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Hydrocarbon Prospectivity of Surma Group in Sylhet Area in Context of Sequence Stratigraphy

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ABSTRACT: This research focuses on studying the Surma Group sediments with an integrated approach of using wireline logs and 2D seismic data from Sylhet structure and outcrop analogy from the Zaflong-Tamabil-Jaintiapur area to explain the geological evolution in the context of sequence stratigraphic framework and its implications to identify the hidden potential of hydrocarbon traps that remains overlooked. The 'SYL-07' well logs divided the encountered sedimentary strata by sequence boundaries (SB) and flooding surfaces (FS) into an upper third-order Lowstand System Tract (3_LST), followed by the third-order Highstand System Tract (3_HST), and underlying third-order Transgressive System Tract (3_TST) which correspond to the Tipam, Boka Bil, and Bhuban formations, respectively. The 3_HST has further been subdivided into fourth-order sequences. Well-to-seismic ties helped in identifying the sequence boundaries in the regional context. Three new prospects in the nose and flank area of the Sylhet structure have been detected based on seismic attributes and log responses. Seismic sweetness attribute anomalies confirmed the existence of these prospects. Rigorous fieldworks provided nineteen facies and seven sets of sedimentary facies associations and helped to establish the sedimentological stacking patterns and corresponding depositional environments. About 2250m lithocolumn constructed from field data revealed four third-order sequence stratigraphic system tracts roughly corresponding to Renji (3_LST), Bhuban (3_TST), Boka Bil (3_HST), and Tipam (3_LST) formations in the bottom-up order, while the obtained facies associations aid in identifying four fourth-order sequences including fourth-order system tracts in the 3_HST. The lithologic column corresponds well with the seismic sections and validates the seismically interpreted third-order system tracts and fourth-order sequences. However, the high-frequency fourth-order system tracts can only be correlated with the log motif patterns due to sub-seismic resolution. The erosional remains of the fourth-order sequences in 3_HST, for instance, the coarsening upward shoreface and shelfal facies topped by transgressive shale, have yielded potential future drilling sites based on seismic attribute and log response analysis. The analogy of field data with well log and seismic data helped the overall evaluation of the hydrocarbon prospectivity of the area.

Keywords: Surma Group; Sequence Stratigraphy; System Tracts; Log Motif; Seismic Attribute

INTRODUCTION

The Surma Basin is a sub-basin of the Bengal Basin that covers much of Bangladesh's northeastern region (Fig. 1) and contains a 17-km-thick Eocene to Recent sedimentary column (Alam et al., 2003; Hiller and Elchi, 1984; Johnson and Alam, 1991). Except for the Eocene Sylhet Limestone, the entire succession is dominated by clastic deposits (Alam et al., 2003). These clastic deposits constitute a significant hydrocarbon source, and several gas fields are located there. Natural gas is the principal energy source in an energy-starving country like Bangladesh. To meet the demand for increased hydrocarbon production, it is necessary to update the current geological understanding of the region using a modern concept of sequence stratigraphy. So far, no strategic approach has been taken to establish the sequence stratigraphy of Bangladesh to modernize the current stratigraphy given by Evans in 1932. Sequence stratigraphy can play an essential role in establishing the correct stratigraphy of Bangladesh on a chronostratigraphic basis. Only structural traps have been prioritized in the Surma Basin's exploration methods thus far (fault-bounded anticlines). Most of the anticlinal structures have already been drilled and are nearing completion. As a result, it is time to revisit new petroleum prospects in the context of sequence stratigraphy. Sequence stratigraphy is a subdivision of geological studies where sedimentary deposits are linked and subdivided into unconformity-bound units or correlative conformities (Catuneanu, 2019; Posamentier and Allen, 1999; Vail, 1987; Van Wagoner et al., 1990). Even in regions that have already been extensively investigated, using digital data gathering techniques in addition to conventional

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field methods and behind-outcrop, well data is an effective tool for studying extensive and inaccessible cliff exposures (Rahman, 2022). The current research focuses on constructing a sequence stratigraphic framework for the Surma Group bounded by underlying Renji and overlying Tipam formations in the Sylhet area using data from field works at the Zaflong-Tamabil-Jaintiapur area, well logs, and seismic sections over Sylhet structure (Fig. 1).

Using a sequence stratigraphic framework to identify reservoir geometry, extent, sealing, and trapping styles can help geologists anticipate reservoir characterization, hydrocarbon distribution, and exploration drilling planning. It will also serve as a proof of concept for re-evaluating similar mature gas field plays in the Surma Basin for additional petroleum opportunities. One upside potential of the study is no additional drilling to get the information. The current data can aid in determining new drilling options.

GEOLOGICAL SETTING

In northeastern Bangladesh, the Sylhet Trough (also known as the Surma Basin) is a sub-basin of the Bengal Basin (Curiale et al., 2002; Hiller and Elchi, 1984; Johnson and Alam, 1991; Uddin and Lundberg, 1998). The Shillong Massif, the only rising topography in the Himalayan foreland, borders the trough to the north. The Shillong Massif comprises Indian Plate Precambrian basement rocks partially covered by Cenozoic sediments (Hossain et al., 2019). The Dauki Fault, which runs east-west, is the primary boundary structure between the Sylhet Trough and the Shillong Massif (Hiller and Elchi, 1984; Johnson and Alam, 1991).

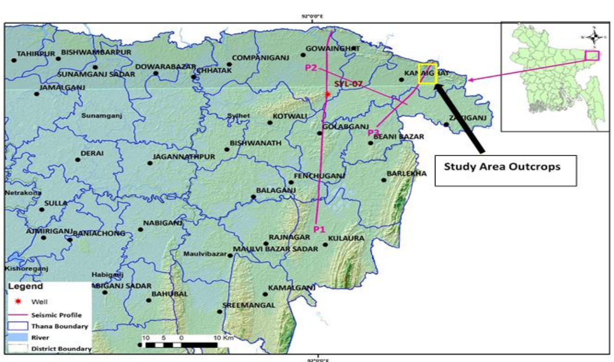

Figure 1: Location Map of the Study Area, The Red Three Lines are the Seismic Lines Designated as P1, P2, and P3, and the Yellow Box is the Zone of Interest

The structural framework, geological evolution, stratigraphy, and petroleum system of the Bengal Basin's Sylhet Trough began with the late Mesozoic Gondwana separation and continues to this day (Alam, 1989). The Dihing Formation, Dupi Tila Formation, Tipam Group (Girujan Clay and Tipam Sandstone formations), Surma Group (Boka Bil and Bhuban formations), Barail Group (Renji and Jenum formations), and Jaintia Group (Kopili Shale and Sylhet Limestone formations) (Evans, 1932; Holtrop and Keizer, 1970; Johnson and Alam, 1991; Reimann, 1993) are the stratigraphic units. Sedimentary rocks exposed along the road and stream sections in the Zaflong-Tamabil-Jainiapur area (Fig. 1) have been found adequate to identify and evaluate the facies and facies associations in the sequence stratigraphic framework. The lithologic subsections in the study area are often differentiated by erosional surfaces that aid in identifying sequence stratigraphic system tracts. The Surma Group sediments and the under- and overlying rock formations were evaluated, while particular emphasis has been given to the exposures of the Boka Bil Formation for hydrocarbon prospectivity analysis in the sequence stratigraphy framework.

