International Journal of Advanced Geosciences, 12 (2) (2024) 115-126

International Journal of Advanced Geosciences

Website: www.sciencepubco.com/index.php/IJAG

Research paper

Sequence stratigraphic architecture and facies analysis of the Oligocene Barail Formation, Surma basin, Bangladesh: implications for depositional dynamics and basin evolution

Md. Abdur Rahman [1] *, Md. Shafiqul Alam [2]

[1,2] Department of Geology and Mining, University of Rajshahi, Rajshahi-6205, Bangladesh
**Corresponding author E-mail: rahman72ru@yahoo.com*

Abstract

This study systematically explores the sequence stratigraphy and depositional history of the exposed Oligocene Barail Formation within the Surma Basin, northeastern Bangladesh, an area recognized for its petroleum potential. Using integrated field observations, sedimentological analysis, and sequence stratigraphy, the research examines the influence of tectonics, climate, and eustatic sea-level fluctuations on sedimentary architecture. A total of ten lithofacies were identified and grouped into three facies associations, indicating fluvial to tide-dominated braided channel systems. The Barail Formation is categorized within Megasequence 2 (MS-2), characterized by a regressive erosional surface (RES) at its base and a transgressive erosional surface (TES) at its top, indicating a shift from progradational to retrogradational stacking patterns. Increased terrigenous sedimentation between 38 to 21 million years ago is attributed to regional tectonic uplift and climate change. The analysis revealed six parasequence sets corresponding to distinct systems tracts: PS1 (lowstand) shows regressive sedimentation, PS2 and PS3 (transgressive) exhibit retrogradational stacking, while PS4 and PS5 (highstand) demonstrate progradational stacking patterns. PS6 represents a regressive phase marked by lateritic conglomerates. These insights enhance the understanding of the Barail Formation's depositional environments and contribute to refining sequence stratigraphic models critical for foreland basin hydrocarbon exploration.

Keywords: *Barail Formation; Depositional Environments; Parasequence Sets; Sequence Stratigraphy; Surma Basin.*

1. Introduction

The Oligocene sedimentary succession within the Surma Basin in Northeast Sylhet, Bangladesh, is a significant geological feature, offering insights into complex depositional processes and notable economic potential. The Surma Basin, as part of the extensive Bengal Basin, is recognized for its thick sedimentary layers and rich hydrocarbon deposits [1]. Understanding the facies and sequence stratigraphy of these Oligocene deposits offers valuable perspectives on past environmental conditions, sedimentary processes, and basin development-insights crucial to both geological research and petroleum exploration. One key component of this succession is the Barail sedimentary succession, which is prominently exposed at specific sites, such as the Jaflong-Assampara road cut and Rangpani-Nayagang river sections in the Gwainghat-Jaintiapur area (Fig. 1). The Barail Formation consists primarily of yellowish, yellow-brown, and red-brown thick, medium to coarse-grained sandstone beds, interbedded with grey shales, coal lenses, and lenticular conglomerate beds. The hilly topography in this region is shaped by the Dauki Fault Zone (DFZ), which separates lower hillocks in the west from the high hills in the east. This Dauki Fault serves as the boundary between Bangladesh and India, with floodplains and channels developed by rivers originating from the Shillong Plateau in Meghalaya.

Facies analysis is fundamental to interpreting the characteristics of rocks within a depositional framework, examining lithology, sedimentary structures, fossil presence, and stratification [2].

This method reconstructs ancient environments and allows researchers to understand how depositional settings are distributed within a basin. In the Surma Basin, defining various facies and their depositional contexts is key to deciphering paleoenvironmental conditions during the Oligocene.

Sequence stratigraphy, a complementary approach, focuses on the spatial and temporal relationships among sedimentary layers in response to sea-level changes, sediment supply, and tectonics [3]. Identifying stratigraphic surfaces-such as sequence boundaries, maximum flooding surfaces, and systems tracts-facilitates the construction of a stratigraphic framework that illustrates sediment accumulation and basin evolution. This technique is especially useful for hydrocarbon exploration, as it provides a predictive model for locating reservoirs, source rocks, and seals [4].

The Oligocene deposits of the Surma Basin present an ideal case for combined facies analysis and sequence stratigraphy, revealing interactions between fluvial, deltaic, and marine depositional environments. Although earlier studies highlight the basin's complexity and hydrocarbon potential, a comprehensive understanding of the distribution and stratigraphic relationships of these sedimentary facies remains incomplete. To address this, a detailed facies and sequence stratigraphic investigation is required to uncover the depositional history and structural architecture of the Oligocene succession in northeastern part of Sylhet district.

This study aims to provide an integrated facies analysis and sequence stratigraphy of the Oligocene succession in Northeast Sylhet. The specific objectives include (1) identifying and characterizing distinct facies, (2) interpreting depositional environments, and (3) constructing a sequence stratigraphic framework. These findings will deepen our understanding of regional geological history and support further research in stratigraphic correlations, basin analysis, and hydrocarbon exploration in similar sedimentary basins worldwide.

