section (Figures 6, 9 and 10). In some units, the facies is associated with parallel laminated sandstones (Spl) with mud caps that indicate the upper part of the Bouma Sequences (Figures 3e and 6).

The facies is produced mainly by the combined action of abundant sediment supply and traction [51,53]. Ripples are preserved where traction transport does not exceed the sediment supply [51,53]. It is a product of a lower flow regime. It can occur where turbidite sedimentation takes place [51].

5.1.6. Spl- Parallel Laminated Sandstone

The parallel laminated sandstone (Spl) facies is comprised of light gray colour, fine grain sandstone with a parallel laminated structure. Individual laminae are 3–5mm thick. This facies is present in the Tetulghat Section along with other facies (Figures 6 and 10). This facies is mostly associated with ripple cross-laminated sandstone (Sr) facies, not occurring alone in the studied succession (Figures 3e and 6). The facies is frequently studied in the Nayagang Section (Figures 3f, 3g, 9 and 5). In the Nayagang Section, flame structures are present in the sand laminae (Figure 3f).

The flatbed phase of the upper flow regime generates the parallel sand lamination where the flow velocity is high and the water depth is shallower [57]. During this condition, ripples and dunes are eroded away and parallel laminations are formed [57]. Sediments are medium to fine-grained in this condition where flame structures may present that indicate rapid sedimentation in high-energy conditions [57].

5.1.7. St- Trough cross-bedded Sandstone

The trough cross-bedded sandstone (St) facies is composed of light gray to yellowish gray coloured, medium to fine-grained, trough cross-bedded sandstone with frequent dark gray coloured mud laminae (both continuous and discontinuous), mud drapes along the forests of trough cross-bedding and mud balls scattered sporadically within sandstone units (Figures 3i and 7). Individual units are 35 cm to 2m thick. The tangential nature of foresets at the base indicates the trough cross-stratification. The facies show a stacking nature. The facies is observed in the upper part of the Surma Group in the West Bank Section (Figures 9 and 10). In the Nayagang Section, the facies is common without any interruption of mud drapes or layers (Figures 3h, 9 and 10).

Trough cross-bedding is produced by the migration of 3D bedforms that can be either small-scale current ripples generating centimeter-scale cross-bedding or dunes (large-scale ripples) generating meter-scale cross-bedding [53].

5.1.8. Sf- Flaser Bedded Sandstone Dominated Heterolithic

The flaser bedded sandstone dominated heterolithic (Sf) facies is composed of light gray to yellowish gray coloured, fine-grained sandstone with bluish gray to dark gray coloured mud flakes along crests and troughs of ripples. It occurs in association with other facies of tidal deposits in the

West Bank Section (Figures 3j, 7 and 10). The thickness of the facies increases upward in the studied succession from 2cm to 10cm. Mud drapes are found along the troughs and crests (as thin flakes occasionally) of the sand ripples that create flaser.

It produces where the supply of sand and mud are available and alternation of periods of current activity and quiescence is present [51]. During the period of current activity, sand deposits as ripples and mud suspends in water [51]. After the end of the current activity, a period of quiescence comes, and suspended mud deposits in the troughs of ripples as floccules [51]. During the next cycle, crests of previous ripples are eroded away and new sets of ripples deposit bury, and preserve the previous ripples with mud streaks [51]. It is common in tidal flats and subtidal environments where the alternation of current activity and quiescence is present [53].

5.1.9. SMw- Wavy bedded sandstone-mudstone heterolithic

The wavy bedded sandstone-mudstone heterolithic (SMw) facies is comprised of yellowish gray to light gray coloured, fine-grained sandstone and bluish gray mudstone of the same proportion. and the equal proportion of alternating sandstone-mudstone composition suggests the facies as wavy wavy-bedded heterolithic. The facies is found in association with other tidal flat facies such as flaser (Sf) and lenticular (Ml) facies in the West Bank Section (Figures 10 and 3j). Individual thicknesses of units are 1cm to 5cm.

It generates along with flaser and lenticular bedding in tidal settings where the simultaneous possibility of deposition and preservation of both sand and mud prevails [43]. It forms where mud fills ripple troughs and thinly covers ripple crests to produce continuous layers [43]. As a result, the alternating ripple sand layers and filled mud layers produce wavy bedding [43].

5.1.10. Ml- Lenticular Bedded Mudstone Dominated Heterolithic

The lenticular bedded mudstone-dominated heterolithic (Ml) facies is comprised of bluish-gray coloured mud with light gray coloured, fine-grained sand lenses, and lenticels (Figure 3j). This facies is observed in the upper part of the Surma Group in the West Bank Section (Figures 7 and 10). It is associated with other facies of tidal deposits including flaser (Sf) and wavy (SMw) facies (Figures 3j and 7). Individual units are 3cm to 7cm thick. Both continuous and discontinuous sand lenses are present in mudstone.

The facies either occurs by the isolation of sand ripples in both vertical and horizontal directions on mud units or by producing incomplete sand ripples on mud units [43]. One cycle is preserved by covering another muddy layer in the next cycle [43]. It is produced where the deposition and preservation of mud are more favorable than that of sand [43]. Therefore, the main environment for this is intertidal [50,51] and subtidal zones [52,53].

5.1.11. Sc- Convolute Sandstone Heterolithic

The convolute sandstone heterolithic (Sc) facies is comprised of sandstone and mudstone where sand is light gray to yellowish gray coloured, very fine to fine-grained and mud is bluish gray coloured and laminated (Figure 3k). This is present in the lower part of the Surma Group in the Nayagang Section (Figures 9 and 10). The thickness of individual units ranges from 25cm to 40cm. Convolutions increase their amplitudes upward and disappear in the top part. Individual laminae in the units can be traced.

There are a number of explanations for the formation of this facies. When hydroplastic sediments are subjected to differential forces convolution may be produced [43]. Differential liquefaction can also produce convolute bedding [43]. It can be also produced from vertical forces due to the overloading of sediments [54,55]. According to Kuenen [56], convolution develops by the deformation of ripples, when current flows over ripples and their crestal part faces vertical suction and the trough faces downward pressure and because of this differential pressure, the hydroplastic sediments become convoluted. Another cause of convolution is the shearing of current when it flows over the sediment layer that is cohesive in nature [57]. A strong current creates strong shear that drags the sediment layer and creates convolution [57].