DATASETS AND METHODOLOGY

Bangladesh Oil, Gas & Mineral Corporation (Petrobangla) provided the material for this investigation, including well logs, 2D seismic data, and software support. Three (3) high-quality 2D seismic lines were used in this study. 25m geophone interval, 100m source interval, 240 live channel, 30 nominal fold, 2ms sampling rate, 6-sec recording length, and 14Hz frequency were the seismic acquisition parameters of the used seismic data (Personal communication with BAPEX). A 12-fold CDP stack was used to process the data. The log responses of 'SYL-07' well were used for a well-seismic tie and log motif analysis in this research. Gamma Ray (GR), Spontaneous Potential (SP), Neutron-Density (N-D), Resistivity, and Sonic logs are among the borehole data.

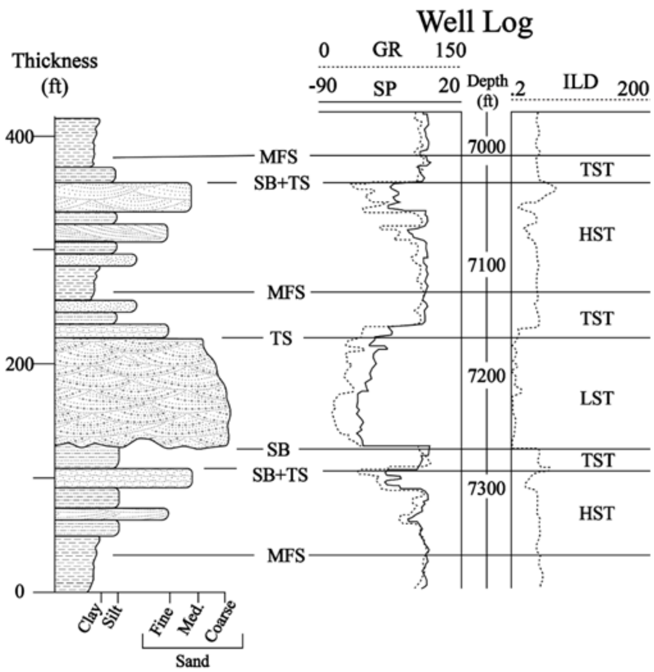

Figure 2: Core and Well Log Data Showing the Relation among Lithologic Attributes, Inferred Depositional Environments, and their Expression on SP, GR, and ILD Well Log Curves. The MFS (Maximum Flooding Surface), TS (Transgressive Surface, SB (Sequence Boundary), LST (Lowstand System Tract), HST (Highstand System Tract), and TST (Transgressive System Tract) are assigned in the figure based on lithologic attributes.

Three rigorous fieldworks in the Zaflong-Tamabil-Jainiapur area were carried out, and a detailed lithologic column was constructed to understand the area's geology. Facies and facies associations were determined, erosional boundaries were identified, and the sequence stratigraphic system tracts and corresponding depositional stacking patterns were established. Following the field investigations, log motif analysis of the SYL-07 well and seismic interpretation of the 2D dataset was performed for correlation and sequence stratigraphic analysis. The application utilized for seismic interpretation was Petrel™ 2018 and Hampson-Russell 11, a PC-based Schlumberger and CGG program. All relevant tools for seismic interpretation were included in the bundle.

The results of the analyses were combined and interpreted to create a sequence stratigraphic framework.

The maximum flooding surfaces, transgressive surfaces, and sequence boundaries were identified from the log motif, and system tracts were established according to the concept of AGI Training Module, Interpreting Sequence Stratigraphy (Fig. 2). However, the theoretical background of the study was adopted from Catuneanu (2019), Catuneanu (2006), Posamentier and Vail (1988), Van Wagoner et al. (1990), Vail (1987), and Vail et al. (1977).

Then well to seismic tie was performed, combining subsurface depth measurements taken at a wellbore with seismic data collected over time. Both well data (logs) and seismic data sets were correlated to see how the sand and shale lithologies in the well data connect to the seismic section's peaks and troughs (Fig. 3). The log values in the SYL-07 well were matched with the seismic section to understand the lithology and properly delineate the petroleum properties.

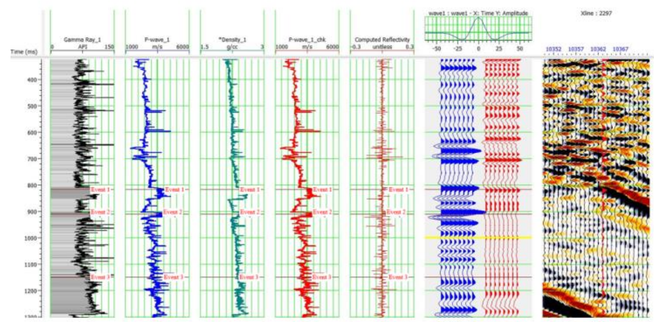

Figure 3: Well to Seismic Tie of the Seismic Data to Synthetic Data Computed from Density and Sonic Logs (Blue: Synthetic Seismic from Well Logs, Red: Average of Seismic Traces). Event 3 is the Sequence Boundary between Tipam and Boka Bil, and Event 2 and Event 1 are the Erosional Surfaces Depicted from Seismic Attributes

RESULTS AND DISCUSSION

Log Motif Analysis and Seismic Interpretation

From the SYL-07 well, the gamma-ray and resistivity logs were taken to determine the lithology, and sedimentological stacking patterns and the demarcation lines were drawn to indicate the bounding surfaces (sequence boundaries, transgressive surfaces, and flooding surfaces), third-order system tracts, and fourth-order sequences. Three third-order system tracts were identified from the SYL-07 well. These are: (i) third-order Lowstand System Tract (3_LST), followed by (ii) third-order Highstand System Tract (3_HST), and (iii) third-order Transgressive System Tract (3_TST) demarcating Tipam, Boka Bil, and Bhuban formations, respectively (Fig. 4). Figure 4 shows that 3_SB differentiates the overlying third-order LST from the underlying third-order HST, while 3_FS(?) differentiates the third-order HST from the underlying third-order TST. Due to insufficient log data below the 3_FS-boundary in well SYL-07, some uncertainty remains in distinguishing the system tract. As mentioned earlier, the main focus of the study is the third order HST which represents the Boka Bil Formation. Four fourth-order sequences, 4_Seq-1 to 4_Seq-4, have been identified in this system tract. Each fourth-order sequence has been further divided into three fourth-order system tracts, including 4_LST, 4_HST, and 4_TST bounded by sequence boundaries, flooding surfaces, and transgressive surfaces labeled as 4_SB1-4, 4_FS1-4, and 4_TS1-4, respectively (Fig. 4). To establish the seismic stratigraphic framework, sub-seismic scale (10^1-10^2m) higher frequency sequences are needed, typically consisting of outcrop scale sequences. So, the outcrop is the only option to demarcate systems tracts of fourth order or further (Catuneanu, 2019).

