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Research paper

Comprehensive sedimentological and sequence stratigraphic characterization of the exposed Boka Bil Formation, Surma Basin, Northeastern Bangladesh

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Abstract

The Surma Basin, situated in northeastern Bangladesh along the northeastern margin of the Indian subcontinent, is a region characterized by tectonic activity. This study investigates the Miocene siliciclastic sedimentary succession exposed at the Hari River section in Lalakhal, Jaintiapur, to explore its depositional environments and sequence stratigraphic architecture. Field observations and sedimentological analysis reveal two primary facies associations within the Boka Bil Formation: FA1 (tide-dominated environments) and FA2 (shelf environments). FA1 includes three facies: Facies A (tidal channel deposits), Facies B (alternating sandstone and mudstone representing overbank deposits), and Facies C (distal overbank deposits), which together depict a lateral transition from tidal channel margins to spillover deposits. FA2 consists of Facies SL1 (inner shelf deposits) and Facies SL2 (outer shelf deposits), representing deeper marine environments. The Boka Bil Formation displays a retrogradational stacking pattern, with a fining-upward sequence that transitions from shallow to deeper marine conditions. This pattern is indicative of a transgressive systems tract, driven by rising sea levels. The deepening-upward facies succession highlights the dynamic interplay between tectonic forces and sea-level changes in an active margin setting. These findings enhance our understanding of sedimentary processes, paleoenvironmental evolution, and regional stratigraphy, providing valuable insights for resource exploration in tectonically influenced basins.

Keywords: *Facies; Sequence Stratigraphy; Shelf; Sea Level Change; Tectonic.*

1. Introduction

The Bengal Basin, situated in the northeastern part of the Indian subcontinent, represents a critical tectonic junction where the Indian, Burmese, and Eurasian plates converge. Within this extensive basin, the Surma Basin acts as a major depocenter, accommodating thick clastic sediment sequences primarily derived from the Ganges, Brahmaputra, and their ancestral river systems, which transport sediments from the rapidly uplifting Himalayas. The sedimentary succession within the Surma Basin reaches an impressive thickness of approximately 17 km, spanning from the Eocene to Recent periods [1-3].

This study focuses on the sedimentary exposures of the Boka Bil Formation along the Hari River section in the northeastern Surma Basin, a prominent hydrocarbon-bearing zone within the Bengal Basin. The study area is geographically bounded by the Khasi-Jaintia Hills and Shillong Plateau to the north, the Goyain Trough and Surma River alluvial plains to the south, the Atgram structure to the east, and the foothills of the Khasi-Jaintia ranges to the west. Stratigraphically, the Surma Basin is dominated by clastic sedimentary deposits, with the Eocene Sylhet Limestone being a notable exception [3].

The sedimentation in the Surma Basin is closely linked to tectonic uplift and erosion processes in the Himalayas and Indo-Burman Ranges, driven by the collision of the Indian plate with the Burmese and Eurasian plates [4-7]. Despite its geological significance, the stratigraphy of the Surma Basin remains poorly defined. Many stratigraphic correlations are based on the adjacent Assam region, which has a distinct tectonic and depositional history [8].

A key limitation in the Surma Basin's stratigraphy is the general lack of significant fossil assemblages, apart from the Eocene Sylhet Limestone, which restricts biostratigraphic correlations. Although previous studies have investigated the exposed outcrops of the Boka Bil Formation, detailed sedimentological and sequence stratigraphic analyses remain scarce. This gap underscores the need for comprehensive research to elucidate the sedimentological characteristics and sequence stratigraphic framework of the Boka Bil Formation, particularly along the Hari River section.

Adopting a sequence stratigraphic approach is essential to unravel the depositional environments and stratigraphic architecture of the Boka Bil Formation. By linking sedimentary patterns to global eustatic sea-level fluctuations, sequence stratigraphy offers a powerful tool for interpreting depositional processes and refining stratigraphic models [9]. This approach not only advances geological understanding but also enhances hydrocarbon exploration by improving the predictability of subsurface reservoir distributions.

In this study, facies analysis and facies associations are employed to characterize the depositional environments of the Boka Bil Formation. These findings are integrated into a sequence stratigraphic framework to establish a detailed sedimentological and stratigraphic model, providing valuable insights for future research and aiding in the identification of potential hydrocarbon reservoirs within the Surma Basin.