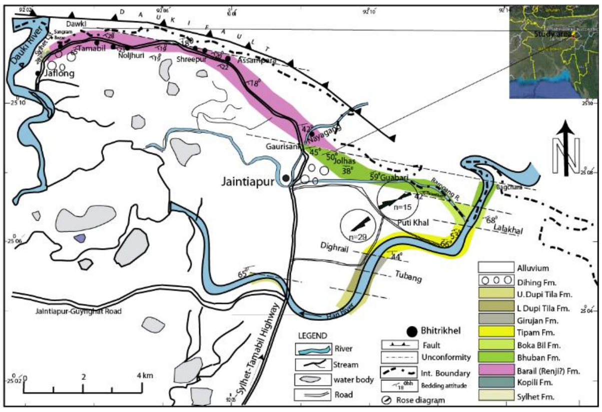

Fig. 1: The Location Map of the Study Area Illustrates the Lithological Distribution of the Exposed Outcrops Around Jaintiapur, Sylhet. The Barail Succession of the Study Area Is Highlighted in Pink As Marked on the Northern Part of the Map.

2. Geological setting and stratigraphy

The Surma Basin, also referred to as the Sylhet Trough, is an important sedimentary basin in northeastern Bangladesh, forming a sub-basin within the Bengal Basin complex. Its formation is linked to continental collision and subsequent subduction of the oceanic portion of the Indian Plate beneath the Eurasian Plate, resulting in a complex tectonic setting that has influenced the basin's stratigraphy and structural framework [5]. Bordered to the north by the Shillong Massif, the Surma Basin features Precambrian basement rocks of the Indian Plate, partially overlain by Cenozoic sediments. The massif, an elevated landform within the Himalayan foreland, plays a crucial role in regional geology, influencing sediment transport and depositional patterns within the basin (Fig. 2).

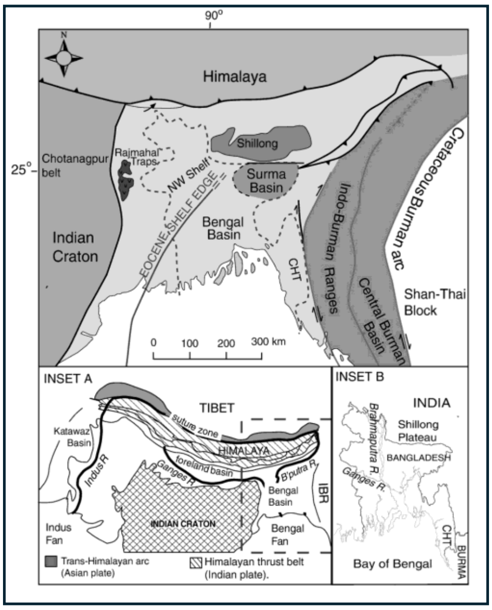

Fig. 2: Map Showing the Surma Basin Along with Major Geological Features and Potential Sediment Source Areas, Including the Himalayas, Indian Craton, And Burman Margin, During Paleogene Sedimentation. The Dashed Line Indicates the Political Boundary of Bangladesh. CHT Refers to the Chittagong Hill Tracts. Inset A Highlights Key Himalayan Sedimentary Repositories Within the Broader Geological Framework of the Mountain Belt, While IBR Denotes the Indo-Burman Ranges [7].

A defining structural feature of the region, the Dauki Fault, runs east-west and has been classified as a dextral strike-slip thrust fault. This fault serves as the primary tectonic boundary between the Surma Basin and the Shillong Massif, marking a zone of active deformation with implications for regional seismicity and basin development [6]. The Surma Basin is further bounded by the Chittagong–Tripura Fold Belt of the Indo-Burman Range to the east and southeast, which consists of a series of N–S trending anticlines and synclines formed by ongoing tectonic compression. Reverse faulting commonly accompanies these anticlines, reflecting the dynamic tectonic interactions in the area. To the west, the basin is bordered by the Indian Shield Platform, contributing to its distinct tectonic boundaries.

The stratigraphic sequence within the Surma Basin is rich and diverse, with lithostratigraphic units that have been correlated with the Assam Basin in northeastern India. Initial correlations established a stratigraphic framework (Fig.3), which includes, from youngest to oldest, the Dihing Formation, Dupi Tila Formation, Tipam Group (comprising the Girujan Clay and Tipam Sandstone formations), Surma Group (including the Bokabil and Bhuban formations), Barail Group (Renji Formation), and Jaintia Group (with the Kopili Shale and

Sylhet Limestone formations) [1,7]. These units collectively record a history of sedimentation influenced by tectonic and sea-level changes over time, with depositional environments ranging from fluvial to deltaic and shallow marine settings [8, 9, 10, 11].
While lithostratigraphic correlation with the Assam Basin provides a general framework, significant differences exist between the Assam and Bengal basins, highlighting their distinct tectonic and sedimentary histories. The Surma Basin exhibits varied depositional flow directions, sediment thicknesses, and sediment compositions that distinguish it from its counterpart to the north. These differences are likely driven by local tectonics, sediment sources, and paleoenvironmental conditions, making the Surma Basin a unique depositional system within the Bengal Basin.