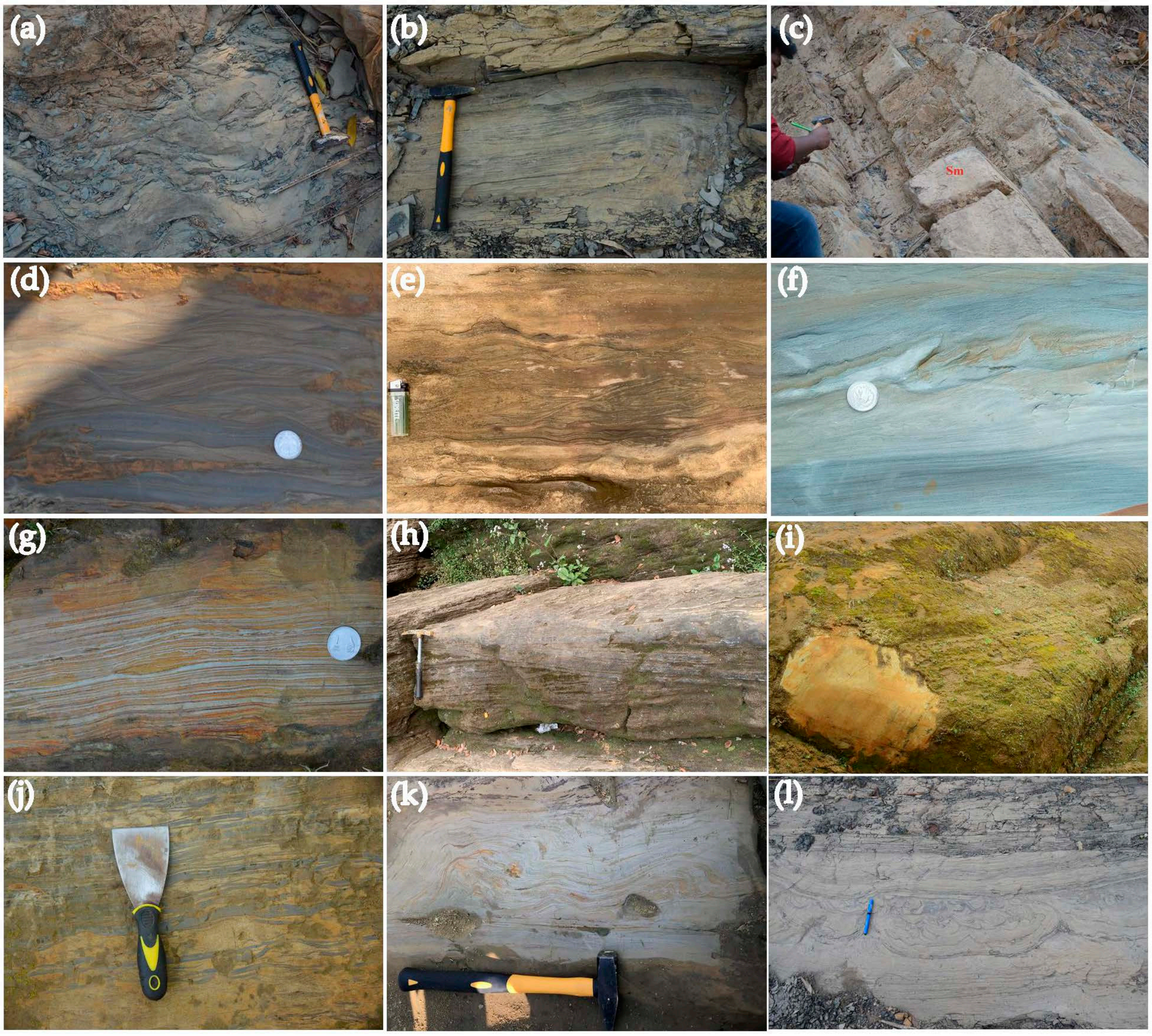

Figure 3. Photographic examples of various facies identified in the studied Surma Group. (a) Massive mudstone (Mm) in Tetulghat Section; (b) mud with silt laminae (Msl) in West Bank Section; (c) massive sandstone (Sm) and massive graded sandstone (Smg) in Tetulghat Section; (d,e) ripple cross-laminated sandstone (Sr) and parallel laminated sandstones (Spl) in Tetulghat Section; (f) parallel laminated sandstones (Spl) with flame structure in Nayagang Section; (g) parallel laminated sandstones (Spl) in Nayagang Section; (h) trough cross-bedded sandstone (St) in Nayagang Section; (i) trough cross-bedded sandstone (St) in West Bank Section; (j) tidal heterolithics comprising flaser-wavy-lenticular facies in West bank Section; (k) convolute sandstone heterolithic (Sc) in Nayagang Section; (l) soft sediment deformation including load structure and convolution in upper part of West Bank Section. .

5.2. Facies Associations

The studied 11 facies were grouped into five facies associations: FA I- prodelta deposits, FA II- lower delta front deposits, FA III- upper delta front deposits; FA IV- tidal channel deposits, and FA V- tidal flat deposits.. The associations are described below.

5.2.1. FA I- Prodelta deposits

FA I is comprised of massive mudstone (Mm), massive sandstone (Sm), massive graded sandstone (Smg), and mud with silt laminae (Msl) (Figures 5, 8 and 10). The mudstone facies

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dominate the FA I, they are dark-grey-cloured and often show bioturbation. Soft-sediment deformations such as load structures and convolution are present in the mudstone (Figure 3l). The deposits are about 60m thick in the Tetulghat Section and about 43m thick in the West Bank Section of the studied Surma Group Succession (Figures 5, 6 and 10).

The dominance of dark grey-coloured mud and the presence of bioturbation and soft-sediment deformation structures indicate the prodeltaic origin of these deposits [51,55]. Mud was deposited from settling out of suspension. The presence of sand units at different intervals indicates a deposition from hyperpycnal flows generated at the river mouth during individual high-discharge floodings and storms [55]. Preservation of sandy facies such as massive sandstone and massive graded sandstone facies indicates the proximity to the river mouth. In the Tetulghat Section, a gradual increase in the frequency of occurrence of silt streaks and laminae towards the top is observed (Figure 10). According to Reineck & Singh [51], the frequent occurrence of parallel and lenticular laminations of silt in the mud indicate proximity to the delta front and massiveness and clay dominance in mud indicate distal prodelta away from the delta front. A gradual change from massive muds to silty muds in the younging direction of the lower part of the Tetulghat Section suggests a gradual change from distal prodelta to proximal prodelta deposits in the Surma Group succession at this point (Figure 10). In the West Bank Section, the deposition of mud with frequent parallel and lenticular silt laminae and the presence of soft sediment deformation suggests proximal prodelta deposits (Figures 3b,l and 10).

5.2.2. FA II- Lower delta front deposits

FA II is comprised of massive sandstone (Sm), massive graded sandstone (Smg), massive mudstone (Mm), ripple cross-laminated sandstone (Sr), and parallel laminated sandstone (Spl) (Figure 7 and Figure 10). The deposits are about 140m thick. Sand units show sheet-like geometry in the deposits.

Alternating patterns among massive sandstone beds, massive graded sand units, ripple cross-laminated sandstone units, and mud units, partial Bouma Sequence consisting of ripple sand and parallel laminated sands, abundance of ripple cross lamination, and sheet geometry of sand bodies characterize the deposits in the Tetulghat Section as delta front deposits formed from rapid deceleration of unidirectional flow at distributary mouth bar environments [51,55]. The thickness of mud layers decreases upward in the younging direction from 13cm to 1cm, which indicates proximal delta front deposits [55]. The frequent presence of interbedded mud layers indicates tidal influence in the delta [55].

5.2.3. FA III- Upper delta front deposits

FA III is comprised of mostly sand-dominated facies although muddy facies are occasionally present (Figure 5). The association is comprised of massive sandstone (Sm), parallel laminated sandstone (Spl), trough cross-bedded sandstone (St), convolute sandstone heterolithic (Sc), ripple cross-laminated sandstone (Sr), and massive mudstone (Mm) facies (Figures 3f–3h,k, 8 and 10). It is found in the lower part of the Surma Group in Nayagang Section and Sand dominance, frequent occurrence of trough cross-bedding, ripple cross lamentation, parallel lamination, and convolution indicate the deposits as shoreface deposits that were deposited on a subtidal platform [51,55] which is an upper delta front deposit. Sandy facies of the association indicate rapid sedimentation through grain flow in a high-energy and high-velocity condition where traction transport was absent in shallow depth. The presence of convolution (Figure 3k) indicates a subtidal sand bar in a tide-influenced setting where hydroplastic sediments were subjected to differential forces and compaction [51]. The muddy portion of the association suggests settling out from suspension during the period of quiescence [51]. The association can be interpreted as a shoreface deposit on a subtidal platform that is a part of the delta front where strong wave activity prevails for a long period [51,53,57,62–67].

5.2.4. FA IV- Tide-influenced fluvial channel deposits

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FA IV is comprised of planar cross-bedded sandstone (Spl), trough cross-bedded sandstone (St), and parallel laminated sandstone (Spl). The cross-bedded sandstones are wedge-shaped and frequently contain mud drapes, mud lamina, and mud balls along the inclined foresets. The upper part of this unit is dominated by tidal heterolithic sequence including flaser-wavy-lenticular facies (Figures 3i, 9 and 10).

Sand units are coarser-grained than adjoining facies, and show a stacking nature and wedge shape geometry that indicates deposition through migration of bars that is supported by the presence of trough cross-bedding [51]. The presence of frequent mud laminae, mud balls, mud drapes in trough cross-bedded sand units, and the presence of tidal flat deposits above these sand deposits, and the thickness of sand bar deposits, ranging from 2m to 5m, strongly suggest that the deposits are a tide-influenced fluvial channel deposits [51,55].

5.2.5. FA V- Tidal flat deposits

FA V is comprised of repeated cycles of tidal heterolithic deposits consisting of flaser-wavy-lenticular facies in the West Bank Section in the Upper Part of the Surma Group (Figures 3j, 9 and 10). It is composed of fine sand and bluish mud. Each tidal cycle ranges from 5cm to 15cm. The association occurs within, in between, above, and below the tidal-influenced channel deposits. The thickness of the association ranges from 12m in between channel deposits to 45m above the channel deposits (Figures 9 and 10).

The cyclic occurrence of tidal heterolithic deposits consisting of flaser, wavy, and lenticular facies suggest the tidal flat origin of these deposits [51,55].