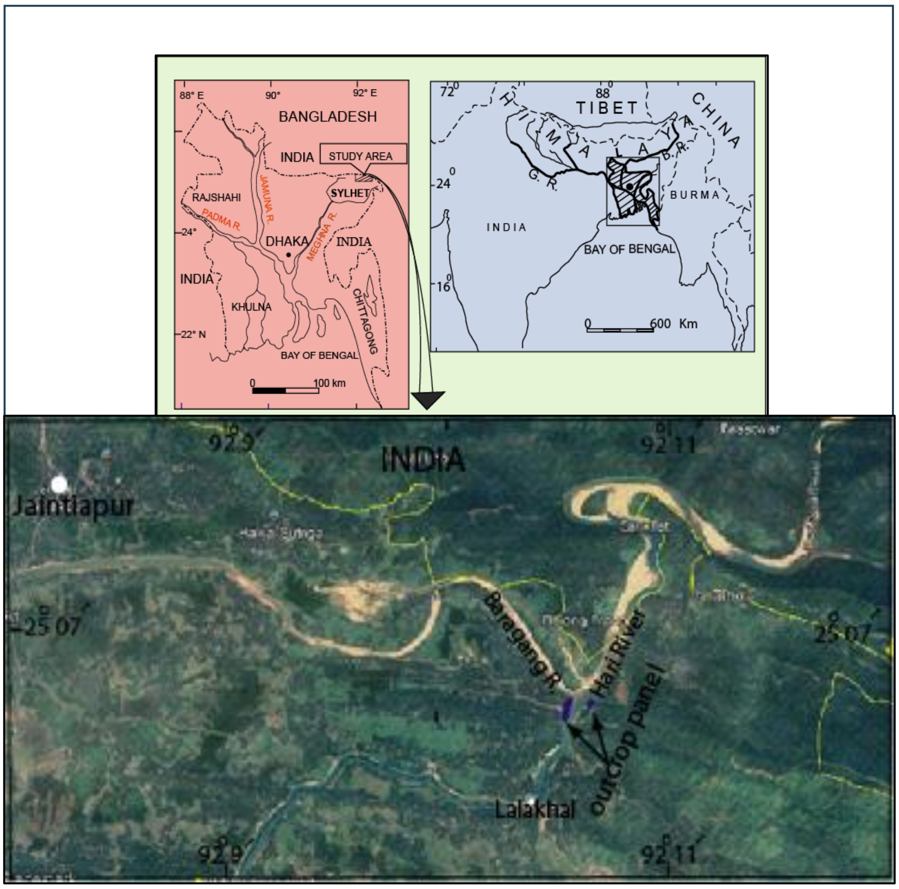

Fig. 1: Location Map of the Study Area.

2. Geologic setting

The Surma Basin, also known as the Sylhet Trough, is a prominent sub-basin of the Bengal Basin, located in the northeastern part of Bangladesh [1], [10], [11]. This basin exhibits significant geological complexity, influenced by a variety of tectonic processes that have shaped its stratigraphy and sedimentary development.

To the north, the Surma Basin is bordered by the Shillong Massif, the sole elevated landform within the Himalayan foreland region. The Shillong Massif is primarily composed of Precambrian basement rocks of the Indian Plate, overlaid by Cenozoic sedimentary sequences [12]. These ancient rocks serve as a key source of sediments that are transported into the basin by large river systems. The eastern boundary is marked by the Dauki Fault, an east-west trending structure that separates the Sylhet Trough from the Shillong Massif. This fault, identified as a thrust fault with a right-lateral strike-slip component, highlights complex tectonic interactions associated with the ongoing convergence of the Indian and Eurasian plates [13]. The Dauki Fault is pivotal in accommodating regional tectonic stress, significantly influencing both the structural evolution and sedimentation patterns in the basin [3], [10].

In the southeast, the basin is constrained by the Chittagong-Tripura Fold Belt, part of the broader Indo-Burman Ranges (Fig. 2). This fold belt is characterized by intense folding and thrust faulting due to the oblique convergence of the Indian Plate along its eastern margin [4]. To the west, the basin is bounded by the stable cratonic platform of the Indian Shield. The juxtaposition of these geological features illustrates the tectonically active nature of the Surma Basin, with profound implications for its sedimentary architecture and basin development.

The Surma Basin functions as a foredeep basin, accumulating substantial clastic sediments primarily sourced from the uplift of the Himalayan orogeny and the Indo-Burman Ranges. This sedimentary influx has contributed to the formation of a thick sedimentary column exceeding 17 km, with deposits spanning from the Eocene to the present [2]. The stratigraphy of the Surma Basin, arranged in ascending order, consists of: Sylhet Formation (Eocene), Kopili Formation (Late Eocene to Early Oligocene), Barail Formation (Oligocene), Bhuban Formation (Early to Middle Miocene), Boka Bil Formation (Middle to Late Miocene), Tipam Formation (Late Miocene), Girujan Formation (Pliocene), Dupi Tila Formation (Pleistocene), Dihing Formation (Pleistocene to Holocene), and Quaternary Alluvial deposits (Table 1).

This study focuses on the Boka Bil Formation, which is well-exposed along the banks of the Hari River. The Boka Bil Formation is characterized by alternating layers of sandstone, siltstone, and shale, indicative of depositional environments transitioning from deltaic to shallow marine settings [14]. This formation is of particular significance, as it presents favorable conditions for hydrocarbon accumulation, with potential as a reservoir unit [2].

The tectonic history of the Surma Basin has played a central role in shaping its stratigraphy. The interplay of tectonic uplift, erosion, and sediment influx from the surrounding orogenic belts has led to the formation of a diverse range of depositional environments [5, 6]. These processes have created conditions conducive to hydrocarbon accumulation, particularly within the deeper sedimentary sequences. The interaction of thrust faulting, sediment compaction, and subsidence has resulted in the development of potential reservoir and trap structures, making the Surma Basin a key target for future hydrocarbon exploration [15]. Comprehensive studies of formations such as the Boka Bil Formation are crucial for advancing understanding of the region's sedimentary processes and tectonic controls, which are essential for optimizing hydrocarbon resource exploration.