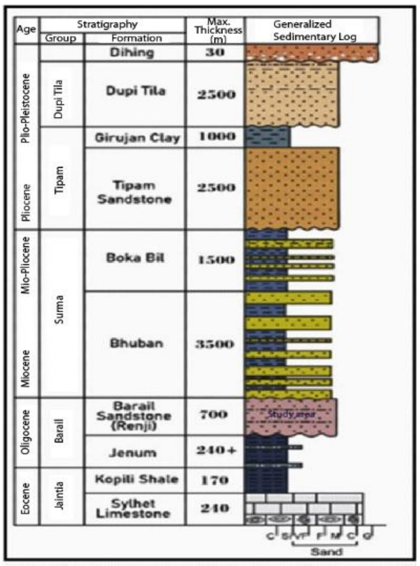

Fig. 3: Generalized Stratigraphic Succession, Adapted from [13].

The stratigraphy and structural setting of the Surma Basin have drawn considerable interest due to their implications for hydrocarbon potential. The thick sedimentary succession, coupled with varied depositional settings and structural traps, make the basin a promising target for hydrocarbon exploration. Previous studies suggest that the basin's structural complexity, including fault-bound traps and anticlinal structures, may play a significant role in the distribution of potential reservoirs [12].

3. Research methodology

3.1. Fieldwork and data collection

The outcrops along road cuts and stream sections within the study area provide optimal natural exposures for detailed facies analysis, facilitating the evaluation of both vertical and lateral variations in the sedimentary layers. High-resolution sedimentary logging was used to accurately document the facies, facies associations, and relationships within the exposed Oligocene successions of the Surma Basin, aiming to reconstruct the depositional architecture and sequence stratigraphy of these units.
Field investigations were conducted at key locations, including Sontila, Tamabil, Noljhuri, Shreepur, Assampara, and Nayagang. Precise stratigraphic logging captured detailed descriptions and interpretations to ensure robust data collection (Fig. 2). Eight sedimentary sections, with an average thickness of approximately 80 meters, were recorded, with section spacing averaging less than 1 kilometer. Bed orientations (strike, dip direction, and dip angle) were measured directly in the field, and vertical profiles were constructed using trigonometric methods [13], allowing for accurate representation of the depositional framework.

3.2. Sedimentological analysis

Utilizing Miall's classification schemes [14], sedimentological properties were systematically documented and photographed, including bed thickness, lateral continuity, sedimentary structures, and textures (such as particle size, sorting, and roundness). These properties were represented in graphical logs to support lithofacies analysis. Based on these sedimentological characteristics, the facies were organized into associations that reflect genetically related facies, denoting distinct sub-environments within the depositional system [15,16].

3.3. Sequence stratigraphy

Principles of sequence stratigraphy were employed to subdivide the rock record into several units, including parasequences, parasequence sets, and systems tracts, based on the identification of bounding discontinuities, such as maximum flooding surfaces, transgressive surfaces, regressive erosion surfaces, and incised valley floors. This analysis allowed for the interpretation of the basin's depositional history, relative sea-level changes, and the tectonic history of the study area. Key stratigraphic surfaces and systems tracts were identified and correlated across various sedimentary logs, enabling the delineation of distinct depositional sequences. These findings were then integrated into the megasequence framework of the Surma Basin, as constructed by Khanam [17].

4. Results and discussion

4.1. Lithofacies and facies associations

A systematic sedimentological logging of the outcrop sections was conducted to identify lithofacies types and facies associations within the Barail succession. This analysis utilized a modified lithofacies classification scheme based on the methodologies of Miall [18]. In total, ten distinct lithofacies were recognized and organized into three facies associations—BFA1, BFA2, and BFA3. The classification was based on an evaluation of both internal and external geometric characteristics, alongside interpretations of their depositional environments. Comprehensive descriptions of these lithofacies and their associated attributes are presented in Tables 1 and 2.

Table 1: An Overview of the Sedimentological Characteristics of Lithofacies Within the Barail (Renji) Formation in the Sangram-Jaintiapur Regions of Sylhet Is Provided. The Lithofacies Are Systematically Categorized Based on Their Depositional Flow Dynamics, Following the Facies Codes Established by Miall [18].