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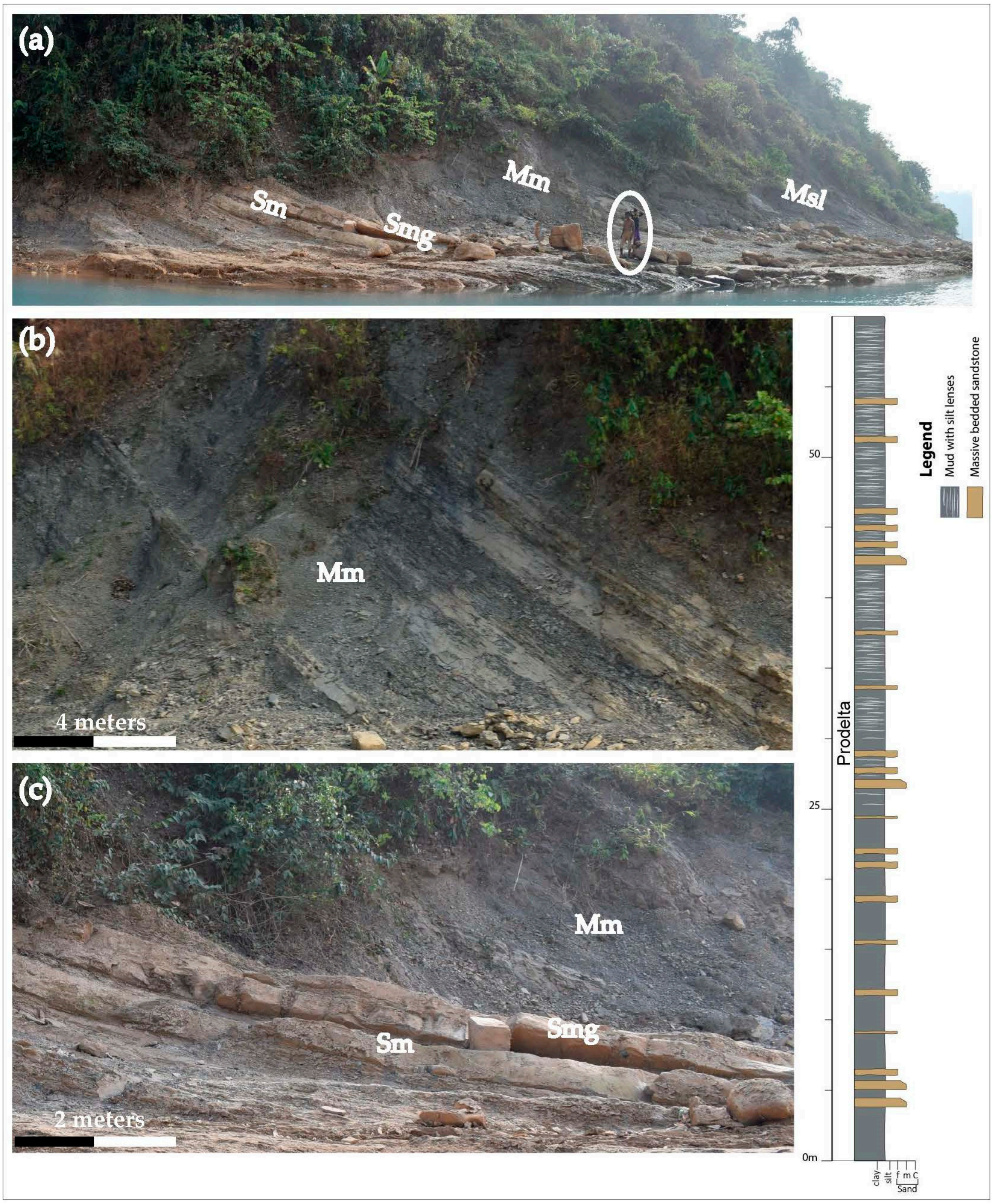

Figure 5. Prodelta deposits (FA I) in the Tetulghat Section. (a) The whole prodelta succession consists of mud and sand units where massive sand (Sm), massive graded sand (Smg), massive mud (Mm), and mud with silt laminae and streaks (Msl); (b) close view of massive prodelta mud (Mm); (c) sand units in prodelta mud such as massive sand units (Sm) and massive graded sand units (Smg). The graphic sedimentary log on the right side of the figure represents the complete prodelta succession of the studied Surma Group exposed in the Tetulghat Section. c. 1.5 meters tall man (white-circled) represents the scale for figure (a).

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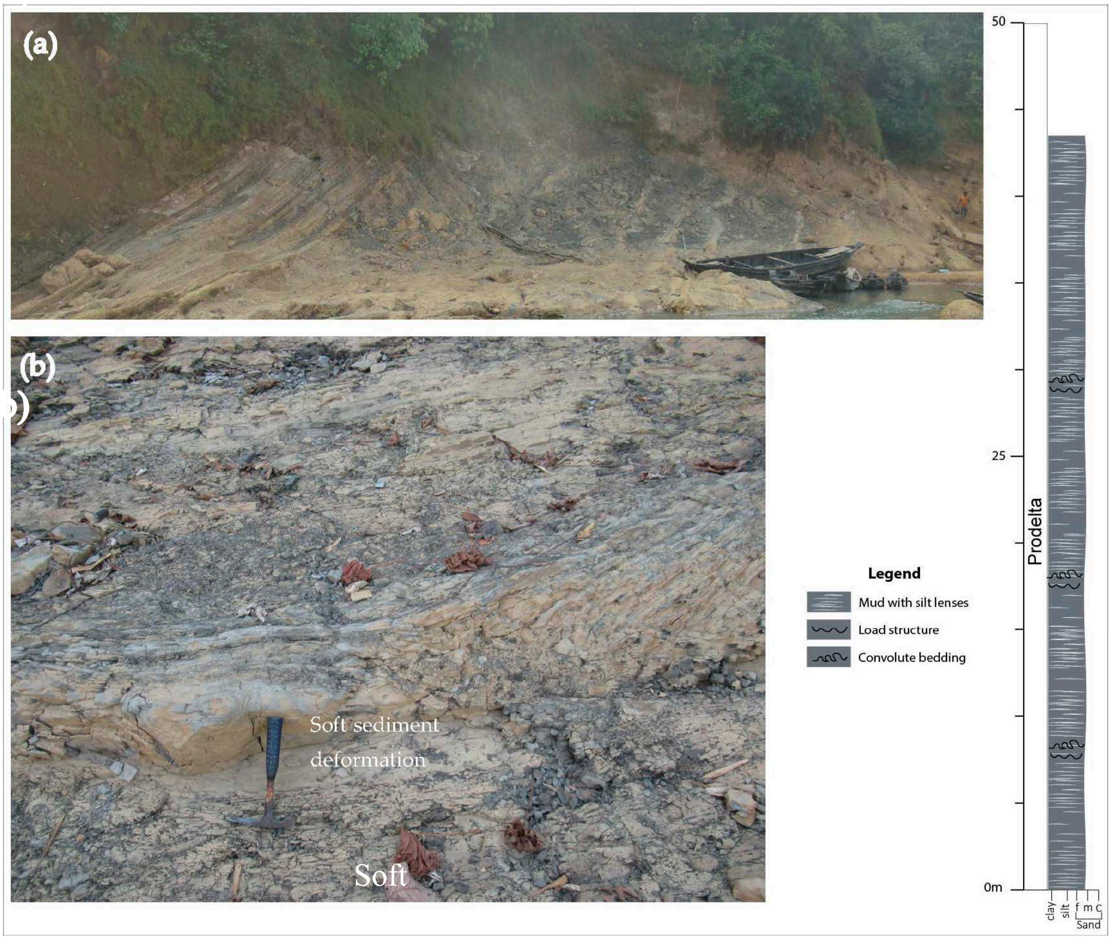

Figure 6. Prodelta deposits (FA I) in West Bank Section. (a) Section view of the prodelta succession of from the upper part of the studied Surma Group; (b) close view of the prodelta deposits mostly mud with silt laminae and streaks with various soft sediment deformations. The graphic sedimentary log on the right side of the figure represents the complete prodelta succession of the studied Surma Group exposed in the West Bank Section. c. A 1.5-meter-tall man (white-circled) represents the scale for the figure (a).