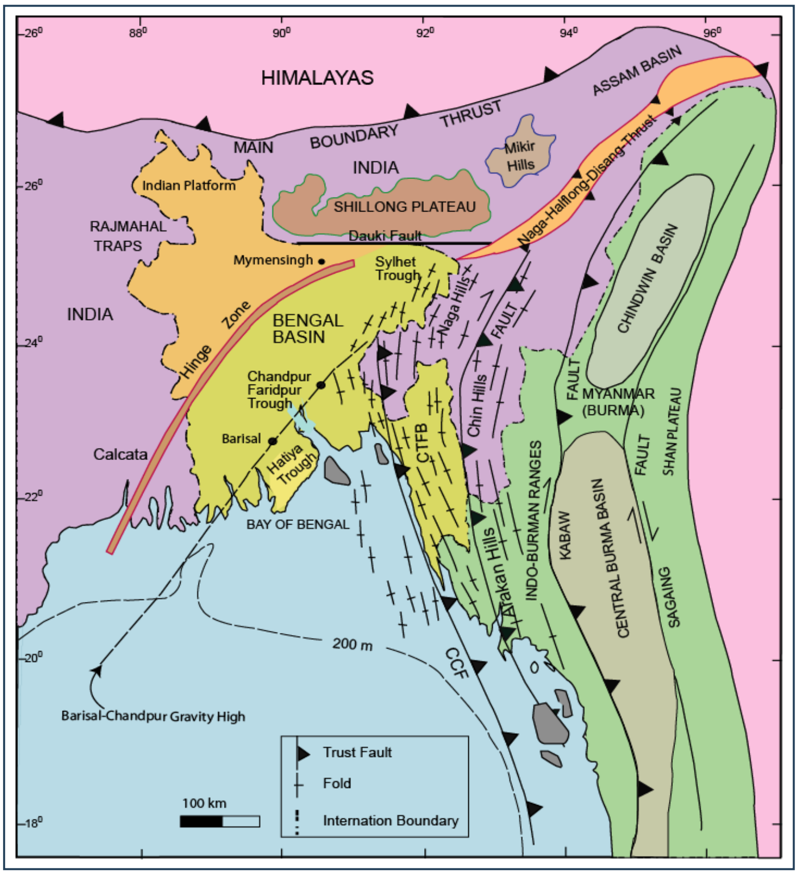

Fig. 2: Tectonic Map of the Bengal Basin and Surrounding Areas [2]. CTFB= Chittagong Tripura Folded Belt, CCF= Chittagong Cox's Bazar Fault.

3. Methodology

The exposed outcrops along both banks of the Hari River present an excellent natural setting for conducting a detailed quantitative facies analysis and assessing vertical and lateral facies variations. To investigate the Miocene sedimentary succession of the Surma Basin, an integrated approach involving fieldwork, sedimentological analysis, and sequence stratigraphy was employed. This multi-faceted methodology aimed to reconstruct the depositional architecture and stratigraphic frameworks essential for understanding the geological history of the region.

Table 1: Summarized Cenozoic Stratigraphy of the Northeastern Surma Basin [1], [14]. Except Tura Sandstone, All Other Formations Are Exposed and Studied in this Work. Seismic Megasequence Framework of Cairn (Modified From [16]) Showing Lithostratigraphy and Its Comparison to the Traditional Stratigraphy

Age (approx.)			Traditional nomenclature [8]		Brief lithology	Depositional environments	Mega-sequence (Cairn)	Mega-sequence (Shell)
Quaternary	Recent		Alluvium		Sand, silt, clay			MS3
	Plio-Pleistocene		Dihing		Granules, pebble, cobble, boulder	Fluvial	MS3	
			Dupi Tila Fm.		Sandstone, Shale			
Neogene			Tipam Group	Girujan Clay Fm.	Clay, mudstone			MS2
				Tipam Sst. Fm.	Sandstone, shale		MS2	
	Miocene	Late	Surma Group	Boka Bil Fm.	Sandstone, shale, siltstone, sandy shale			
		Early Middle		Bhuban Fm.	Shale, sandstone, silty shale	Deltaic		
Paleogene	Oligocene		Barail Group	Renji Jenam Laisong	Sandstone, shale		MS1	MS1
	Eocene		Jaintia Group	Kopili Shale	Shale, minor limestone	Shallow marine		
				Sylhet Limestone	Limestone			
	Paleocene			Tura Sandstone	Coarse grained sandstone with minor limestone			

3.1. Fieldwork and data collection

In the field, lithofacies were identified through systematic observations of lithological characteristics, including rock type, bedding structures, grain size, texture, fossil content, and primary sedimentary and syn-depositional features. A high-resolution sedimentary logging method was employed to document facies, facies associations, and their spatial relationships across multiple stratigraphic sections. Detailed stratigraphic sections were logged at key outcrop exposures to capture the vertical and lateral variability of the sedimentary units (Fig. 3). To quantify the orientation of bedding planes, the strike, dip direction, and dip angle of exposed sections were measured using a geological compass. These measurements were used to construct vertical profiles through trigonometric calculations [17]. The documented data include sedimentological attributes such as bed thickness, lateral continuity, sedimentary structures, textural properties (e.g., grain size, sorting, and roundness), and unit boundaries. These features were graphically represented in sedimentary logs for subsequent facies analysis following the protocols outlined by Miall [18].

3.2. Sedimentological logging and facies analysis

The logged sections were meticulously analyzed to classify lithofacies based on their sedimentological attributes. Facies were grouped into facies associations, reflecting genetically related facies indicative of specific sub-environments within a broader depositional system [19, 20]. This classification helps elucidate the depositional environments that influenced the sediment accumulation processes in the Miocene strata of the Surma Basin.
Photographic documentation of key sedimentological features was conducted to supplement the graphical logs, ensuring a comprehensive record of the outcrops. Parameters such as bedding style, sedimentary structures (e.g., cross-bedding, ripple marks), and bioturbation intensity were carefully documented to facilitate accurate facies interpretation.

3.3. Sequence stratigraphy approach

The study further integrated sequence stratigraphic principles to delineate the depositional history of the study area. Sequence stratigraphy provides a framework for dividing the rock record into discrete units (parasequences, parasequence sets, and systems tracts) based on the recognition of key stratigraphic surfaces and stacking patterns [20]. This approach was crucial in identifying surfaces such as maximum flooding surfaces, transgressive surfaces, and sequence boundaries, which are essential for interpreting changes in relative sea level and sediment supply.
The identification of systems tracts allowed for the differentiation of depositional sequences, facilitating a more detailed understanding of the sedimentary architecture. These systems tracts were interpreted in the context of accommodation space, sediment supply, tectonic influences, and relative sea-level fluctuations within the basin. By analyzing the stacking patterns of parasequences, insights were gained into the cyclic nature of sedimentation and basin evolution.

3.4. Integration with regional stratigraphic framework

The sedimentological and sequence stratigraphic data obtained from this study were integrated into the established mega-sequence framework of the Surma Basin, as outlined by Najman [5]. This synthesis enabled a correlation of the exposed Miocene strata with subsurface units, contributing to a more comprehensive stratigraphic model for the region. The results provide critical insights into the depositional history and potential hydrocarbon reservoirs within the basin.