Lithofacies	Facies code	Description	Interpretation
1. Clast-supported conglomerate	G_m	The conglomerates exhibit poor sorting and are predominantly clast-supported, characterized by random orientation and sub-angular to sub-rounded clast shapes. Clast sizes range from pebbles to granules, with occasional inclusions of sandstone, shale, quartzite, and gneiss. Color variations in the conglomerates range from yellowish to deep brown hues. Additionally, approximately 20% of the conglomerate composition consists of coarse to fine sand, predominantly in shades of yellow to brown.	Substantial bed-load transport, characterized by granules and pebbles, contributed to the formation of bars within the channels. These deposits primarily resulted from the action of bypassing turbulent flows.
2. Massive sandstone	S_m	This lithofacies is characterized by massive sandstone with colors ranging from yellowish-brown to grayish-yellow. In some areas, faint and patchy lamination is occasionally observed.	Sediment deposition primarily occurs via gravity-driven flow mechanisms.
3. Trough- cross-stratified sandstone	T_x	This lithofacies comprises fine- to medium-grained sandstones that are well-sorted to moderately sorted, featuring sub-angular to sub-rounded grains. The beds are medium- to thick-bedded and exhibit abundant basal scours and amalgamation surfaces, with sporadic interbedded mudstone drapes. Internally, the sedimentation units display ungraded or crudely normally graded characteristics, often lacking distinct structures. Some beds show faint to well-developed parallel lamination near the upper boundaries. Lateral continuity is variable, influenced by erosional cuts associated with lenticular features, while bedding architecture between successive erosional surfaces typically follows a thinning-upward trend.	Thick-bedded, amalgamated sandstone beds, which can appear either massive or normally graded, are commonly understood to form from rapid suspension deposition during the collapse of sediment-laden turbulent flows. The plane-parallel lamination observed at the tops of some of these beds indicates that initial deposition took place from less energetic, low-density residual currents. Additionally, the occurrence of mud drapes within trough cross-beds suggests changes in flow dynamics throughout the sedimentation process.
Continued next page			
4. Planar- cross-stratified sandstone	Sp	This facies is characterized by a color range that includes brick-red, pink, pinkish-yellow, reddish-brown, and yellowish-gray hues. It primarily consists of moderately to well-sorted, medium- to fine-grained sandstones, with occasional interbeds of siltstone. The foresets exhibit lateral morphological variations, including angular, tangential, concave, and sigmoidal shapes, with dip angles progressively decreasing in the down-current direction.	These sediments result from deposition linked to the migration of extensive two-dimensional dunes within ebb channels or ebb bars.
5. Horizontal laminated sandstone-siltstone	Sh	This lithofacies consists of medium to fine-grained sandstones in pinkish-yellow, yellowish-gray, and gray hues, with occasional intercalations of siltstone. Concentrations of organic matter and mica flakes can be seen along the lamination or bedding planes. Furthermore, mud drapes are present within this lithofacies.	These sediments were deposited under the influence of an upper flow regime, indicating their formation in shallow tidal channels or tidal flats due to dynamic fluctuations in energy levels.
6. Ripple cross-laminated sandstone-siltstone	Sr	This lithofacies consists of fine to very fine-grained sandstones and siltstones in yellowish-gray, gray, and light yellowish-brown colors. Most ripple structures exhibit unidirectional cross-lamination, with lee slopes oriented in the opposite direction. Additionally, bidirectional current ripples are present within this lithofacies.	Sedimentary processes in meandering channels are characterized by the intermittent migration of sandy dunes and ripples, along with the deposition of mud and silt from suspended sediments. These processes occur alongside significant variations in flow velocity throughout the height of the point bars.

Continued next page

7. Flaser bedded and laminated sandstone-siltstone	Sf	This lithofacies is characterized by massive sandstone, displaying colors that range from gray to yellowish-gray. The sedimentary unit features flaser bedding structures, which appear as simple, bifurcated, or wavy patterns, often represented by thin laminae.	The flaser bedding structures in this lithofacies indicate a dynamic depositional environment influenced by fluctuating flow conditions. The thin laminae with simple, bifurcated, or wavy patterns reflect variations in sediment supply and flow energy.
8. Lenticular laminated sandstone-siltstone	Fsl	This lithofacies consists of very fine-grained sandstones and siltstones in pinkish-white, brownish-gray, and grayish-brown hues, intercalated with shale or mud layers. These sedimentary units display a bi-convex lens-shaped morphology.	This lithofacies indicates a significant phase of sedimentary quiescence, characterized by mud deposition that is intermittently interrupted by periods of current activity. During these active intervals, lens-shaped structures resembling starved ripples were formed.
9. Parallel laminated silty shale-shale	Fl	This lithofacies comprises laminated silty shale to shale, exhibiting colors that range from gray to brownish-gray and pinkish-gray, with varying organic content. Layers enriched in organic material typically display darker or blackish-gray hues. Additionally, sporadic leaf impressions and root traces are observed within this lithofacies.	This lithofacies indicates a sedimentary environment conducive to organic material accumulation, as shown by laminated silty shale and shale with varying colors. The darker hues suggest higher organic content, linked to periods of increased biological productivity. Furthermore, leaf impressions and root traces indicate a terrestrial or shallow marine setting that supported vegetation and sediment incorporation.
Continued next page			
10. Mudstone	Fm	The lithofacies is characterized by massive mudstone in pinkish-gray, gray, and dark gray colors. It commonly appears in the uppermost sections of heterolithic sequences or as mud drapes within trough and planar cross-stratified sandstone facies. Additionally, it may contain root traces, leaf impressions, burrows, and mud cracks.	These deposits are formed in standing water pools resulting from the abandonment of channels during low-flow stages, indicating sedimentation within a low-energy depositional environment.