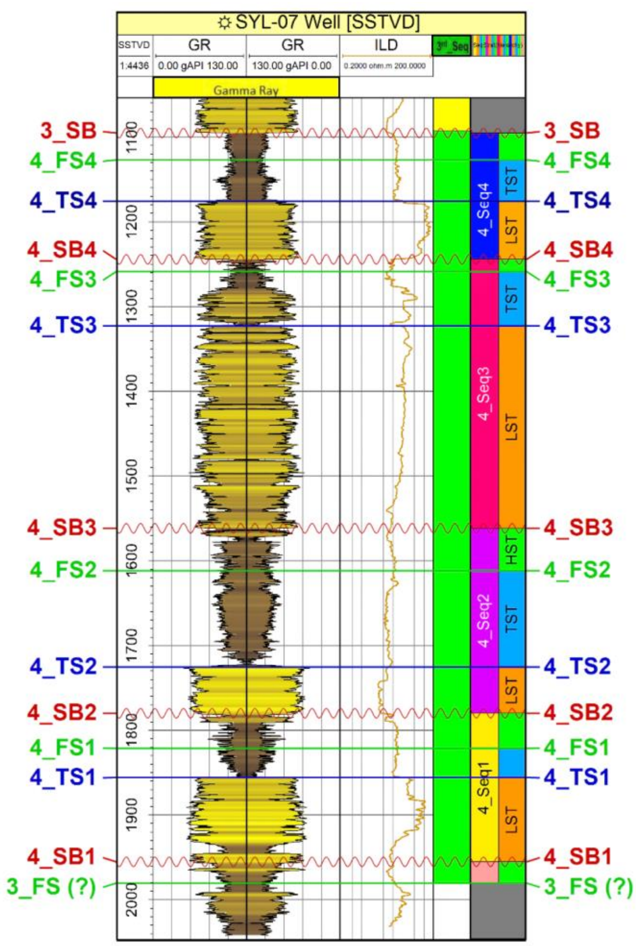

Figure 4: Log Motif Analysis and Identification of Depositional Stacking Patterns for Well-SYL-07. Gamma-ray and Deep Resistivity Logs for the Depth Ranging from ~1075m to 2025m (1^{st} Tract) have been Shown in the Display's 2^{nd}, 3^{rd}, and 4^{th} Tracts. Third-Order System Tracts and Fourth-order Sequences, Including System Tracts, are Shown in the Display's 5^{th} – 7^{th} Tracts. Sequence Boundaries, Flooding, and Transgressive Surfaces with Labeling are Marked with Red, Green, and Blue Lines. Arrowheads Show Log Motifs

The log motif patterns of GR responses adopted from Rider (1990) have been used to identify the system tracts and their depositional stacking patterns (Fig. 4). Description of the system tracts, stacking pattern, and depositional environments are provided in **Table 1.**

Table 1: Description of the Fourth-order System Tracts and Their Corresponding Sequences from the Log Motif of 'SYL-07' Well. The Log Motif Patterns of Gamma-ray Responses Adopted from Rider (1990) Helped Describe the System Tracts, Stacking Patterns, and Depositional Environments

System Tracts of 3^{rd} Order Sequence	4^{th} Order Sequences	System Tracts of 4^{th} Order Sequences	Description
3_LST	----	----	The lower segment above the depth of 1075m of well-SYL-07 is a cylindrical-shaped log motif that indicates an aggrading stacking pattern with braided fluvial deposits. The lithology is mainly sandstone with low resistivity (water saturated) and low GR values. An erosional base (sand/shale sharp contrast) with overall finning upward sand-dominated sequence indicates an LST.
3_HST	4_Seq4	4_HST4	This log segment shows a fining upward sequence. The sharp erosional boundary at the top, the flooding surface at the base (high GR), and the shale-dominated bell-shaped log motif indicate a retrograding HST with tidal flat, channel-fill, or prodeltaic shelfal deposits.
		4_TST4	In this segment, the log shows an hourglass-shaped log motif, meaning coarsening upward sequence at the bottom and a fining upward sequence at the top. A flooding surface at the top and a transgressive surface (shale/sand sharp contrast) at the bottom indicates tidal flat and transgressive shelf deposits.
		4_LST4	The cylindrical-shaped log

			motif indicates a prograding stacking pattern with an overall fining upward sequence (LST). The lithology comprises mainly sand-dominated prograding delta front, mouth-bar, and distributary tidal channel fill deposits bounded by a transgressive surface at the top and an erosional surface at the base (sand/shale sharp contrast).
	4_Seq3	4_HST3	Here the log pattern is a sawteeth-shaped coarsening upward sequence with an aggrading stacking pattern. The sharp erosional boundary at the top, flooding surface at the bottom, and shale-dominated tidal flat, channel-fill, or prodeltaic shelfal deposits indicate HST.
		4_TST3	The overall log pattern is a fining upward sequence (bell-shaped). A flooding surface bounds this retrograding depositional system at the top and a transgressive surface at the base delineating TST with lower sand-dominated tidal flat to upper shale-dominated transgressive shelf deposits.
		4_LST3	This aggrading sequence shows a cylindrical or blocky-shaped log motif with an overall coarsening upward trend indicating mainly shoreface and delta front deposits. An erosional boundary at the base with a general fining upward sequence defines it as an LST.
	4_Seq2	4_HST2	The sequence coarsens upward (funnel-shaped) with an erosional sharp top and flooding surface at the base indicating HST with shoreface or delta front deposits.
		4_TST2	The overall log pattern is an hourglass-shaped sequence indicating basal prograding and upper retrograding stacking patterns. The flooding surface at the top and transgressive surface at the bottom shows a TST with regressive to transgressive delta plain deposits.
		4_LST2	The log pattern is cylindrical or blocky, indicating aggrading/prograding stacking pattern. An erosional base at the bottom with the domination of shoreface sand deposits indicates an LST.
	4_Seq1	4_HST1	This fining upward sequence (bell-shaped) shows retrograding stacking pattern. An erosional base at the top and flooding surface at the bottom isolate this HST with tidal flat to shallow marine deposits.
		4_TST1	This stacking pattern shows a funnel-shaped log motif (coarsening upward sequence). The flooding surface at the top and transgressive surface at the bottom define this section as a TST with delta plain deposits.
		4_LST1	The overall log pattern is bell-shaped (fining upward sequence) with an aggrading/prograding stacking pattern. The sharp erosional surface at the base and transgressive surface at the top define this section as an LST with shoreface sand to prograding delta front deposits (sand/shale sharp contrast).