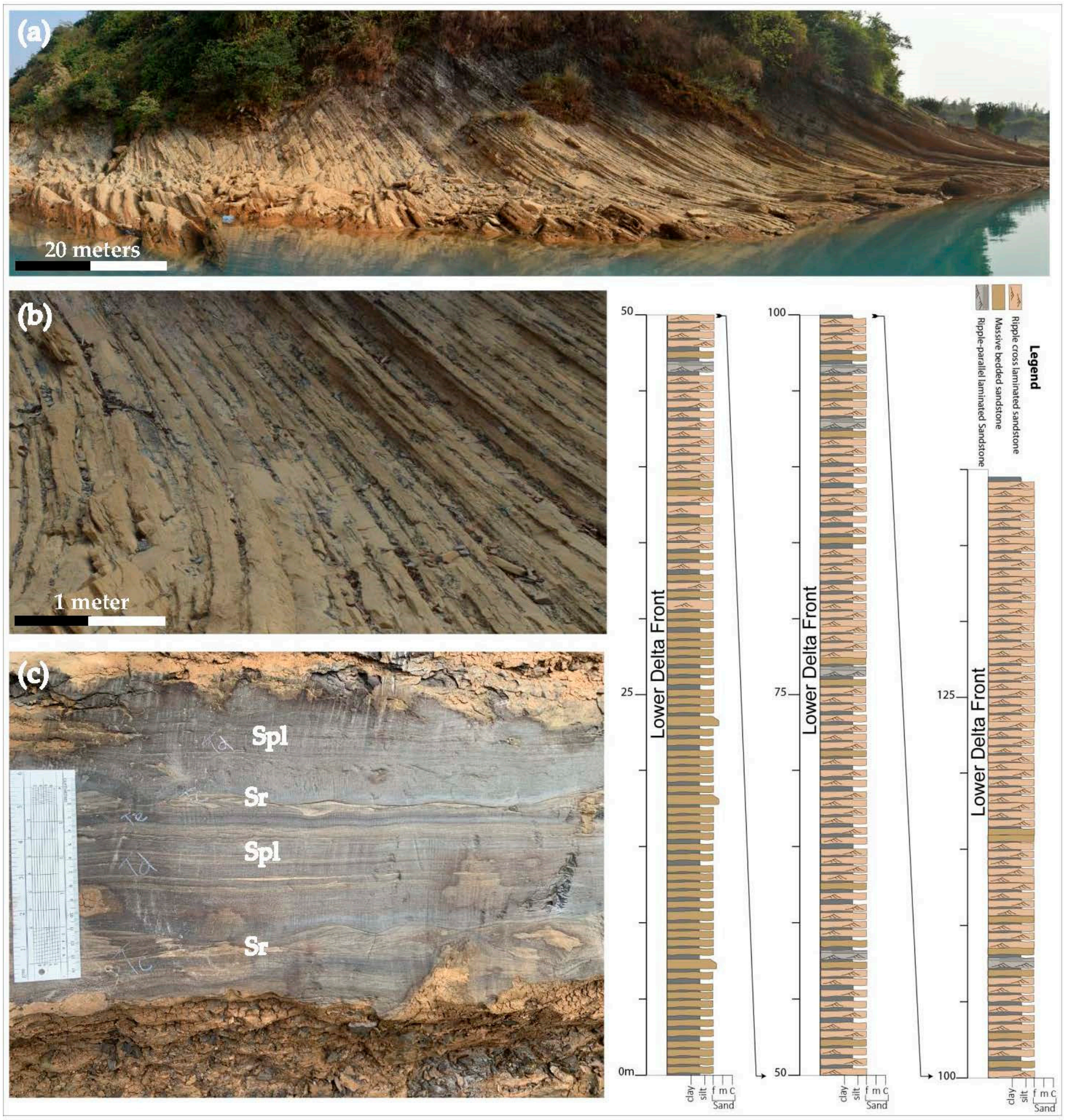

Figure 7. Lower delta front deposits (FA II) in the Tetulghat Section. (a) Whole delta front deposits in Tetulghat Section; (b) close view of delta front succession where dominance of sand and alternating pattern of sand and mud units is shown; (c) partial Bouma Sequence consisting of ripple sand and parallel laminated sand units in the delta front succession in Tetulghat Section. The graphic sedimentary log on the right side of the figure represents the complete lower delta front succession of the studied Surma Group exposed in the Tetulghat Section.

Figure 8. Upper delta front deposits (FA III) succession in Nayagang Section. (a) Section view of the Upper delta front deposits exposed in Nayagang Section; (b) Close view of the deposits where trough cross-bedded and ripple cross-laminated sand units are shown. The graphic sedimentary log on the right side of the figure represents the complete Upper delta front succession of the studied Surma Group exposed in the Nayagang Section. c. The hammer (white-circled) represents the scale for the figure (b).

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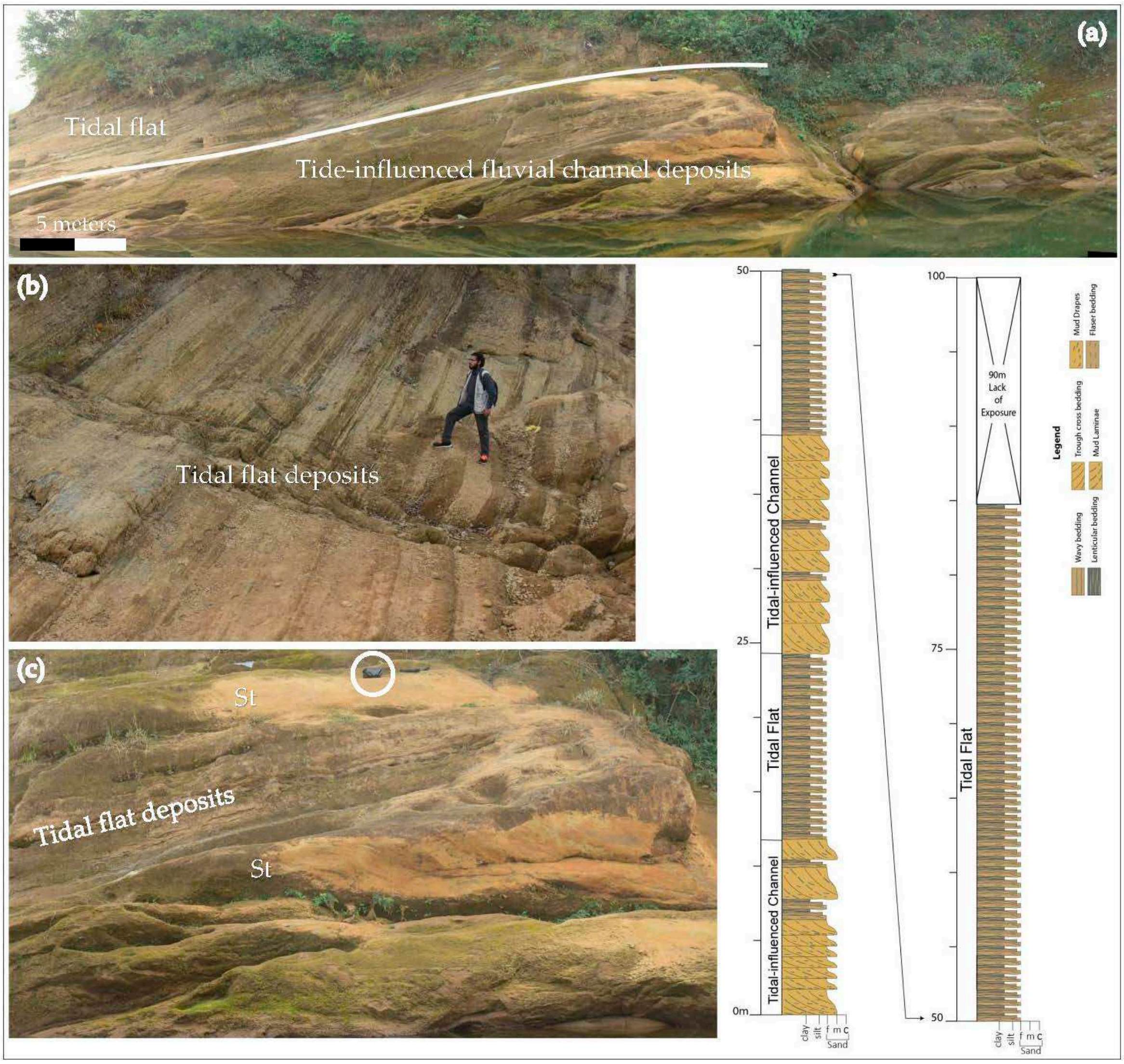

Figure 9. Alluvial to Delta plain succession comprising tide-influenced fluvial channel (FA IV) and tidal flat (FA V) deposits in the West Bank Section. (a) Macro-scale view of delta plain deposits where tide-influenced fluvial channel and tidal flat deposits are shown together separated by white colored line; (b) close view of tidal flat deposits consisting of tidal rhythmites; (c) Close view of tide-influenced fluvial channel deposits observed in the West Bank Section. The graphic sedimentary log on the right side of the figure represents the complete delta plain succession of the studied Surma Group exposed in the West Bank Section. c. A 1.5-meter-tall man represents the scale for Figure (b) and a white-circled 30cm wide bag represents the scale for figure (c).