4. Results

4.1. Facies associations of the Boka Bil Formation

This study investigates the sedimentary successions of the Bokabil Formation within the Surma Group, identifying two principal facies associations: the Tide-Dominated Facies Association (FA1) and the Shelf Facies Association (FA2). These facies associations, arranged in a stratigraphic sequence from older to younger deposits, directly overlie the Bhuban Formation. This stratigraphic framework provides valuable insights into the depositional environments and sedimentary processes that prevailed in the region during the late Miocene to early Pliocene.

FA1: Tide dominated facies association

The Tide-Dominated Facies Association (FA1) primarily comprises the upper section of the Bhuban Formation and the lower part of the Bokabil Formation. The 70-meter-thick sedimentary succession of these formations demonstrates significant lateral facies variability and constitutes a channel-fill complex. This facies association is represented by three distinct facies: Facies A, Facies B, and Facies C (Fig. 3).

Facies A: Tidal channel deposits

This facies comprises massive and cross-stratified, medium-grained sandstone, with a total thickness of approximately 10 meters. The massive sandstone bed, measuring about 5 meters thick, lacks evidence of grading and bioturbation. Frequent occurrences of mud clasts are observed within this bed. Overlying the massive bed are cross-stratified sandstone layers, characterized by tangential, planar, or sigmoidal cross-stratification patterns. These cross-stratified units often contain thin mud layers, referred to as mud drapes (Fig. 3A). The foreset beds within this interval vary in thickness from 2 to 35 cm. Notably, the foresets are frequently accentuated by continuous or discontinuous mud drapes and trains of millimeter-sized mud clasts.The sandstone layers in the cross-stratified section exhibit systematic lateral thickness variations, which are indicative of a typical tidal bundle sequence [22]. Some foreset beds also display ripple cross-lamination, with ripples oriented up-dip along the foreset slope. The paleoflow direction inferred from the cross-stratification is toward the northwest (NW). Laterally, this facies transitions into the adjacent Facies B, as shown in Figures 3 and 4.

Interpretation

The features described suggest that this facies represents tidal channel deposits. The massive sandstone bed indicates rapid sedimentation from suspension fallout, which inhibits the formation of tractional sedimentary structures [23]. This rapid deposition is interpreted as the result of density currents, such as turbidity currents. The cross-stratification, which includes ripple cross-laminations on the foreset beds, exhibits flow reversals, as evidenced by ripple orientations opposite to the foreset dip direction. This suggests frequent changes in flow direction during deposition, a characteristic feature of tidal environments. The presence of mud drapes over foreset beds and superimposed ripples indicates periods of flow stagnation before the flow direction reversed, consistent with tidal current dynamics. The occurrence of typical tidal bundle sequences further supports a tidal origin for these facies [22]. Additionally, the mud clasts are likely the result of minor erosion of underlying mud layers. The absence of bioturbation in this facies suggests a high sedimentation rate, preventing the establishment of benthic organisms during deposition.

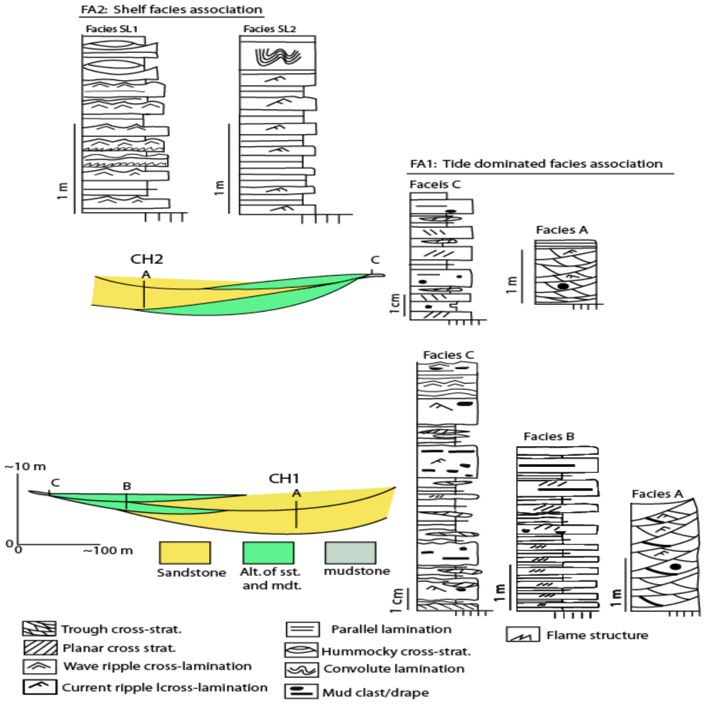

Fig. 3: Schematic Columnar Cross-Sections of Facies Associations FA1 and FA2 from the Lower Part of the Boka Bil Formation are Presented. These Diagrams Clearly Illustrate the Spatial and Vertical Relationships Among the Three Identified Facies, Using A Simplified Schematic Format for Enhanced Understanding.

Facies B (Overbank deposits)

The facies B is characterized by alternations of fine sandstone and mudstone. This facies passes laterally from Facies A and then grades into Facies C (Fig. 3). The sandstone beds vary in thickness from 5 to 40 cm and contain small-scale cross-stratification. The sandstone bases are commonly erosive, and mud clasts are scattered in the sandstones. Within the sandstone bed, mud clasts are occasionally found. The medium to thinly-bedded mudstone shows parallel lamination. Some of the sand beds rapidly thin toward the directions away from the Facies A sandstone beds (Fig. 4E).

Interpretation

The facies is interpreted as an overbank deposit, or the deposits accumulated in the marginal part of the tidal channel. Changes of lithology from the facies A (i.e., sandy facies to muddy facies) imply that the velocity was rapidly waned away from the channel. The presence of mud drapes is also suggestive of the influence from the tidal currents on the sediment accumulation.