Table 2: Presence of Facies in Each Facies Association

Facies associations		Containing facies	Interpretation of depositional environments
Massive bedded coarse to medium-grained	BFA1	Gm, Sm	Predominantly alluvial and braided fluvial channels
Major tabular and lenticular sandstone	BFA2	St, Sp, Sh, Sr, Sm	Tide-dominated braided channels
Laminated fine-grained sandstone	BFA3	Sr, Fsl, Fl, Fm	Tidal flat depositional environment

4.2. Massive bedded coarse to medium-grained facies association (BFA1)

Description: The facies association comprises massive sandstone (Sm) and clast-supported conglomerate (Gm). The clast-supported conglomerate facies is characterized by its yellowish-brown color, poor sorting, and sub-angular to sub-rounded clasts, with thicknesses ranging from 10 cm to 45 cm. The matrix consists of red to greyish-brown quartz, feldspars, and other rock fragments. These conglomerates, known as intraformational conglomerates, are found interbedded with sandstone layers in the Tamabil to Sonatila region [19]. The massive sandstone facies (Sm) displays structureless, pink, yellowish-brown, and greyish-brown coarse to medium-grained sediments interspersed with mud clasts and mud drapes (Fig. 4). Sandstone units are consistently found either overlaying or embedded within the conglomerates.

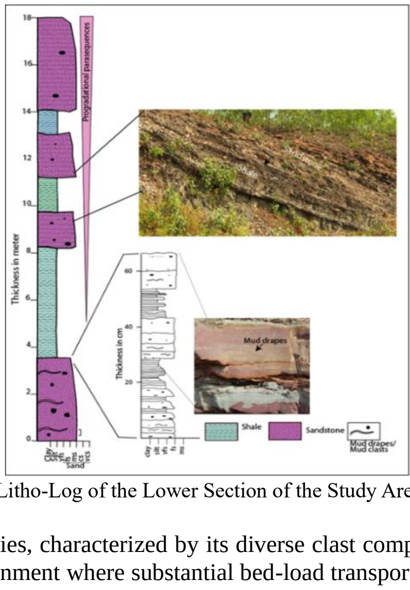

Fig. 4: Representative Litho-Log of the Lower Section of the Study Area, Near Sangram Bazar.

Significance: The polymictic conglomerate facies, characterized by its diverse clast composition and notable structural complexity, suggests deposition in a high-energy fluvial environment where substantial bed-load transport of granules and pebbles prevailed. This poorly sorted nature indicates that these conglomerates likely formed as channel lags or longitudinal bars within low-sinuosity streams, where episodic high-flow events contributed to clast accumulation. Such dynamic depositional conditions, potentially linked to seasonal or climatic variability, align with the formation of alluvial or fluvial fans, which are often associated with tectonic uplift and fault activity along basin margins. This tectonic influence would have driven increased sediment influx and fan development, contributing to the conglomerate's structural variability. The massive sandstone (Sm) facies, characterized by occasional mud clasts and drapes, further suggests a tidal or estuarine depositional setting, where fluctuating energy conditions allowed for periodic mud deposition followed by reworking during higher-energy phases. This facies' range of colors-from yellowish-brown and pink to grayish-yellow and gray-suggests sedimentation under oxidizing conditions, likely in a humid climate. The observed hues indicate prolonged exposure to oxygen, possibly from intermittent subaerial exposure or episodic flooding, which would enhance iron oxidation and result in the varied coloration. Together, these facies suggest a dynamic depositional environment where fluvial and tidal processes interacted, with tectonic activity playing a significant role in sediment supply and facies distribution [15], [16].

4.3. Major tabular and lenticular sandstone facies association (BFA2)

Description: The Barail succession is characterized by a dominant facies association of tabular and lenticular sandstone, referred to as BFA2. This association is systematically composed of the lithofacies St, Sp, Sh, Sr, and Sm, arranged in descending order of abundance (see Tables 1 and 2). The contact between BFA1 and BFA2 is generally sharp, with floodplain sediments overlying and passively capping the sandstone units, creating a distinct facies transition. BFA2 occurs in both single-layered and multilayered forms, with each layer defined by prominent erosional bases that delineate individual strata.

Within individual BFA2 strata, upper sections typically feature ripple cross-laminated sandstone (Sr) and low-angle cross-stratified sandstone (Sh), often inclined at approximately 15°. In contrast, lower sections are dominated by trough cross-stratified sandstone (St) and planar or tabular cross-stratified sandstone (Sp), with occasional massive sandstone (Sm) present. BFA2 deposits display a channelized structure, with well-defined channels that show a gradual thinning of wings along the margins (Fig. 5a). Channel bases are frequently composed of trough cross-stratified sandstone (St), planar/tabular cross-stratified sandstone (Sp), and ripple cross-laminated sandstone (Sr) (Fig. 5b). In certain instances, BFA2 forms extensive sandstone bodies marked by pronounced channel features and minimal internal erosional surfaces, reflecting continuous sediment transport and deposition within a high-energy channelized environment.