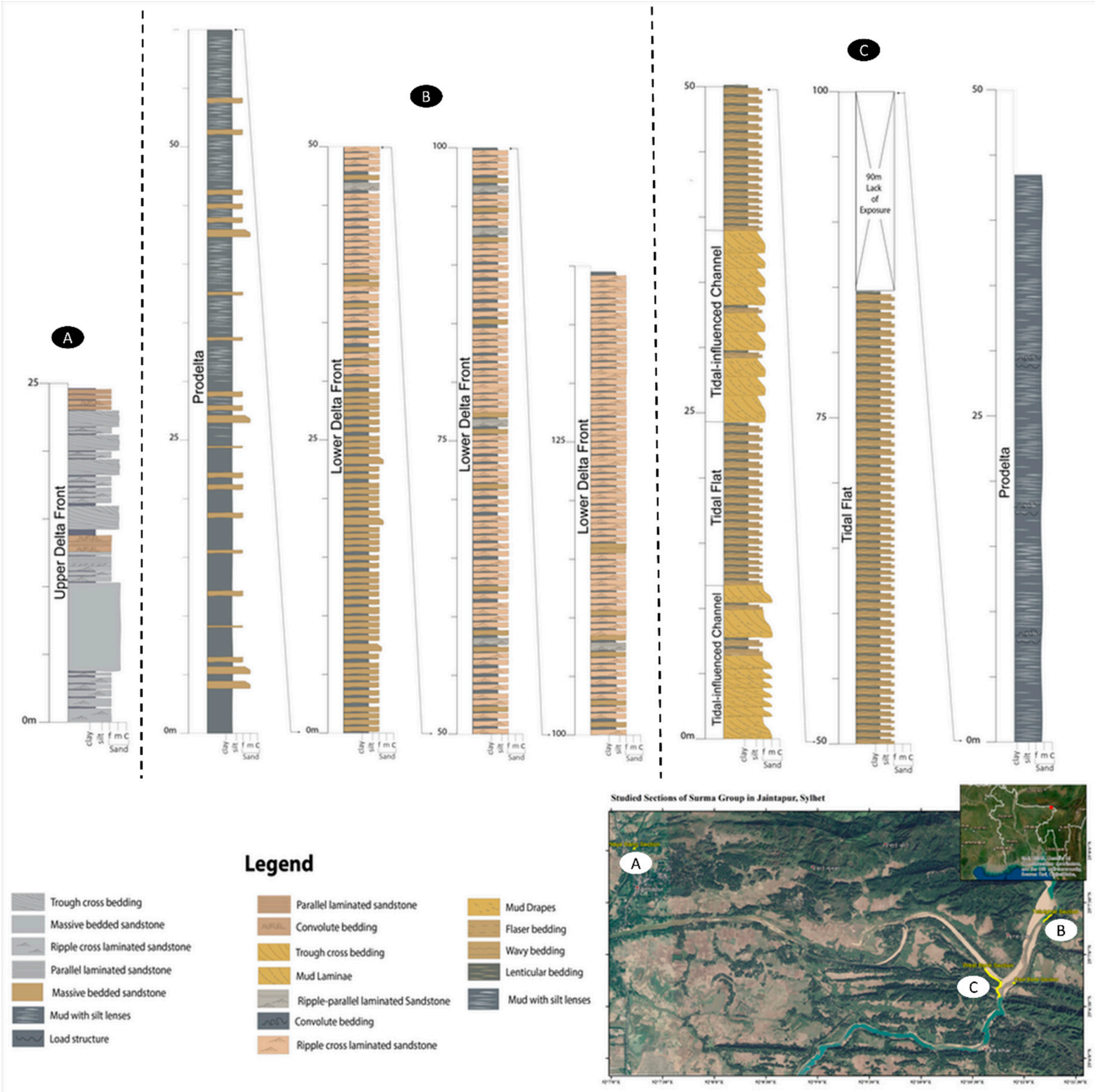

Figure 10. Composite log of the studied Surma Group recorded from different sections. A on the map indicates the location and position of the Nayagang Section, B on the map designates the location of the Tetulghat Section, and C on the map indicates the location and position of the West Bank Section. Logs in the lower portion of the figure represent different facies, facies associations, and their respective depositional settings. Logs are arranged according to their relative position, from the bottom to the top (A–C) within the Surma Group.

5.3. Heterogeneity

Heterogeneity is studied at various scales in the studied Surma Group. Five heterogeneity levels have been identified in the studied succession of the Surma Group. Heterogeneity found in field scale are labeled with a continuous numeric value ranging from large to small scale such as HL-I means heterogeneity level I, the largest heterogeneity level, and in a similar way other heterogeneities are described. Prodelta mud (FA I) can act as HL-I in the studied succession of the Surma Group which is 40–60m thick mud-dominated deposits with little or no sandstone units scattered in the mud (Figure 10). In between adjacent channel bar deposits in the tidal-influenced channel deposits (FA IV), thick tidal heterolith deposits ranging from 5–12m thick act as HL-II that separates bar deposits from each other (Figure 10). In delta plain tidal-influenced fluvial channel deposits (FA IV), HL-III is present within a single bar deposit, where sand beds ranging in thickness from 3m to 6m are

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separated from each other by mud-dominated tidal deposits ranging from 30cm to 1m thick (Figure 10).

Within sand-dominated lower delta front (FA II) and upper delta front deposits (FA III), individual mud units ranging from 5cm to 10cm thick can be considered HL-IV where sandstone units are separated by interbedded mud layers (Figure 10). Within tide-influenced fluvial channel sands units (FA IV), HL-V is present as 2mm to 5mm intercalated thick mud layers are found along foresets of trough cross-bedded sandstone units of channel deposits (Figure 10). Within the tidal deposits of tidal flat (FA V), HL-V is studied, where lenticular mud and mud layers within wavy beds range from 2mm to 1cm thick, create a barrier between adjacent flaser sand units (Figure 10). Due to tidal influence in the delta, frequent occurrence of mud drapes within different associations is common which are several millimeters thick and considered as HL-V (Figure 10).

6. Discussions

The detailed sedimentary facies analysis of Surma Group successions exposed in different sections in the Surma Basin revealed different facies and facies associations that were deposited in various depositional settings. The studied 11 facies were grouped into five facies associations: FA I: prodelta deposits, FA II: lower delta front deposits, FA III: upper delta front deposits, FA IV: alluvial to delta plain tide-influenced fluvial channel deposits, and FA V: subaqueous delta plain tidal flat deposits. Facies analysis results have been used to address i) the sand body architecture and depositional settings of the Surma Group successions and ii) the heterogeneity levels and their impact on reservoir quality. These aspects are described in the following sections.

6.1. Depositional environment and Sandbody architecture

Depositional settings of the Surma Group change from the upper delta front through prodelta, lower delta front, and alluvial to delta plain and again to prodelta representing the cyclic marine transgression and regression (Figure 10). The Surma Group is divided into Lower Surma (Bhuban Formation) and Upper Surma (Boka Bil Formation) in terms of discussion where the Lower Surma is extended from Nayagang Section to Tetulghat Section and the Upper Surma is extended from the Tetulghat Section to the West bank Section. The presence of Laterite beds at the base of the Surma Group studied in the Nayagang Section indicates the unconformable lower boundary of the Surma Group [68]. On top of the laterite bed, at the lowermost part of the Lower Surma studied in the Nayagang Section, the succession has been interpreted as upper delta front deposits (shoreface) on a subtidal platform where a high-energy depositional condition prevailed with strong wave activity in the basin [51,53,57,62–67]. The presence of mud drapes and convolutions in the lower part of the Lower Surma indicate the presence of tidal influence and rapid sedimentation during that time [51]. The migration of coastal processes toward inland suggests the onset of marine transgression in the lower part of the Lower Surma. Further southeast towards the strike direction, the depositional settings shifted from the upper delta front to prodelta settings in the middle part of the Lower Surma where mud dominates over sand (Figures 5, 9 and 10B). In between upper delta front deposits in Nayagang Section (stratigraphic low) and prodelta deposits in Tetulghat Section (stratigraphic up) the lower delta front deposits are not studied due to lack of exposure, but from the continuation of depositional settings, it can be assumed that lower delta front deposits exist in between upper delta front and prodelta deposits in the Lower Surma. The prodelta deposits are characterized by mud dominance with occasional discontinuous sand beds of sheet-like geometry indicating the presence of an estuary nearby where a hyperpycnal flow was active that deposited a few sand beds during the flooding and storms [55]. The shifting of the delta front to prodeltaic depositional settings in the middle part of the Lower Surma Group suggests that marine transgression prevailed during the deposition. In the southern part of the Tetulghat Section, at the upper part of the Lower Surma, the sand-dominated deposits with sheet geometry suggest the lower delta front succession [51,55]. A gradual shift from prodelta setting to the lower delta front setting indicates the retreating of shoreline and sea level fall (Figures 5, 6 and 10).