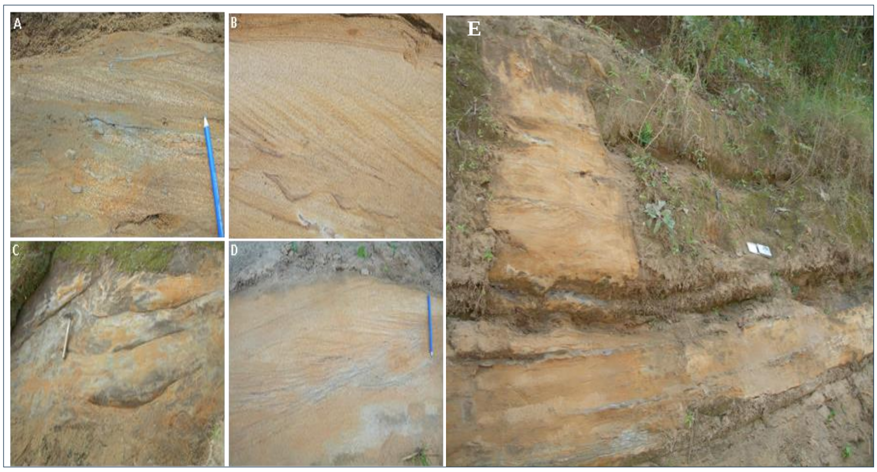

Fig. 4: Close-Up Photographs Illustrate Cross-Stratified Sandstone (Facies A) from the Boka Bil Formation. (A) Displays Cross-Stratified Sandstone with Small Mud Clasts, Using A 15 Cm Scale. (B) Sigmoidal Cross-Stratification in An Outcrop Approximately 30 Cm High. (C) Highlights Trough Cross-Stratification, Where Individual Units Are Separated by Prominent Mud Drapes; A 30 Cm Trowel Is Used For Scale. (D) Depicts Cross-Stratified Sandstone Featuring A Tidal Bundle Sequence, With A 15 Cm Scale For Reference. (E) Exhibits The Stratigraphic Alternation of Sandstone and Mudstone within Facies B, with A Distinct Thinning of the Beds From Left to Right. A Clinometer Is Provided for Scale Reference.

But the laminated mudstone covering the sandstone beds implies that the calm condition continued between the depositions of sandstone beds. Sand was supplied, suggesting in the deposition of the marginal part of the channel or the area adjacent to the channel (overbank), only when the strong currents passed within the channel. Even when strong current (e.g., turbidity current) passed within the channel and surrounding area, the deposition was influenced by tidal current as shown by mud drapes within the beds. Laminated mudstone contains very thin sandstone layers, which are probably associated with the tidal current in the calm periods.

Facies C (Distal overbank deposits)

This facies is dominated by mudstone-rich sediments interbedded with thin sandstone layers. It comprises three sub-facies: lenticular-bedded facies (C1), flaser-bedded facies (C2), and wave ripple-laminated sandstone-mudstone facies (C3).

Lenticular bedded facies (C1) consists of light gray to yellowish gray, very fine-grained sandstone and coarse to fine siltstone having the appearance of biconvex lenses embedded in muddy layers. These lenses have ripple cross-lamination and are isolated or weakly connected to each other (Fig. 5a). The length of lenses varies from 5 mm to 3 cm, and their average thickness is 6 mm. The thickness of the sub-facies C1 is up to 65 cm. This facies is commonly observed in the lowermost part of the facies C. The internal structure of the lenses shows ripple cross-lamination, commonly referred to as "starved ripples" [24]. The ripples are commonly asymmetrical in nature, but occasionally symmetrical types are found in this facies. Bidirectional paleocurrents trends are observed in these ripples. Above and below this facies, Facies C2 sandstone beds can be recognized.

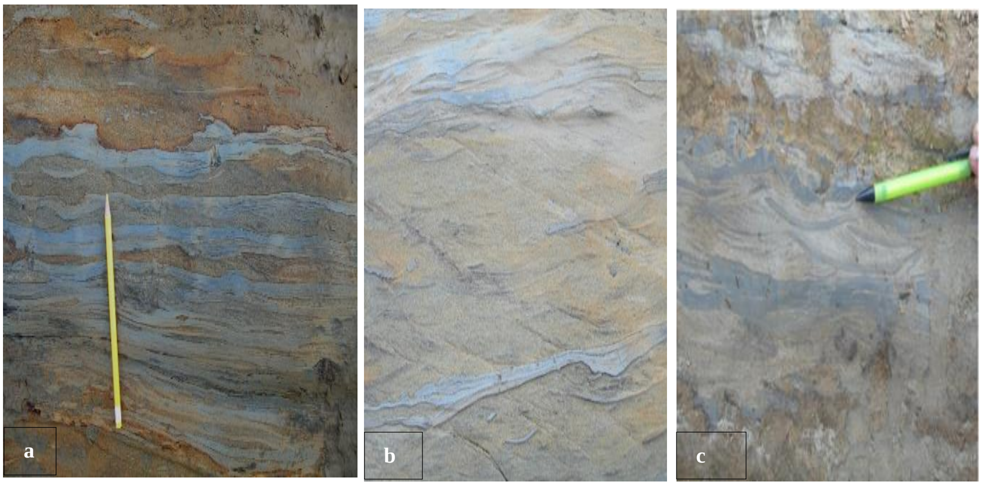

Fig. 5: (A) The Photograph Illustrates Lenticular Bedding (Facies C1) Within the Mud-Dominated Section at the Basal Part of the Boka Bil Formation. A Color Pencil (17 Cm in Length) Is Provided for Scale Reference. The Upper Section of the Photograph Reveals an Increasing Hydrodynamic Influence, As Indicated By The Presence of Mud Drapes, Mud Clasts, and the Characteristic Lenticular Bedding Architecture (B) Photograph Shows Flaser Bedding (Facies C2) in the Lower Part of the Boka Bil Formation (C) Close Up Photograph of the Wave Ripple Cross-Lamination in the Facies C3 in the Lower Most Part of the Boka Bil Formation. the Pencil (7 Cm) Is for the Scale.