The sequence stratigraphic system tracts and the bounding surfaces obtained from log motif analyses of well SYL-07 have been interpreted in the regional content based on the 2D seismic data. The seismic data were utilized for reconstructing the stratigraphy of the study area. Besides, the outcrop analogy validates the seismic interpretation up to third-order system tracts and fourth-order sequences. However, to correlate the fourth-order system tracts, the log motif patterns obtained from SYL-07 have been used (Fig. 4).

For correlation purposes, Line_P1 was interpreted as this is the closest line to 'SYL-07' well. The sequence boundaries were drawn in the seismic section following the attributes (erosional surfaces). But, Line_P1 is not proximal to the outcrops of the Zaflong-Tamabil-Jaintiapur area. Line_P2 intersects both Line_P1 and Line_P3, and Line_P3 is closest to the outcrops. Therefore, to reach the locations where the field works were conducted, Line_P2 and Line_P3 were interpreted. The seismically interpreted sequence boundaries within 3_HST are extrapolated to the litholog for correlation (Fig. 5).

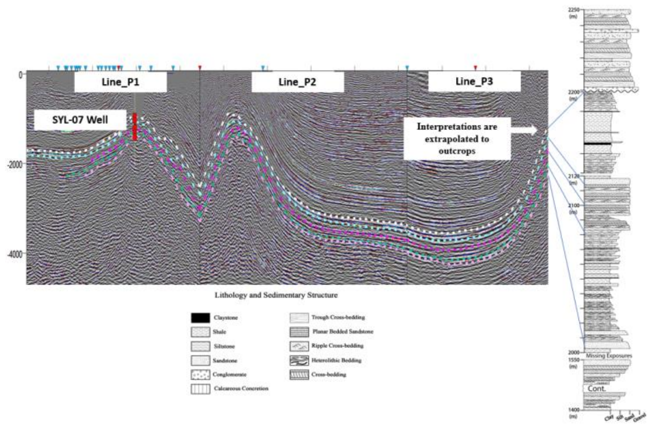

Figure 5: The Dotted Lines are Erosional Surfaces Drawn based on Seismic Attributes, and the Surfaces are Extrapolated to the Outcrop. The Blue Lines Connect the Erosive Boundaries in the Seismic Section to the Outcrop. Lithology and Sedimentary Structures are Provided in the Middle Bottom of the Figure

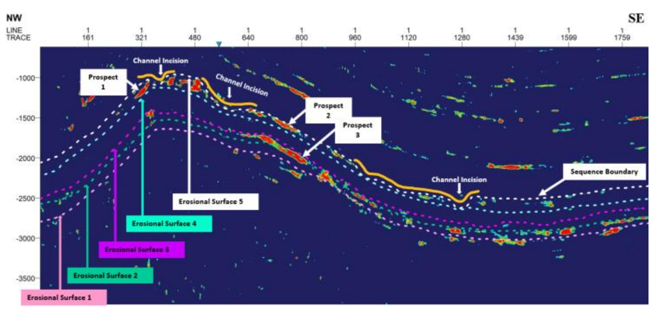

Figure 6: Hydrocarbon Prospects from the Seismic Attribute of Line P3 based on Sweetness Attribute Anomaly. Five Erosional Surfaces are Shown as Dotted Lines, and the Yellow Lines Show Channel Incisions. The Red Zones are Prospect Zones as They Indicate High Hydrocarbon Saturation Considering Structure and Depth

After log motif and seismic interpretation, the seismic attributes were analyzed. Three new prospects in the nose and flank area of the Sylhet structure have been identified based on seismic attributes and log responses. Seismic sweetness attribute anomalies confirmed the existence of these prospects (Fig. 6). Sweetness attribute anomalies may be due to hydrocarbon saturation. These high attribute zones indicate hydrocarbon richness. The thing is that these areas are pretty separated from the present drilling zones. Thus, these zones have the potential to store hydrocarbon and fulfill all the criteria for being a prospective hydrocarbon system and are potential candidates for future drilling.

Litho-facies and Facies Associations

The outcrop investigation provided nineteen facies and seven sets of facies associations in the study area (Fig. 7-8). Detailed sedimentological logging aided in facies interpretation. Seven facies associations were set based on their depositional characteristics, a detailed lithocolumn was constructed, and the sequence stratigraphic system tracts were envisaged (Fig. 9-10).

Table 2: Description of the Lithofacies (Color, Compaction, Sorting, Grain Size, Structures) and Their Depositional Environments. The Corresponding Figures of the Litho-Facies are Mentioned in the Table

Lithofacies	Description of the lithofacies	Depositional Environment
Channel lag (conglomerates)	These are primarily matrix-supported rocks composed of pebbles, sandstone cobbles, claystone, and shale clasts. Usually observed as channel lags in Renji, Boka Bil, and Tipam Sandstone formations.	These occur in the fluvial or tidal channels, incised valleys, and shallow marine canyons.
Massive to thick-bedded sandstone	Very thick homogeneous stratification. Fine to medium-grained sandstone varies in color and has no particular structure (Fig. 7d and 8h). Tipam and upper Boka Bil units contain massive bedded sandstone of 5-7m thickness.	Fluvial channel and delta front shoreface environment.
Graded bedded sandstone	In graded beds, coarse sand dominates the bottom and grades into fine sediments as it progresses—grey to greyish-brown in color, with no internal structures.	Graded sandstones are deposited in fluvial, shoreface, and tidal-influenced channel-fill environments.
Hummocky cross-bedded sandstone	Strong storm surges like hurricanes may form the hummocky cross-bedded sandstone. It comprises a series of crescent-shaped bodies with sideward downward curvature, crosscutting each other (observed in the UGS of the upper Boka Bil unit).	These facies occur in shallow marine shoreface, shelf, storm-surged tidal flat, and fluvial environments.
Trough cross-bedded sandstone	These have lower surfaces that are curved, truncate the underlying beds, and are medium to coarse-grained	Tidal flat (broad and shallow subtidal environment),