Fig. 5: A) The Photograph Depicts Tabular Cross-Stratified Sandstone Interbedded with Shale in the Lower Section of the Study Area, Near the Tambil Locality.

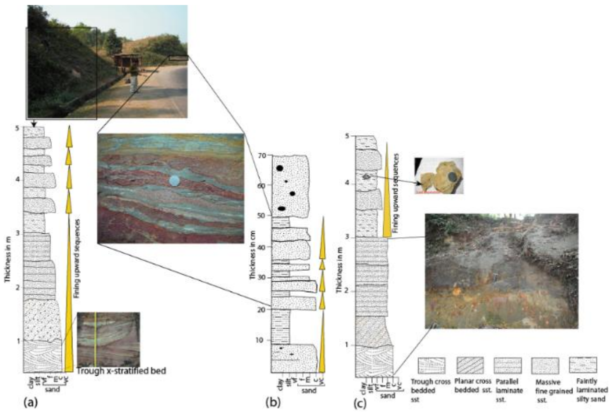

Fig. 5: B) The Representative Litho-Logs Illustrate the Presence of Trough Cross-Stratified Sandstone (St), Planar/Tabular Cross-Stratified Sandstone (Sp), and Ripple Cross-Laminated Sandstone (Sr).

Trough cross-stratified sandstone (St): This facies is frequently observed within the studied region (Fig. 6). It comprises medium to coarse-grained, lightly cemented pink to pinkish-yellow sandstone with sub-angular to sub-rounded grains. Partially consolidated mud layers are sporadically found near the base of the trough sets. Troughs exhibit heights ranging from 20 to 85 cm and widths spanning 0.40 to 3.8 m.

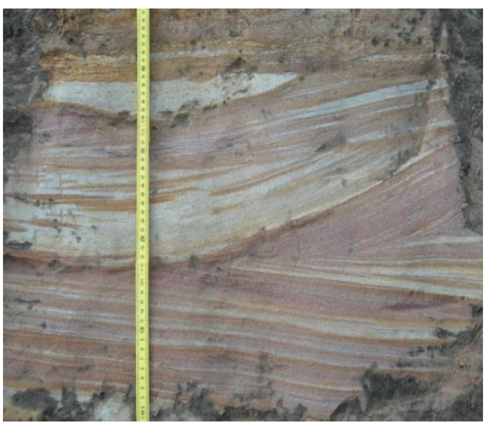

Fig. 6: Photograph Shows Trough Cross-Bedded Sandstone (St) at Noljuri Locality. The Lower Part of the Photograph Exhibits Horizontal Laminated Sandstone (Sh).

Planar cross-stratified sandstone (Sp): This facies dominates the research area. The sandstone within this facies exhibits hues of brick red, pinkish yellow, and yellowish-grey, and ranges from medium to fine-grained with occasional siltstones. Within these deposits, tidal bundle sequences (neap-spring) sometimes display sigmoidal to tangential morphological forms. Small-scale planar sets range from 1 mm to 15 cm in height, while large-scale planar sets span from 2 cm to 65 cm.
Horizontal laminated sandstone-siltstone facies (Sh): This facies is found in the shallower portions of the channel fills. It is characterized by sub-horizontal to horizontal layers of yellowish-gray to grey, fine-grained, relatively well-sorted minerals, including mica, quartz, feldspar, and minor quantities of dark-colored minerals. Portions of these deposits exhibit clear leaf imprints and coal fragments.
Ripple Cross-Laminated Sandstone-Siltstone (Sr): The lithofacies identified as Sr exhibit fine-grained, ripple cross-laminated sandstone and siltstone, displaying hues ranging from yellow to yellowish-grey. Typically, Sr occurs either independently above the parallel-laminated sandstone-siltstone facies (Sh) and planar stratified sandstone facies (Sh), or concurrently with them (Sl) (Fig. 7). Crest lines within these facies vary in morphology, presenting as straight, sinuous, or lunate formations. Occasionally, ripple peaks may be truncated. Unidirectional cross-lamination is indicative of ripple formation, with certain regions demonstrating bidirectional paleocurrent patterns.

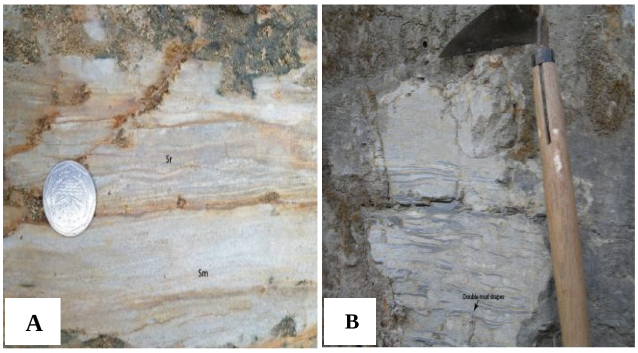

Fig. 7: A) The Photograph from Tambil Illustrates Ripple Cross-Laminated, Fine-Grained Silty Sand (Sr) in the Upper Section, Overlying Massive Sandstone (Sm) in the Lower Part. B) the Image Shows Massive Sandstone (Sm) Interbedded with Double Mud Drapes.