Flaser-bedded facies (C2) is represented by light gray to grayish-brown, fine-grained sandstone with dark gray numerous mud flasers and occasionally mud intraclasts. The thickness of this facies is up to 45 cm. The base of the sandstone is a flat or undulatory erosive surface. The sandstone contains ripple cross-stratification and mud clasts in some places. The mud drapes and flaser-shaped mud layers (Fig. 5b) are also in the beds, but they are commonly discontinuous beds. This facies appears just above the sub-facies C1, and the contact boundary between the sub-facies C1 and C2 is gradual.

Wave-ripple laminated sandstone facies (C3) is represented by fine sandstone and mudstone. This facies overlies the sub-facies C2. The thickness of Facies C3 is up to 40 cm. Primary structures are symmetrical wave ripple cross-stratifications (Fig. 5c) in which offshoot and chevron structures are commonly contained and parallel stratifications. This sandstone bed also contains mud drapes, and some of the ripple cross-stratifications are covered by mud drapes. The bases of some beds are erosive and truncate the underlying intervals (Fig. 6a).

Interpretation

The lenticular bedded facies (C1) is interpreted as the deposit of distal overbank environments because this is the distal equivalent of the facies A and B. The lenticular bedded facies, in which the lenticles are internally micro-cross laminated, indicate weak currents in a predominantly low-energy environment. The presence of the cross-stratification showing bidirectional paleoflow suggests that the depositional facies are also affected by tidal current [22]. The flaser bedded facies (C2) is thought to be the product of tidal current and currents spilled over the channel. In this facies, sandstone beds show the normal grading passing upward into the Facies C3 beds, suggesting that the sediments are transported by temporary currents spilled over the channels as interpreted as in Facies B. Mud drapes and flaser-shaped mud drapes suggest that tidal currents are superimposed on the temporary flows. The wave ripple cross-lamination found in the Facies C3 clearly indicates that the facies was accumulated in an environment shallower than the storm wave base. Because the sediments in this interval are predominated by tidal facies and there are many distinct erosional surfaces in the wave ripple cross-laminated sandstone beds, the erosion happened prior to the deposition of the beds, and the preservation of wave ripple lamination might be owing to the sedimentation from the storm waves that overwhelmed the stronger tidal currents. In the Facies C as a whole, tidally influenced sediments are predominant, and the muddy sediments are the major components, together with minor wave-generated sedimentary structures. Therefore, it can be interpreted to be accumulated in an environment, distal overbank of channels developed between fair-weather and storm wave bases.

FA2: Shelf facies association

This facies association is predominantly found in the middle and upper parts of the Boka Bil Formation. It comprises two distinct facies: Facies SL1, representing an inner shelf environment, and Facies SL2, corresponding to an outer shelf to slope environment, each occupying the middle and upper sections of the Boka Bil Formation, respectively (Fig. 3).

Facies SL1 (Inner shelf deposits)

This facies is characterized by fine-grained sandstone beds with wave ripple cross-lamination and hummocky cross-stratification (HCS) and mudstones. The thickness of this facies is approximately 20 m. The thickness of HCS sandstone (Fig. 6C) is about 20 cm. The wave ripple cross-lamination (Fig. 6 A, B) comprises mainly asymmetrical ripples, but on occasion symmetrical ripples are found. The internal structures of the wave ripple cross-lamination represent bundle-wise building up foreset laminae, offshooting and draping foresets, and swollen lenticular sets. Moreover, the load structures are occasionally found on the base of the wave ripple cross-laminated sandstone beds.

Interpretation

This facies is interpreted to have accumulated in an inner shelf environment between fair-weather and storm wave bases. Alternation of sandstone with wave-generated sedimentary structures and mudstone obviously indicates that these structures are formed in the storm periods and mudstones in the fair-weather periods [25]. The presence of load structures within the wave ripple cross-lamination is thought to be the result of differential loading caused by the erosional incision and sand–mud interface deformation by density-driven gravitational instability [26].

Facies SL2 (Outer shelf deposits)

Facies SL2 consists of bluish-gray to black laminated mudstone interspersed with silty sand streaks or lenses. This facies reaches an approximate thickness of 70 m and is overlain by Facies SL2. Facies SL2 includes sandstone layers exhibiting convolute lamination (Fig. 6D). The silty sand streaks within the laminated mudstone range in thickness from less than 1 mm to several millimeters. These streaks vary in continuity, appearing as either continuous or discontinuous layers. Bioturbation and storm-related sedimentary structures, such as hummocky cross-stratification, are absent in these facies. Slump folds are observed in the upper portion of the Boka Bil Formation

Interpretation

Facies SL2 is believed to have formed in an outer shelf environment, as indicated by the absence of wave-generated structures, suggesting deposition occurred below the storm wave base [25]. While the origin of the thinly bedded sandstone lenses or streaks remains unclear due to the lack of clear flow indicators, these features may be associated with tidal currents, which were a dominant sediment transport mechanism during the deposition of the lower Boka Bil and Bhuban formations.