	and moderately sorted (Fig. 8d). Due to high energy conditions, the troughs are formed by erosion.	fluvial channel, overbank, crevasse splay, intertidal, to shoreface environments.
Planar cross-bedded sandstone	Cross-bedded sandstones with essentially planar bounding surfaces and a considerable horizontal extent compared to the set thickness—yellowish-brown, medium to fine-grained sandstone (Tipam Sandstone, the lower part of Bhuban and upper part of Boka Bil units, (Fig. 8d).	Shoreface and fluvial braided channel environments.
Parallel bedded sandstone	Laminae with parallel but nonplanar boundaries, fine to medium grained sandstones, and internally shows parallel laminated sandstones (Fig. 8d).	These are formed in the fluvial channel, shoreface, and intertidal environments.
Ripple laminated sandstone	Facies with exposures of ripple laminations, fine to medium-grained, well sorted, grey to light brownish grey (Fig. 8f).	Occur in the fluvial channel, overbank, crevasse splay, intertidal, to shoreface environments.
Silty sandstone	Silt-dominated sandstones, grey to bluish-grey color, flaser, wavy bedding, and micro cross-stratifications are seen.	Intertidal, supratidal, crevasse spays, fluvial, and tidal overbank environments.
Calcareous sandstone	These facies represent light grey, fine-grained, hard, compact sand or silt with no internal structures (Fig. 7b). These are diagenetic features and destroy porosity significantly, and may act as seals if they occur regionally.	Common in Surma Group sediments of subaqueous depositional environment.
Flaser bedded sandstone	These are composed of alternating fine to medium-grained rippled sand layers and discontinuous light grey mud. Contain high sand content (Fig. 8g).	Tidal flat to shoreface deposits formed in supratidal to intertidal environments.
Wavy bedded sandstone	Identified by alternating straight to slightly wavy alternation of bluish grey shale and grey colored silty sandstone (Fig. 8g).	Tidal flat deposits formed in supratidal to intertidal environments.
Lenticular bedded sandstone	Light to dark grey shaly facies contains thin flat sand lenses (connected or isolated, Fig. 8g).	Tidal flat deposits formed in supratidal to intertidal environments.
Facies with soft sedimentary deformations	Soft sedimentary deformations containing ripple laminated sandstone with deformed lenses, loadcast, flame, and convolute structures (Fig. 8e) are observed in lower Bhuban and upper Boka Bil units.	Fluvial channel, delta plain, and intertidal environments.
Silty shale	Silt-dominated shale, bluish grey, moderately sorted, moderately compact.	These facies may deposit in the floodplain, crevasse splay, delta plain, tidal flat, and prodeltaic environments.
Dark-fissile shale	Dark grey thinly laminated fissile shale (Fig. 8b) and observed at the middle and upper Bhuban and upper Boka Bil (UMS) units.	These sediments may deposit in the prodeltaic, shallow to open marine environments.
Mudstone or claystone	Bluish grey, very fined-grained massive mudstone predominantly composed of unidentified clays with occasional silty streaks. It lacks internal sedimentary structures except for minor lamination.	The mud or clay may deposit in prodeltaic, shallow marine, flood basins, tidal mud flats, and lacustrine environments.
Nodular Shale	Shale has loosely packed nodules, predominantly composed of dark grey clays with fine-grained silty streaks and occasional siltstone. The nodules might be of a tectonic or diagenetic origin and observed in the anticline's highly disturbed inflection zone (Bhuban Formation).	The mud or clay may deposit in prodeltaic, shallow marine, flood basins, tidal mud flats, and lacustrine environments.
Laterite	Dark brown indurated, and compact rocks, rich in ferruginous cement, contain shaly pebbles and vesicular structures (Fig. 7c and 8c). These are formed by post-depositional diagenesis and are observed in the contact of Renji and Bhuban formations and Tipam Sandstone.	Laterites are formed in tropical and subtropical warm and humid fluvial to littoral environments.

FACIES ASSOCIATIONS

Fluvial Channel Facies Association

This facies association consists of channel lag deposits (conglomerate), massive sandstone, cross-bedded sandstone, and parallel- and ripple-laminated sandstone. The Tipam Sandstone Formation and the upper part of the Boka Bil Formation have good exposure for this association. While braided facies characterize the channel deposits of the Tipam Sandstone Formation, the upper part of the Boka Bil Formation is preferably characterized by tidal channel bar facies with fluvial influence. Channel facies are deposited under high-energy conditions (Fig. 7a); therefore, the sedimentary structures, clay galls, mud balls, and occasional quartz pebbles in the Tipam Sandstone represent the fluvial depositional environment. This facies association, composed of a cylindrical lower part within an overall fining-upward sequence with basal erosional surface and predominantly sandstone with minor shale, can be characterized as LST (Fig. 10) to the third-order sequence.

Open Marine Facies Association

The thick dark-grey shale sequence of 80m known as Upper Marine Shale (UMS) (Imam, 2013; Parvin, 2019) is seen above the UGS of the upper Boka Bil unit (Fig. 10). This shale unit is the regional seal capping the hydrocarbons trapped in the UGS. These shale-dominated facies consists of claystone with silty streaks and occasional calcareous bands. Above the UMS, a small unit of heterolithic beds was seen below the massive Tipam Sandstone unit. The litholog characteristics show fourth-order TST, and this transgressive facies association offers an overall upward fining of grain size.

Delta Front Shoreface Facies Association

Regressive facies association includes fluvial-influenced, tide-dominated lithofacies within upward coarsening units. A massive to thick-bedded sandstone unit of about 50m (Upper Gas Sand, UGS) is underlain by heterolithic beds and shale with fragile sand lenses or silty streaks (Fig. 7d and 8h). The sandstone unit consists of hummocky cross-stratification, trough cross-bedding, and parallel laminated sandstone (Fig. 8d-f), indicating high energy conditions. The lithofacies are mainly shoreface deposits composed of an overall cylindrical sequence with basal erosional surfaces, and predominantly sandstone with minor shale can be characterized as LST (Fig. 10) and belongs to the fourth-order sequence.

Delta Plain Facies Association

The facies association includes fluvial-influenced lithofacies within overall coarsening upward units of tide-dominated deposits; individual cycles represent a fining upward sequence. This facies association consists of thickly-laminated to bedded sandstones followed by heterolithic beds and shale with fragile sand lenses or silty streaks (Fig. 8h). The lithofacies are mainly delta plain deposits with prograding muddy sediments of flood basins, crevasse-splay, point bar deposits of tidal rivers, and coastal embayments between tide-influenced bay-head delta deposits between the distributary channels. Despite lateral changes, this facies association starts with a basal shale lithology and is gradually enriched by a succession of sandy lithologies ending in an erosional surface. This association can be identified as the HST (Fig. 10), which belongs to the fourth-order sequence.

Tidal Flat Facies Association

This kind of facies association primarily comprises heterolithic beds including flaser, wavy, and lenticular bedding deposits with occasional thickly laminated to bedded sandstone. Bhuban and Boka Bil formations have good exposure for this facies association in Naya Gang, Tetulghat, Afifanagar Tea-garden, and Shari River sections. Tidal flat deposits are characterized by fluctuating energy conditions in the intertidal and supratidal deltaic depositional environment (Fig. 8f, g). This facies association, composed of an overall coarsening-upward sequence with basal erosional surfaces and predominantly sandstone with subordinate shale, can be characterized as LST (Fig. 9).