With time, the depositional environment started to be shallower as the Bengal Delta is a southward prograding delta system [15,69]. Further, in the southward direction from the lower delta front setting in the upper part of the Lower Surma, the depositional environment was more terrestrial according to different studies completed based on seismic and wireline log data and the global Miocene sea-level curve [33,73–76]. The entire lower part and a portion of the middle part of the Upper Surma are not well exposed over a thickness of about 1100 meters in the study area. The middle part of the Upper Surma in the West Bank Section can be interpreted as alluvial to delta plain deposits composed of FA IV: tide-influenced fluvial channel deposits and FA V: tidal flat deposits [55] (Figures 7 and 10). In alluvial to delta plain deposits, the tide-influenced channel deposits are composed of sand bars of wedge-shaped geometry. However, the composite channel deposits show a sheet-like geometry (Figure 9a,c). Above the FA IV c. 45m thick successions of cyclic tidal heterolithic deposits of sheet geometry represent the tidal flat deposits (FA V). In the upper part of the Upper Surma at West Bank Section, sedimentary successions are not exposed over a thickness of 90 meters, and above that gap, a proximal prodelta deposit is studied that indicates a deepening of the depositional environment and shifting from coastal in the middle part to shallow marine in the upper part of the Upper Surma (Figures 9 and 10).

The overall two cycles of shifting in the depositional environment can be interpreted in the Surma Basin during the deposition of the studied Surma Group succession. The early cycle started from the top of the fluvial Barail Group [34]. After the deposition of the Barail Group in a fluvial setting, landward shifting of the shoreline was started and the depositional settings started to shift from fluvial through shallow marine subtidal to shallow marine shelf indicated by the presence of upper delta front deposits in the lower part of the Lower Surma (Lower Bhuban) and prodelta mud deposits in the middle part of the Lower Surma (Middle Bhuban). The missing coastal deposits between the Barail Group and Surma Group along their contact indicate a subaerial unconformity supported by the presence of laterite [68]. With further landward migration of shoreline, the depositional condition within the Sumra Basin became deeper and more marine that formed prodelta deposits over delta front deposits within the basin. With time, the shoreline started to retreat seaward possibly due to global sea level fall, increasing rate of sediment supply to the basin, and the change of other climatic and tectonic conditions. This shoreline retreating caused the shallowing of depositional settings from the prodelta to delta front settings in the Surma Basin. Different distributary channels were active during that time that deposited huge amounts of coarser sediments in their mouth bars by rapid deceleration of unidirectional flow generated in the upstream rivers [51,55]. A thick succession of fluvial sediments have been interpreted by numerous researchers in different studies, most of those works are based on seismic or outcrop studies conducted further downstream in other parts of the Bengal Basin [33,73–76]. Previous studies based on outcrops and indications from wireline logs suggest that the unexposed Surma Group deposits in the study area are deltaic and braided fluvial deposits [74]. The exposed outcrop immediately above the gap is a delta plain deposit in the middle part of the Upper Surma that indicates another cycle of marine transgression started from the upper part of the unexposed deposits of the Surma Group (Figure 10). A continuous succession in the West Bank Section shows the shifting of tidally influenced channel deposits into tidal flat deposits (Figures 7 and 10) that indicates the deepening of the depositional setting due to the landward shifting of the shoreline. This cycle ends with the presence of proximal prodelta deposits in the uppermost part of the Upper Surma (Figures 9 and 10).

5.2. Different levels of heterogeneity and their impact on reservoir quality

The present study demonstrates that the Surma Group succession was deposited in a range of fluvio-deltaic environments and exhibits various levels of reservoir heterogeneities that can act as hydrocarbon flow barriers at different levels. Understanding of the various levels of reservoir heterogeneities is important to better characterize the fluvio-deltaic reservoirs and produce hydrocarbon from them (7–12,14).

Heterogeneity in the siliciclastic Surma Group occurs due to the presence of mud in sand units that can act as a barrier for hydrocarbon flow in both vertical and horizontal directions due to the

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impermeable nature of mud. Most of the heterogeneity levels identified in the present study are sub-seismic scales except for the HL 1. As the Surma Group successions were deposited in a range of depositional settings, the heterogeneity levels are different in different deposits. For example, in the delta front deposits and delta plain deposits, the heterogeneity level is not similar. The heterogeneity level of the prodelta mud (FA I) is designated as HL-I which can act as a barrier for large-scale hydrocarbon migration between hydrocarbon reservoirs of adjacent delta front deposits. Within the sandier successions of the delta front (FA II and III), the heterogeneity level of interbedded alternating thick to thin mud units are scaled as HL-IV which can create a blockade and affect the vertical movement of hydrocarbon among individual delta front sand-sheet units. As a result, the overall reservoir performance will be lesser practically than the estimated performance due to these hidden barriers in the sandy successions. In tide-influenced fluvial channel deposits (FA IV), tidal heterolithic deposits of different thicknesses within adjacent tidal bar deposits are designated as HL-II and HL-III and can act as barriers for uninterrupted vertical hydrocarbon flow among reservoir units of tidal bars. Within thick trough cross-bedded sand units of tidal bars, thin mud drapes along foresets and in the tidal flat deposits (FA V), mud drapes in flaser bedding, mud lamina in wavy bedding and lenticular beds are labeled as HL-V that can intercept the internal lateral flow of hydrocarbons within the reservoir sand units as well as vertical flow by creating baffles. The heterogeneous muddy deposits within sand bodies increase the tortuosity of reservoirs by blocking and creating small-scale lateral and vertical obstructions to fluid flow within the hydrocarbon reservoir. These sub-seismic scale heterogeneities can lead to misunderstanding the performance of the reservoir by affecting reservoir characteristics such as reservoir compartmentalization, reduction of effective permeability, an increase of flow path tortuosity, misunderstanding of hydrocarbon saturation prediction, a decrease of sweep efficiency, etc. [2,20–25,72]. Hence, for reservoir modelling and reserve estimation of the Surma Group, the sub-seismic scale heterogeneities identified and described in the study are crucial, and must be considered.

7. Conclusions

The study documents the reservoir heterogeneities of the fluvio-deltaic successions through analyzing the Surma Group outcrop analogue exposed in the Surma Basin. Eleven (11) facies and five (05) facies associations: prodelta deposits (FA I), lower delta front deposits (FA II), upper delta front deposits (FA III), alluvial to delta plain tide-influenced fluvial channel deposits (FA IV), and subaqueous delta plain tidal flat deposits (FA V) are identified based on the facies analysis. Facies analysis results suggest that the studied succession of the Surma Group was deposited in the fluvio-deltaic settings where depositional environments are shifted with time from delta front through prodelta, delta front, and delta plain and again to prodelta. Two cycles of shifting of the depositional environment are interpreted based on depositional settings change that is related to shoreline shifting and sea level change. A total of five different levels of heterogeneity are identified in various facies associations: the largest scale (40–60m thick mud) of heterogeneity level (HL-I) is studied in the prodelta mud deposits (FA I), large scale (5–12m thick tidal heterolithic) HL-II, medium scale (30cm–1m thick mud) HL-III, small scale (5–10cm thick interbedded mud) HL-IV and the smallest scale (2mm–5mm thick intercalated mud) HL-V are studied in the tide-influenced fluvial channel deposits (FA IV), HL-IV and HL-V are studied in the tidal heterolith deposits (FA V), HL-IV and HL-V are studied in the lower and upper delta front deposits (FA II and FA III) These various levels of heterogeneities create various types and scale of barriers in reservoirs that might lead to reservoir compartmentalization, reduction of effective permeability, and increase of flow path tortuosity.