Massive sandstone (Sm): The Sm facies is characterized by massive, structureless sandstone composed of coarse- to medium-grained particles, ranging in color from gray to yellowish-gray. These sand bodies exhibit orientations parallel and perpendicular to the paleoflow direction of the underlying fluvial channels. Erosional features are evident at the lower boundary. This facies serves to establish continuity with the basal surface, often exhibiting primitive laminae parallel to its margins. Mud clasts and drapes are observed within the Sm facies (Fig. 8).

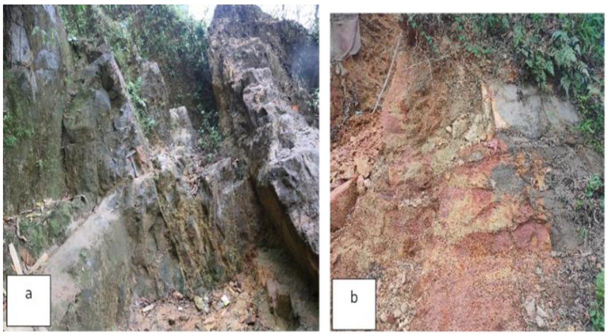

Fig. 8: The Photograph Illustrates: A) Thickly Bedded Pink Sandstone (Sh), B) Massive Bedded Pink Sandstone (Sm), Both Located Near the BGB Camp at Tamabil.

Significance: The BFA2 unit exhibits distinct geological attributes resulting from its deposition within tidal environments. Its close juxtaposition with floodplain sediments suggests an erosional genesis. The presence of massive structures signifies rapid sediment accumulation and subsequent erosion, likely influenced by fluctuating tidal currents. The notable thickness (>1 m) and steep channel margins of the sandstone body, alongside its erosional base, indicate substantial erosional processes, possibly driven by intense tidal dynamics. Sedimentary features within the sandstone, including low-angle trough cross-bedding, parallel laminations, planar cross-bedding, and a fining-upward grain size trend, reflect the complex interplay of tidal processes and sediment deposition. The absence of macrofossils or trace fossils indicates minimal bioturbation in this dynamic tidal environment. The observation of repetitive fining-upward sequences suggests cyclic variations in sediment supply and tidal influence. Moreover, the presence of a conglomerate bed approximately 3.8 meters thick above the pinkish sandstone unit suggests a significant depositional transition, likely marking an unconformity between distinct sedimentary sequences within the basin.

4.4. Laminated fine-grained sandstone facies association (BFA3)

Description: BFA3 is characterized by lithofacies Fsl, Fl, and Fm, featuring minimal Sr content. These lithofacies predominantly comprise fine-grained sandstone, carbonaceous siltstone, and coal deposits. Individual beds, ranging from 0.3 to 100 meters thick, exhibit lateral continuity spanning distances of 10 to 100 meters. The lithofacies display primarily massive to parallel laminated textures (Fm, Fl), interspersed with light grey, silty sandstone, and darker grey, reddish-brown, or carbonaceous mudstone layers. Shale facies within BFA3 include micaceous, pyritic, and ferruginous compositions. Contacts between lithofacies are delineated by sharp or gradational boundaries, defining their top and bottom contacts. Typically, BFA3 overlies sandstone and siltstone lithofacies.
Ripple Laminated Sandstone-Siltstone Facies (S_r): This facies consists of fine to very fine-grained sandstones and siltstones, exhibiting gray, yellowish-gray, and light yellowish-brown hues (Fig. 9). It is frequently associated with parallel-laminated sandstone-siltstone facies

(Sl) and planar-stratified sandstone facies (Sh), which often overlie planar cross-stratified sandstone facies (Sp), either individually or in combination. Observations reveal crest lines that are straight, linguoid, or lunate in shape. Occasionally, smaller crests are observed on certain ripples. The internal cross-lamination of the ripples predominantly aligns in a single direction. However, in the lateral or vertical succession of ripples, bi-directional paleo-currents produce internal cross-laminations resembling current-generated ripples.

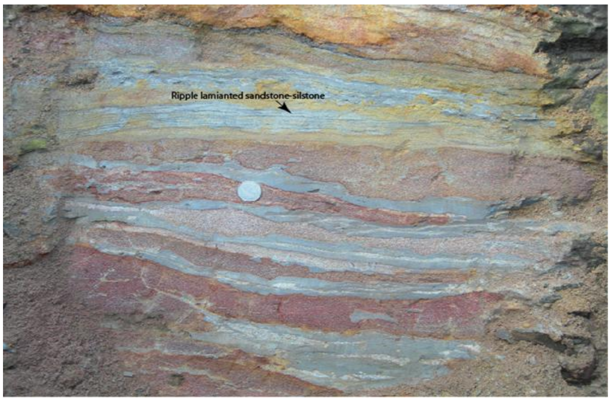

Fig. 9: The Photograph Shows Ripple-Laminated Sandstone (Sr) Interbedded with Flaser-Bedded Sandstone (Sf) and Siltstone (Fl)), Observed at Noljhuri, Near Tambil.