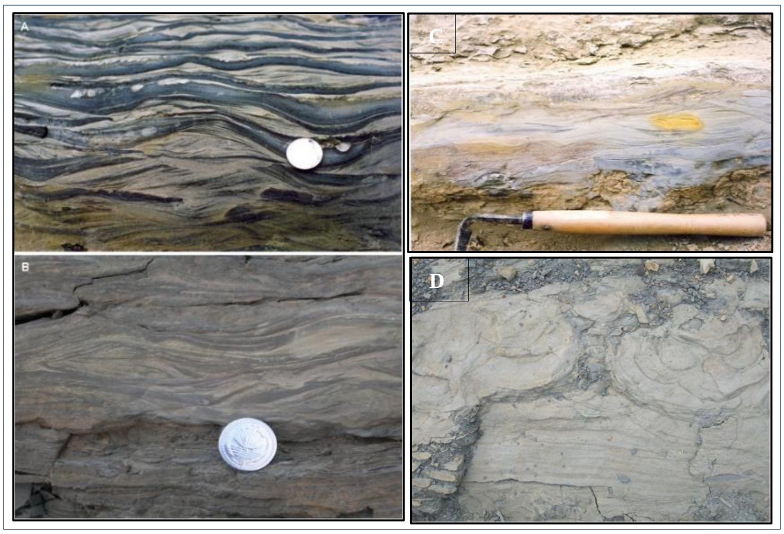

Fig. 6: A) Wave Ripple Cross-Lamination (SL1) in the Middle Part of the Boka Bil Formation. B) Close View of Wave Ripple Cross Lamination. the Coin (2.5 Cm in Diameter) Is for Scale. (C) Small Scale Hummocky Cross-Stratification (Facies SL1) in the Middle Part of the Boka Bil Formation. the Trowel Is 30 Cm Long. (D) Photograph Showing Convolute Lamination (Facies SL2) in the Upper Part of the Boka Bil Formation.

The presence of convolute lamination points to deformation during sediment deposition, likely caused by partial liquefaction, while retaining some cohesion. Slump deposits in the upper part of the Boka Bil Formation further suggest a gravitationally unstable environment during deposition. Consequently, Facies SL2 is interpreted to have formed in a transitional environment between the outer shelf and the slope.

5. Depositional systems and sequence stratigraphy

Sequence stratigraphy is a method used to categorize depositional environments based on their relationship to relative sea-level changes. It is defined as "the study of rock relationships within a chronostratigraphic framework, where rock successions are cyclic and composed of genetically related stratal units" [27]. To reconstruct sequence stratigraphic units from outcrop studies, it is essential first to identify the depositional systems. Through facies analysis, two primary facies associations were identified: tidal-dominated facies association (FA1) and shelf facies association (FA2).

The Miocene succession along the Hari River begins with a tidal-dominated system, characterized by tidal channels and overbank deposits (Facies A, B, and C). While tidal influences dominate the channel-fill deposits, the presence of massive sandstone beds of gravity-flow origin is also noted. These channels do not exhibit lateral accretion patterns, suggesting they are similar to those typically found in tidal flat environments [28]. Sandstones of Facies A indicate the formation of sand bodies in consistent locations, with the potential for these channels to develop an aggradational system, which is unusual in typical tidal-dominated systems.

As the tidal-dominated system transitions upward, it changes into a shelf system (Fig. 7). The lower part of this system is represented by inner shelf deposits (Facies FL1), which gradually transition into outer shelf deposits (Facies FL2) at higher stratigraphic levels. In the uppermost part of the shelf system, slumped deposits are observed, suggesting deposition occurred in a marginal shelf to upper slope environment.

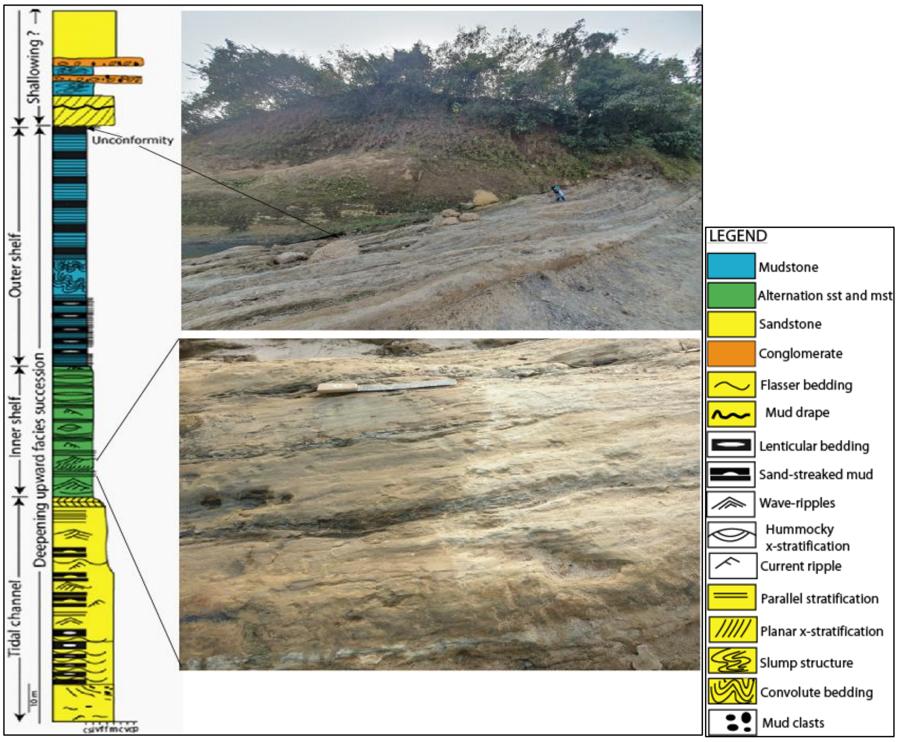

Fig. 7: Representative Lithological Succession of the Study Area, Systematically Depicting Vertical Variations in Depositional Systems and Their Stratigraphic Organization.

5.1. Stacking pattern

The Miocene siliciclastic sedimentary succession initiates with a tide-dominated system, characterized by tidal channel and overbank deposits (Facies A, B, and C). This tide-influenced regime transitions vertically into a shelf system. The lower interval of the shelf succession comprises inner shelf deposits, which grade upward into outer shelf facies (Fig. 8). The uppermost portion of the shelf sequence contains slumped deposits, indicative of post-depositional deformation. These deposits are interpreted to have formed within a transitional zone between the outer shelf and upper slope, reflecting sediment accumulation under conditions influenced by both shallow marine processes and gravitational instability on the slope.