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References

1. Boateng, C.D.; Li-Yun F.; Sylvester K.D. Characterization of complex fluvio–deltaic deposits in Northeast China using multi-modal machine learning fusion." *Scientific Reports* **2020**, *10*, 13357.
2. Choi, K.; Jackson, M.D.; Hampson, G.J.; Jones, A.D.W.; Reynolds, A.D. Predicting the impact of sedimentological heterogeneity on gas–oil and water–oil displacements: fluvio-deltaic Pereriv Suite Reservoir, Azeri–Chirag–Gunashli Oilfield, South Caspian Basin. *Petroleum Geoscience* **2011**, *17* (2), 143–163.
3. Deshpande, A.; Flemings, P.B.; Huang, J. Quantifying lateral heterogeneities in fluvio-deltaic sediments using three-dimensional reflection seismic data: Offshore Gulf of Mexico. *Journal of Geophysical Research: Solid Earth* **1997**, *102*(B7), 15385-15401.
4. Maharaj, V.T.; Wood, L.J. A Quantitative Paleogeomorphic Study of the Fluvio-Deltaic Reservoirs in the Atoka Interval, Fort Worth Basin, Texas, USA **2009**.
5. Oudjida, A. Geologically oriented reservoir modeling of a fluvio-deltaic reservoir: The TAGI of the Ourhoud field, Berkine Basin, Algeria. *AAPG HEDBERG CONFERENCE "Paleozoic and Triassic Petroleum Systems in North Africa"*, Algiers, Algeria **2003**.
6. Yassin, M.; Abdullatif, O.; Hariri, M. Sedimentology and Reservoir Characteristics of Early Cretaceous Fluvio-Deltaic and Lacustrine Deposits, Upper Abu Gabra Formation, Sufyan Sub-basin, Muglad Rift Basin, Sudan. In *EGU General Assembly Conference Abstracts* **2017**, 8695.
7. Keogh, K.J.; Martinius, A.W.; Osland, R. The development of fluvial stochastic modelling in the Norwegian oil industry: A historical review, subsurface implementation and future directions. *Sedimentary Geology* **2007**, *202*(1-2), 249-268.
8. Jordan, D.W.; Pryor, W.A. Hierarchical levels of heterogeneity in a Mississippi River meander belt and application to reservoir systems. *AAPG bulletin* **1992**, *76*(10), 1601-1624.
9. Miall, A.D. Reservoir heterogeneities in fluvial sandstones: lessons from outcrop studies. *AAPG bulletin*, **1988**, *72(6)*, 682-697.
10. Howell, J.A.; Martinius, A.W.; Good, T.R. The application of outcrop analogues in geological modelling: a review, present status and future outlook. *Geological Society, London, Special Publications* **2014**, *387*(1), 1-25.
11. Manzocchi, T.; Carter, J.N.; Skorstad, A.; Fjellvoll, B.; Stephen, K.D.; Howell, J.A.; Matthews, J.D.; Walsh, J.J.; Nepveu, M.; Bos, C.; Cole, J. Sensitivity of the impact of geological uncertainty on production from faulted and unfaulted shallow-marine oil reservoirs: objectives and methods. *Petroleum Geoscience* **2008**, *14*(1), 3-15.
12. Pranter, M.J.; Hewlett, A.C.; Cole, R.D.; Wang, H.; Gilman, J. Fluvial architecture and connectivity of the Williams Fork Formation: use of outcrop analogues for stratigraphic characterization and reservoir modelling. *Geological Society, London, Special Publications* **2014**, *387*(1), 57-83.
13. Robinson, J.W.; McCabe, P.J. Sandstone-body and shale-body dimensions in a braided fluvial system: Salt Wash Sandstone Member (Morrison Formation), Garfield County, Utah. *AAPG bulletin* **1997**, *81*(8), 1267-1291.
14. Rahman, M.M.; Howell, J.A.; Macdonald, D.I. Virtual outcrop-based analysis of channel and crevasse splay sandstone body architecture in the Middle Jurassic Ravenscar Group, Yorkshire, NE England. *Journal of the Geological Society* **2022**, *179*(3), jgs2021-017.
15. Alam, M.; Alam, M.M.; Curray, J.R.; Chowdhury, M.L.R.; Gani, M.R. 2003. An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history. *Sedimentary Geology* **2003**, *155*(3-4), 179-208.
16. Holtrop, J.F.; Keizer, J. Some aspects of the stratigraphy and correlation of the Surma Basin wells, East Pakistan. *ECAFE mineral resources development series* **1970**, *36*, 143-154.
17. Imam, B. *Energy resources of Bangladesh*; University grants commission of Bangladesh: Dhaka, Bangladesh, 2013, pp. 277.

18. Reimann, K.U. and Hiller, K. *Geology of Bangladesh*; Gebruder Borntraeger: Berlin–Stuttgart, Germany, 1993.
19. Ajdukiewicz, J.M.; Lander, R.H. Sandstone reservoir quality prediction: The state of the art. *AAPG Bulletin* **2010**, *94* (8), 1083-1091.
20. Yıldız, G.; Yılmaz, İ.Ö. Reservoir heterogeneity of Ordovician sandstone reservoir (Bedinan Formation, SE Turkey): Diagenetic and sedimentological approaches. *Marine and Petroleum Geology* **2020**, *118*, 104444.
21. Worden, R. H.; Barclay, S.A. The effect of oil emplacement on diagenetic clay mineralogy: the Upper Jurassic Magnus Sandstone Member, North Sea. *Clay Mineral Cements in Sandstones* **1999**, 453-469.
22. Kim, J. C.; Lee, Y. I.; Hisada, K. I. Depositional and compositional controls on sandstone diagenesis, the Tetori Group (Middle Jurassic–Early Cretaceous), central Japan. *Sedimentary Geology* **2007**, *195*(3-4), 183-202.
23. Morad S.; Al-Ramadan K.; Ketzer M.; De-ros L.F. Impact of diagenetic alterations on reservoir quality and heterogeneity of paralic and shallow marine sandstones: links to depositional facies and sequence stratigraphy. *AAPG Bulletin* **2010**, *94*(8), 1267-1309.
24. Al-Ramadan, K. Illitization of smectite in sandstones: the Permian Unayzah reservoir, Saudi Arabia. *Arabian Journal for Science and Engineering* **2014**, *39*, 407-412.
25. Craigie, N. W.; Breuer, P.; Khidir, A. Chemostratigraphy and biostratigraphy of Devonian, Carboniferous and Permian sediments encountered in eastern Saudi Arabia: An integrated approach to reservoir correlation. *Marine and Petroleum Geology* **2016**, *72*, 156-178.
26. Amaefule, J. O.; Altunbay, M.; Tiab, D.; Kersey, D. G.; Keelan, D. K. Enhanced reservoir description: using core and log data to identify hydraulic (flow) units and predict permeability in uncored intervals/wells. In *SPE annual technical conference and exhibition*, **October 1993**, OnePetro.
27. Gunter G.W.; Finneran J.M.; Hartmann D.J.; Miller J.D. Early determination of reservoir flow units using an integrated petrophysical method. paper SPE 38679 prepared for presentation at the *1997 SPE Annual Technical Conference and Exhibition* held in San Antonio, Texas, 5-8 October **1997**, 1-8.
28. Pittman, E. D. Relationship of porosity and permeability to various parameters derived from mercury injection-capillary pressure curves for sandstone. *AAPG bulletin* **1992**, *76*(2), 191-198.
29. Castillo, P.; Ou, L.; Prasad, M. Petrophysical description of tight gas sands. In *SEG Technical Program Expanded Abstracts* **2012**, 1-5.
30. Lietz, J.K.; Kabir, J. Prospects and constraints of oil exploration in Bangladesh. In: *Proceedings of 4th Offshore Southeast Asia Conf.*, **1982**, Singapore, pp. 1–4.
31. Hiller, K.; Elahi, M. Structural development and hydrocarbon entrapment in the Surma Basin/Bangladesh (northwest Indo Burman fold belt). In *Southeast Asia Show* **February 1984**, OnePetro.
32. Khan, M.A.M.; Ismail, M.; Ahmed, M. Geology and Hydrocarbon prospects of the Surma Basin, Bangladesh. In: *Seventh Offshore South Asia Conference*, **1988**, Singapore, pp. 364–387.
33. Alam, M. Geology and depositional history of Cenozoic sediments of the Bengal Basin of Bangladesh. *Palaeogeography, Palaeoclimatology, Palaeoecology* **1989**, *69*, 125-139.
34. Johnson, S.Y.; Alam, A.M.N. Sedimentation and tectonics of the Sylhet trough, Bangladesh. *Geological Society of America Bulletin* **1991**, *103*(11), 1513-1527.
35. Shamsuddin, A.H.M.; Brown, T.; Lee, S.; Curiale, J. Petroleum Systems of Bangladesh. In: *Proceedings of the 13th Southeast Asia petroleum Exploration Society (SEAPEX) Exploration Conf.*, **2001**, Singapore 4th–6th April.
36. Gani, M.R.; Alam, M.M. Sedimentation and basin-fill history of the Neogene clastic succession exposed in the southeastern fold belt of the Bengal Basin, Bangladesh: a high-resolution sequence stratigraphic approach. *Sedimentary Geology* **2003**, *155*(3-4), 227-270.
37. Islam, M.A. Diagenesis and reservoir quality of Bhuban sandstones (Neogene), Titas Gas Field, Bengal Basin, Bangladesh. *Journal of Asian Earth Sciences* **2009**, 35, 89–100.
38. Mitchell, A.H.G.; Reading, H.G. Sedimentation and tectonics. In *Sedimentary environments and facies*; Reading, H.G., Eds.; Blackwell Scientific Publications: Oxford, England, 1986, pp. 471-519.
39. Curray, J.R.; Emmel, F.J.; Moore, D.G.; Raitt, R.W. Structure, tectonics, and geological history of the northeastern Indian Ocean. The ocean basins and margins: *The Indian Ocean* **1982**, 399-450.
40. Molnar, P. Structure and tectonics of the Himalaya: Constraints and implications of geophysical data. *Annual Review of Earth and Planetary Sciences* **1984**, *12*(1), 489-516.
41. Chen, W.P.; Molnar, P. Source parameters of earthquakes and intraplate deformation beneath the Shillong Plateau and the northern Indoburman ranges. *Journal of Geophysical Research: Solid Earth* **1990**, *95*(B8), 12527-12552.