Pro-deltaic Facies Association

A pro-deltaic environment is where fissile shale, shale with silt streaks, and nodular shale with current ripple siltstone form. Shale is deposited from suspension, and the subordinate claystone, heterolithic bedding, and occasional calcareous bands are associated with this shaly unit when the depositional environment is undisturbed. Pro-delta shales can be an excellent source rock for hydrocarbon generation when organic materials are present, and because of the impermeable shale layers, this unit can be a potential seal to cap the reservoirs. This pro-deltaic facies association is classified as a TST according to the interpretation of the litholog (Fig. 9).

Tidal-influenced Channel Fill Facies Association

This facies association consists of channel lag deposits, massive to thick-bedded sandstone (pink), trough cross-bedded sandstone, parallel- and ripple-laminated sandstone, and occasional heterolithic beds. The Renji Sandstone Formation has good exposure for this facies association in Tamabil and Naya Gang sections. Channel deposits are characterized by multi-storied and laterally coalesced channels indicating high energy conditions in the tidally influenced fluvio-deltaic depositional environment (Fig. 8a). This facies association, composed of an overall fining-upward sequence with basal erosional surfaces and predominantly sandstone with subordinate shale, can be characterized as LST (Fig. 9).

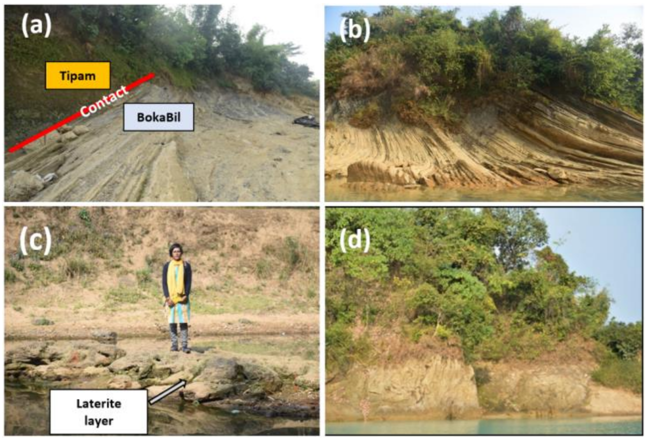

Figure 7: Photographs Show (a) The Contract between Tipam and Boka Bil; (b) Heterolithic Beds in Surma Group with Occasional Calcareous Bands; (c) Laterite Layer Marking Contact between Surma and Barail Formations, (d) Upper Gas Sand (UGS)

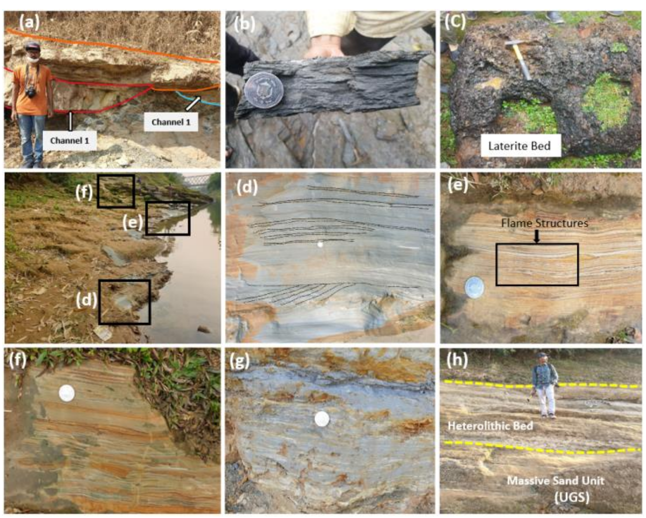

Figure 8: Photographs Show (a) Channel Sand Facies in Tamabil Section, (b) Dark-colored Shale in Rangapani Section, (c) Laterite Facies in Naya Gang Section, (d) Trough Cross-bedding and Parallel Bedded Sandstone Facies, (e) Flame Structures, (f) Ripple-laminated Sandstone Facies, (g) Heterolithic Bedding, and (h) Massive Bedded Sandstone (UGS)

The lithofacies in the sedimentary succession of the Surma Group and the under-and overlying Renji and Tipam formations in the Zaflong-Tamabil-Jaintiapur area is demonstrated in Figures 9 and 10. About 2250m of sedimentary lithocolumn is constructed from the information collected from the field. At the bottom, an erosional contact through channel-lag, stacked channels, and channel fill deposits is noted, indicating the base of the Renji Formation. However, at the top, a laterite bed (~1m thick) appears as the end of the Renji sandstones, where the Bhuban Formation begins (Fig.7c, 8a, and 9). The laterite facies were seen in between Bhuban and Renji formations. The presence of laterite indicates sharp changes in depositional setting, sediment supply, and climatic conditions. Laterite forms due to intense and extended weathering of the host rocks, often when there are high temperatures and significant rainfall with alternative wet and dry climates. Washout holes and larger pore spaces are seen here due to weathering and erosion of soft lithologies (Fig. 7c and 8c). About 1500m of a sedimentary succession of the Surma Group over the Renji Formation was obtained from fieldwork (Fig. 10). A regional 80m thick dark-grey shale (UMS) has been observed near Surma Group's top. UMS is underlain by UGS of Boka Bil Formation and overlain by a small sequence of heterolithic beds, which is terminated by a regional unconformity marked by the conglomerate bed and a massive sandstone of Tipam Group.

The lithology and the sedimentary structures are shown in the lithocolumns. Taking the 'SYL-07' log as a reference (Fig. 4), the transgressive surface, maximum flooding surface, sequence boundaries, and system tracts are marked in the composite log (Fig. 9, 10). A third-order sequence is bounded by two sequence boundaries (3_SB1 and 3_SB2). In the lithocolumn, the third order system tracts are denoted as 3_LST (Renji Formation), 3_TST (Bhuban Formation), 3_HST (Boka Bil Formation), and 3_LST (Tipam Formation), respectively, from bottom to top. The top 3_LST (Tipam Formation) is separated from the underlying sequence by a sequence boundary (3_SB2). The fourth-order sequences are shown as 4_SB3-4, fourth-order flooding surfaces as 4_FS3-4, and fourth-order transgressive surfaces as 4_TS3-4 in the Boka Bil Formation. Contact between Bhuban and Boka Bil formations is in the missing section from 1300 to 1400m.