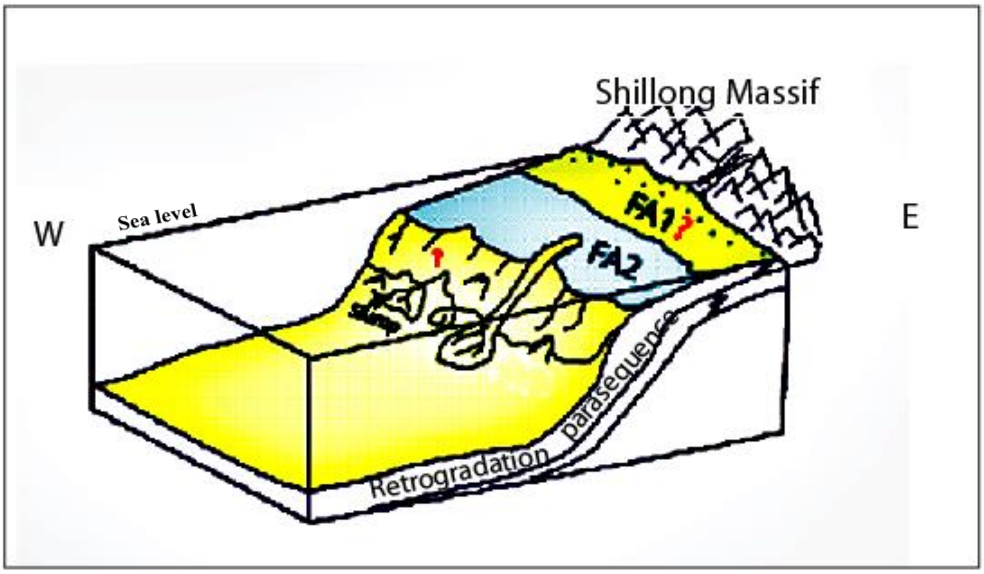

Fig. 8: Conceptual Paleogeographic Model of the Miocene Period Illustrating the Retrogradational Sedimentation Pattern Along the Active Margin of the Shillong Massif and the Indo-Burmese Plate Boundary.

6. Discussion

This study reconstructs the sedimentary facies architecture and its temporal evolution in the exposed Miocene succession of the Surma Basin. Previous studies by Hiller and Elahi [10], Johnson and Alam [11], Reimann [14], Alam et al. [2] and Khanam et al. [1] indicate that the Surma Group sediments were deposited in shallow marine to tide-dominated coastal environments. The sedimentary sequences in the Surma Basin exhibit a hierarchical arrangement, progressing from tide-dominated systems to shelf environments.

In the tide-dominated systems, cross-stratified sandstones accumulate in tidal channels where density-driven turbidity currents play a significant role. These channels exhibit interfingering relationships with overbank deposits, where the velocity of turbidity currents decreases.

The overbank deposits are influenced by tidal currents during calmer periods, reflected by alternating sandstone and mudstone intervals. Approximately 500 meters along strike from the overbank deposits, mudstone-dominated intervals are primarily influenced by tidal currents and are interpreted as the distal parts of the overbank channels.

Tidal signatures are clearly recorded in the Surma Group outcrops, particularly in the Sitapahar and Mirinja anticlines [29] in the southeastern folded belt of the Bengal Basin. These deposits indicate basinward progradation from deep marine to shallow marine and then to continental-fluvial environments.

The Surma Group strata in the Surma Basin reflect deposition in a shallow marine shelf to tide-dominated transitional environment. Sedimentological evidence suggests alternating transgressive and regressive phases, driven by subsidence and changes in relative sea level, as indicated by Sultana [30]. These phases reveal the dynamic nature of the sedimentary processes and the influence of tectonic forces on the deposition of the Surma Group sediments.

As the tide-dominated systems transition into a fining-upward shelf system, the inner shelf deposits show sedimentary structures such as hummocky cross-stratification and wave ripple cross-lamination, developed between the fair-weather and storm wave bases. In contrast, the outer shelf deposits are primarily mudstone and lack storm-generated structures, indicating deposition below the storm wave base. The presence of slump deposits within the outer shelf suggests sediment instability and accumulation near the slope.

boundary.

The vertical relationships between the facies and facies associations provide valuable insights into the depositional history of the Surma Basin. These findings highlight the complex sedimentary architecture of the Miocene succession, offering a clearer understanding of the paleoenvironmental evolution of the basin.

7. Conclusion

The Miocene siliciclastic succession exposed at the Hari River section in the Surma Basin exhibits a retrogradational stacking pattern, signifying a transition from shallow to deep marine environments. This succession reflects the tectonic influence of the active Indo-Burmese plate margin. Based on grain size, sedimentary structures, and bed geometry, the succession is divided into two primary facies associations: FA1 and FA2, arranged from oldest to youngest.

Facies association FA1 is interpreted as representing tide-dominated environments and includes three distinct facies: Facies A, Facies B, and Facies C. Facies A, characterized by sandstone, interfingers with the alternating sandstone and mudstone intervals of Facies B. These facies are laterally aligned, indicating deposition in tidal channels (Facies A), overbank areas (marginal channel) (Facies B), and distal overbank deposits (Facies C), where reduced current velocities play a key role in sedimentation.

Facies association FA2 reflects shelf environments, comprising two facies: Facies SL1 (inner shelf deposits) and Facies SL2 (outer shelf deposits). The observed fining-upward trend in the Boka Bil Formation suggests a deepening-upward succession, primarily driven by relative sea-level rise. This pattern marks a transition from more energetic shallow marine conditions to calmer, deeper marine environments.

The Boka Bil Formation demonstrates a deepening-upward facies succession, highlighting the role of relative sea-level fluctuations in shaping sedimentary processes within the Surma Basin. These findings provide valuable insights into the paleoenvironmental conditions and depositional dynamics of the Miocene. Additionally, the study emphasizes the influence of tectonic activity and sea-level changes on sedimentary successions, contributing to regional stratigraphic models and offering critical implications for subsurface resource exploration in tectonically active basins.

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