 doi:10.20944/preprints202401.1259.v1

42. Murthy, M.V.N.; Talukdar, S.C.; Bhattacharya, A.C.; Chakrabarti, C. The Dauki fault of Assam. *Bull. Oil Nat. Gas Comm. (India)* **1969**, *6*, 57–64.
43. Molnar, P. The distribution of intensity associated with the great 1897 Assam earthquake and bounds on the extent of the rupture zone. *Journal of Geological Society of India (Online archive from Vol 1 to Vol 78)* **1987**, *30*(1), 13-27.
44. Murphy, R.W.; Staff of BOGMC. Bangladesh enters the oil era. *Oil & gas journal* **1988**, *86*(9), 76-82.
45. Seeber, L.; Armbruster, J.G. Great detachment earthquakes along the Himalayan arc and long-term forecasting. *Earthquake prediction: an international review* **1981**, *4*, 259-277.
46. Ahmed, A. (1983). *Oligocene stratigraphy and sedimentation in the Surma Basin, Bangladesh*. [unpublished M. Sc. thesis], University of Dhaka.
47. Khan, M.R.; Muminullah, M. Stratigraphy of Bangladesh. In *Petroleum and Mineral Resources of Bangladesh: Seminar and* Exhibition October **1980**, pp. 35-40.
48. Miall, A.D. *The geology of fluvial deposits: sedimentary facies, basin analysis and petroleum geology*; Springer-Verlag Inc.: Heidelberg, 1996, p. 582.
49. Dreyer, T.; Scheie, Å.; Walderhaug, O. Minipermeameter-based study of permeability trends in channel sand bodies. *AAPG bulletin* **1990**, *74*(4), 359-374.
50. Haldorsen, H. H. Simulator parameter assignment and the problem of scale in reservoir engineering. *Reservoir characterization* **1986**, *6*, 293-340.
51. Reineck, H.E.; Singh, I.B. *Depositional sedimentary environments: with reference to terrigenous clastics*, 2nd ed.; Springer Science & Business Media: Berlin-Heidelberg, 1980.
52. Weber, K.J. Influence of common sedimentary structures on fluid flow in reservoir models. *Journal of Petroleum Technology* **1982**, *34*(03), 665-672.
53. Boggs, S. *Petrology of sedimentary rocks*, 2nd ed.; Cambridge university press: Cambridge, UK, 2009.
54. Pickering, K.T.; Hiscott, R.N. *Deep marine systems: processes, deposits, environments, tectonics and sedimentation*; John Wiley & Sons: Oxford, UK, 2015.
55. Bhattacharya, J.P. Deltas. In *Facies Models 4*; James, N.P., Dalrymple, R.W., Eds; Geological Association of Canada: Newfoundland & Labrador, Canada, 2010.
56. Tucker, M.E. *Sedimentary Petrology–An Introduction to the Origin of Sedimentary Rocks*, 3rd ed.; Blackwell Scientific publication: Oxford, UK, 2001.
57. Collinson, J.D.; Mountney, N.P. *Sedimentary structures*, 4th ed.; Dunedin Academic Press Ltd.: Edinburgh, London, UK, 2019.
58. Reineck, H.E. SedimentgefUge im Bereich der siidlichen Nordsee. *Abh. senckenbergische naturforsch* **1963**,*Ges. 505*, 138.
59. Reineck, H.E.; Dörjes, J.; Gadow, S.I.B.Y.L.L.E.; Hertweck, G.U.N.T.H.E.R. Sedimentologie, Faunenzonierung und Faziesabfolge vor der Ostküste der inneren Deutschen Bucht. *Senckenbergiana lethaea* **1968**, 4.
60. Häntzschel, W. Die Schichtungs-Formen rezenter Flachmeer-Ablagerungen im Jade-Gebiet. *Senckenbergiana* **1936**, *18*, 316-356.
61. Van Straaten, L.M.J.U. Composition and structure of recent marine sediments in the Netherlands. *Leidse Geologische Mededelingen* **1954**, *19*(1), 1-108.
62. Mckee, E.D.; Reynolds, M.A.; Baker, C.H. Laboratory studies on deformation in unconsolidated sediment. *Short Papers in Geology, Hydrology, and Topography; Articles 120-179: Geological Survey Research 1962; Scientific Notes and Summaries of Investigations* **1962**, 151.
63. Mckee, E.D.; Goldberg, M. Experiments on formation of contorted structures in mud. *Geological Society of America Bulletin* **1969**, *80*(2), 231-244.
64. Kuenen, P.H. Significant features of graded bedding. *AAPG Bulletin* **1953**, *37*(5), 1044-1066.
65. Sanders, J. E. Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms. In: Middleton, G. V., ed., Primary sedimentary structures and their hydrodynamic interpretation. *Soc. Econ. Paleontologists Mineralogists Spec. Publ.* **1965**, *12*, 192-219.
66. Reineck, H.E. Longitudinale Schrägschicht im Watt. *Geologische Rundschau* **1958**, *47*(1), 73-82.
67. Wunderlich, F. Die Entstehung von "convolute bedding" an Platenrändern. *Senckenbergiana lethaea* **1967**, *48*(3/4), 345-349.

68. Haque, A. K. M.; Downey, W. S.; Alam, M. M.; Islam, M. A.; Faruk, M. O.; Islam, R. Eocene-Miocene Stratigraphy of the Surma Trough, Bengal Basin: A Sequence Stratigraphic Approach. *Petroleum & Coal* **2019**, *61*(3).
69. Curray, J. R. The Bengal depositional system: From rift to orogeny. *Marine Geology* **2014**, *352*, 59-69.
70. Sultana, D.N.; Alam, M.M. Facies analysis of the Neogene Surma group succession in the subsurface of the Sylhet Trough, Bengal Basin, Bangladesh. *10th Geological Conf. In Bangladesh Geol. Soc.* **2001**, *Abstracts*, 70.
71. Mode, A. W.; Anyiam, O. A.; John, S. I. Depositional environment and reservoir quality assessment of the "Bruks Field," Niger Delta. *Journal of Petroleum Exploration and Production Technology* **2017**, *7*, 991-1002.
72. Reynolds, A. D.; Simmons, M. D.; Bowman, M. B.; Henton, J.; Brayshaw, A. C.; Ali-Zade, A. A.; ...; Koshkarly, O. Implications of outcrop geology for reservoirs in the Neogene Productive Series: Apsheron Peninsula, Azerbaijan. *AAPG bulletin* **1998**, *82*(1), 25-49.
73. Haq, B. U.; Hardenbol, J.; Vail, P. R. Mesozoic and cenozoic chronostratigraphy and cycles of sea-level change. *Sea-Level Changes, 1988, 71–108*. https://doi.org/10.2110/pec.88.01.0071.
74. Hossain, S.; Shekhar, H.; Rahman, N. Facies and architectural element analysis of the Upper Bokabil Sandstone in the Bengal Basin. *Sedimentary Geology, 2023, 453, 106433*. https://doi.org/10.1016/j.sedgeo.2023.106433.
75. Shreya, S.; Bhuiyan, M. A.; Hossain, S.; Sultana, T. Petrophysical Reservoir Characterization of Habiganj Gas Field, Surma Basin, Bangladesh. *The Dhaka University Journal of Earth and Environmental Sciences, 2021, 10(1), 1–10*. https://doi.org/10.3329/dujees.v10i1.56275.
76. Kamruzzaman; Hossain, D.; Sarker, M. R.; Khatun, M.; Shahriar, M. U. Improving Insights Into Petrophysics using Geophysical Data for the Habiganj Structure, Surma Basin, Bangladesh. *Handbook of Petroleum Geoscience, 2022, 394–412. Portico.* https://doi.org/10.1002/9781119679998.ch21.