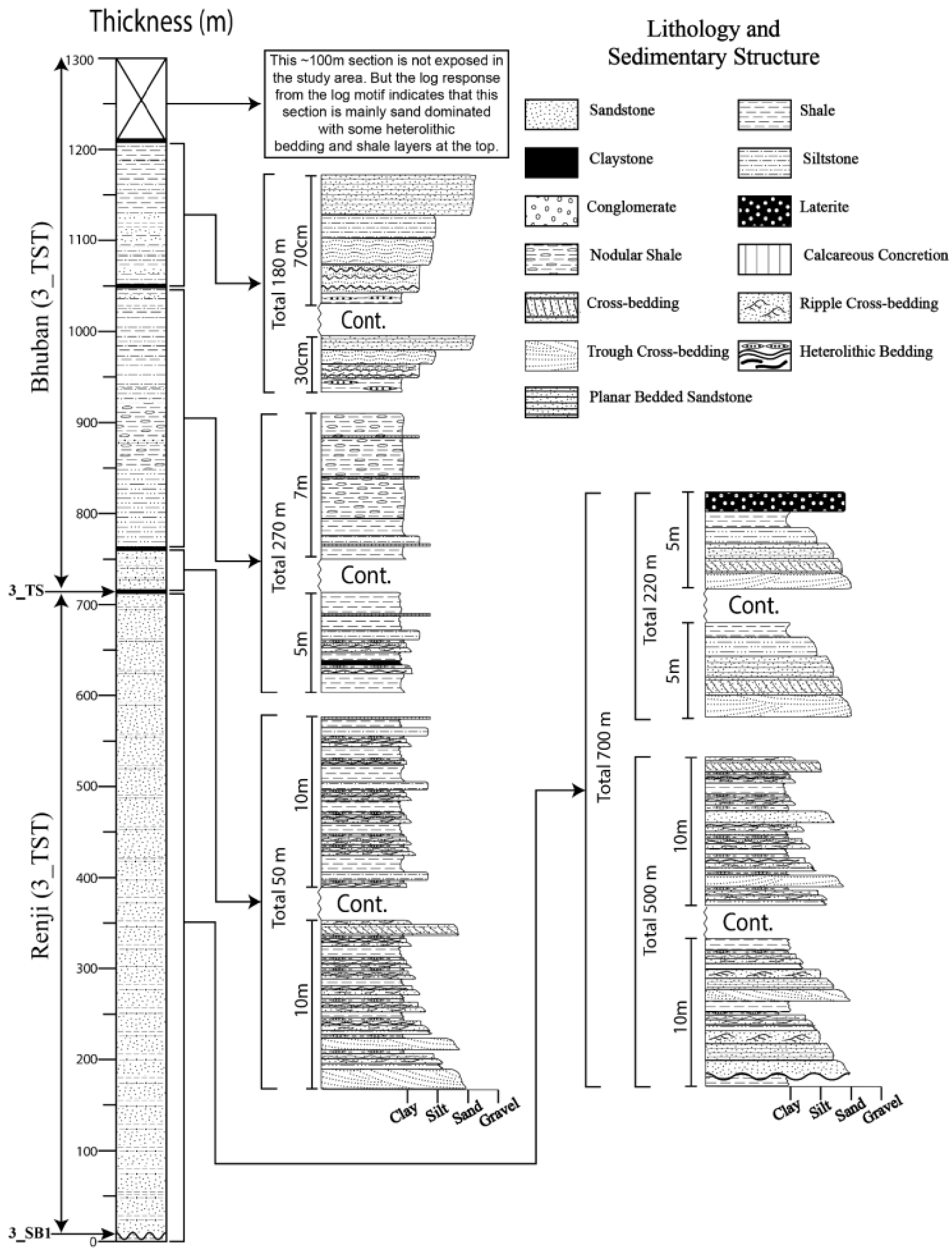

Figure 9: Schematic Composite Litholog of Surma Group in Sylhet Area (1). The Log is Subdivided into Five Sections, and a detailed log is drawn for each Section. The Zigzag Lines Correspond to the Continuation of the Rock Sections, which are Similar in Their Lithologic Characteristics. The Top of the Log is a Missing Section as this Part was not Encountered in the Field. The Third-order Regional Sequence Boundary at the Bottom is marked as 3_SB1, and the Transgressive Surface is Demarcated as 3_TS. Renji and Bhuban Formations are denoted as 3_LST and 3_TST, Respectively. Lithology and Sedimentary Structures are Provided with Symbols in the top Right Part of the Figure

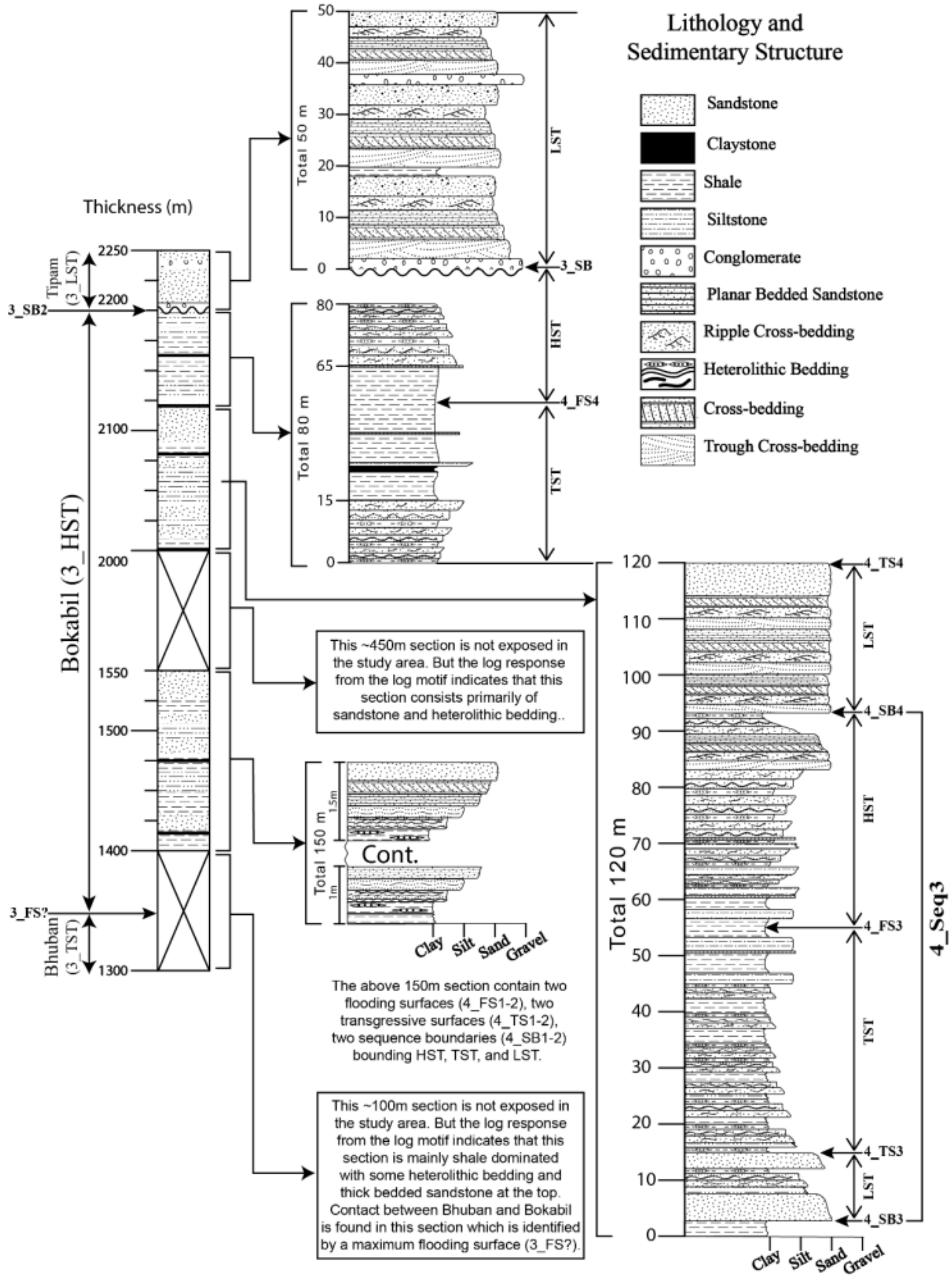

Figure 10: Schematic Composite Litholog of Surma Group in Sylhet Area (2). The Log is Subdivided into Six Sections, and a Detailed Log is Drawn for each Section. The Zigzag Lines Correspond to the Continuation of the Rock Sections, which are Similar in Their Lithologic Characteristics. The Missing Section is the Bottom of the Log and the Section from 1550 to 2000m. Arrowheads Show the Sequence Boundaries and the Surfaces (Flooding and Transgressive). The Boka Bil and Tipam Formations are Denoted by 3_HST and 3_LST, Respectively. The Contact between Bhuban and Boka Bil Formations (3_FS?) is in the Missing Section between 1300 and 1400m. But as the Boundary was not Encountered in the Field, a Question Mark (?) was Provided. Fourth order Sequences (4_Seq3) and System Tracts (LST, TST, HST). Lithology and Sedimentary Structures are Provided with Symbols in the Top Right Part of the Figure

This is a flooding surface denoted by 3_FS? (Fig. 10). The exact location of the contact has not been determined from the field investigations; therefore, some uncertainty remains in the delineation of this contact. Massive to thick-bedded sandstones of the Surma Group often show graded-bedding, low-angle cross-bedding, parallel- and ripple-laminated structures, and medium- to fine-grained, high-porosity textures (15–25%). All these characteristics in UGS and other sandstones in the middle and lower part of the Surma Group indicate reservoirs with the highest potential. These sandstones occur as high-frequency LST or HST, where the erosional remnants are overlain by TST (fourth order in this case). Most sandstones have excellent textural and compositional homogeneity and lateral continuity, which allows hydrocarbons generated at depth and transported through fractures, joints, and faults to accumulate in the reservoir. The overlying thick shale layers (high-frequency HST or TST; UMS, for instance) often act as the regional seal.

Despite the widely used stratigraphic scheme proposed by Evans (1932), many researchers have challenged the acceptance of the so-called practiced stratigraphy of Bangladesh (Holtrop and Keiser, 1970; Gupta, 1977; Lietz and Kabir, 1982; Johnson and Alam, 1991; Reimann, 1993; Gani and Alam, 2003; Davies, 2003; Imam, 2013). Instead of traditional stratigraphic classification, chronostratigraphy of the Bengal Basin can be established by resolving lithostratigraphic ambiguities in the sequence stratigraphic framework (Lietz and Kabir, 1982; Hubbard et al., 1988; Davies, 2003; Gani and Alam, 2003; Najman et al., 2012). The proposed system tracts bounded by confining surfaces are equivalent to the Renji, Bhuban, Boka Bil, and Tipam formations. This proposition is comparable to the seismic megasequence framework proposed by Hubbard (1988), which followed the stratigraphic framework given by Van Wagoner (1988), sequences of Galloway (1989), parasequences of Van Wagoner (1990), etc.

Hence, the proposed third- and fourth-order sequence-based framework is demonstrated by utilizing petrophysical, seismic, and field investigation data and the published work and data of Lietz and Kabir (1982), Salt et al. (1986), Lindsay et al. (1991), Davies (2003), Gani and Alam (2003), and Najman et al. (2012). Detailed studies in a basin-scale framework might be more beneficial in establishing the stratigraphy of the Bengal Basin. However, analyzing petroleum systems in a sequence stratigraphic framework is helpful from an exploration and development perspective. Because in this case, it is easy to analyze and evaluate the petroleum system by analyzing the lateral and vertical facies variations.

CONCLUSIONS

The research was a commendable effort to establish the sequence stratigraphic framework that can aid in evaluating the hydrocarbon prospectivity of the Surma Group sediments in the Sylhet area. In this study, the log responses of the 'SYL-07' well were employed for log motif analysis and a well-seismic tie. Three (3) high-quality 2D seismic lines were used to correlate the log motif with the outcrops. From the 'SYL-07' well, an upper third-order Lowstand System Tract, followed by the third-order Highstand System Tract, and underlying third-order Transgressive System Tract were detected, which correspond to Tipam, Boka Bil, and Bhuban formations, respectively. The fourth-order sequences, including fourth-order system tracts, were identified (bounded by sequence boundaries, flooding, and transgressive surfaces) in the regional context by analyzing seismic attributes, which were done after performing well to seismic tie. The composite lithocolumn of about 2250m corresponds to Renji (3_LST), Bhuban (3_TST), Boka Bil (3_HST), and Tipam (3_LST) formations from bottom to top. From the study following conclusions can be drawn.

- This is an integrated approach of field data, seismic, and well-log data interpretation, which help identify sequence stratigraphic system tracts with their corresponding depositional environments. This is an excellent research method to establish the sequence stratigraphic framework.
- A total of nineteen (19) facies and seven (7) facies associations aid in determining the depositional environments, stacking patterns, and third-order system tracts.

- The fourth-order sequences, including system tracts in the 3_HST, provide evidence of petroleum system elements in the study area.
- Three new prospects in the nose and flank area of the Sylhet structure have been identified based on seismic attributes and log responses. Seismic sweetness attribute anomalies confirmed the existence of these prospects.
- The erosional remains of the fourth-order system tracts in the 3_HST (Boka Bil Formation) covered by intermittent transgressive shale, UMS, for instance, have provided a proper combination of petroleum system elements for the Surma Basin.
- The upper 3_LST (Tipam Formation) is not considered a petroleum reservoir as any seal has not overlain this.

This research is a noble approach to evaluating the hydrocarbon system in mature fields or frontier settings. This study has shown that a comprehensive stratigraphic analysis of the Sylhet area based on a seismic sequence stratigraphic framework and an outcrop study can help predict and discover commercial hydrocarbon accumulations.

RECOMMENDATION

i) High-resolution close-grid 2D seismic data can improve understanding of the seismic attribute and aid in evaluating hydrocarbon prospectivity.

ii) 3D seismic data can be acquired to understand stratigraphic prospects' extent and geometry better and reduce hydrocarbon exploration and development uncertainties.

iii) The sequence stratigraphic framework obtained from this study would be significantly improved by introducing Biostratigraphic analysis on appropriate core and outcrop sample

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