Lenticular Laminated Sandstone-Siltstone Facies (F_{Sl}): This facies consists of very fine-grained sandstone and siltstone, exhibiting pinkish white, brownish gray, and grayish brown colors. It is primarily composed of mud or shale, which constitutes about two-thirds of the facies, while silty sand makes up the remaining third (Fig. 10). The units contain lens-shaped structures with thicknesses ranging from 0.1 to 0.8 meters and wavelengths from 0.9 to 4.3 meters. Paleocurrent patterns are observed in both directions within the fore-sets of these lenses.

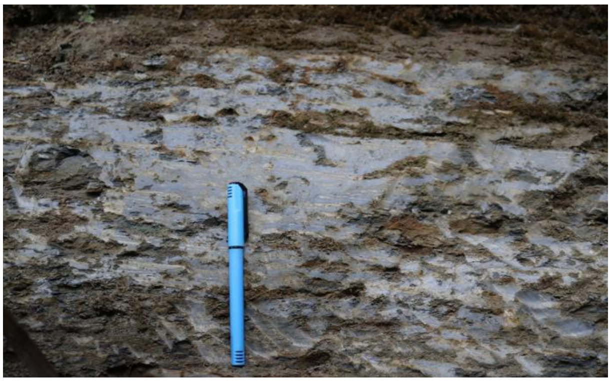

Fig. 10: Lenticular Bedding (Fsl) Observed in the Tamabil Area, With the Scale Provided by the Pen Shown in the Photograph.

Significance: The lenses formed as starving ripples in this facies indicate a period of quiescence where mud was primarily deposited, with occasional interruptions from current activity. The bidirectional paleocurrent patterns suggest a tidal environment that favors mud deposition over sand [20]. This facies is prevalent in tidal flat habitats, characterized by alternating layers of sand and mud due to deposition from slack water conditions. Comprising about two-thirds mud or shale, it reflects low-energy environments such as tidal flats, lagoons, or shallow marine areas that promote fine sediment accumulation. The lens-shaped structures, ranging from 0.1 to 0.8 meters in thickness, indicate intermittent energy fluctuations, with thicker lenses corresponding to stronger tidal currents or storm events, and thinner lenses reflecting calmer deposition [21]. Additionally, bidirectional paleocurrent patterns highlight the tidal influence, enabling sediment transport in both directions and marking the dynamic depositional environment typical of tidal flats or estuaries. Overall, this facies provides strong evidence for shallow, tidal-dominated deposition where fluctuating energy conditions controlled the accumulation of fine-grained materials and the formation of sand lenses [22], [23].

Parallel Laminated Silty Shale (F_l): This facies is predominantly composed of laminated silty shale, exhibiting colors such as gray, brownish gray, and pinkish gray, often containing traces of organic material. In strata with higher organic content, the color may transition to blackish gray or become significantly darker. This facies also features root traces and leaf imprints (Fig.11). The thickness of this facies ranges from 0.05 to 0.3 meters.

Fig. 11: Parallel-Laminated Silty Shale (Fl) Exposure Observed at the Assampara Locality.

Significance: The presence of leaf impressions within the laminated silty shale indicates that it was likely deposited in mud-dominated environments such as tidal flats, intertidal zones, back swamps, and river floodplains. These settings are characterized by conditions conducive to the preservation of organic material and sediment accumulation [24].

Mudstone Facies (Fm): This facies is distinguished by prominent sedimentary structures that exhibit shades of gray, pinkish-gray, and dark gray (Fig. 12). It is frequently found as mud drapes interbedded within trough and planar cross-stratified sandstone facies or positioned at the top of litho-sequences. This facies often features various sedimentary structures, including mud cracks, burrows, leaf impressions, and root traces. Furthermore, it displays a significant presence of localized bioturbation, evidenced by structures such as Skolithos and Ophiomorpha.

Fig. 12: The Photograph Illustrates Mudstone (Fm) as Indicated by the Hammer, with Underlying Sandstone Beds Visible Beneath the Hammer at the Tamabil Locality.

Significance: The Mudstone Facies (Fm) is interpreted as having been deposited in low-energy environments where fine-grained sediments predominantly accumulate. Laminated structures and mud drapes suggest sedimentation occurred during calm conditions, allowing finer particles to settle from suspension, indicative of settings such as tidal flats, estuaries, or floodplains, where fluctuating energy levels contribute to the deposition of both mud and coarser sediments [15]. The presence of mud cracks indicates periods of desiccation and exposure, implying intermittent subaerial conditions that may reflect seasonal variations or changes in water levels [23]. Additionally, leaf impressions and root traces suggest nearby vegetative cover, contributing organic material to the sediment and influencing its consolidation and structure [18]. The localized bioturbation evidenced by structures such as Skolithos and Ophiomorpha highlights active benthic communities involved in sediment mixing and alteration, indicating favorable conditions for both sediment deposition and biological activity.

4.5. Sequence stratigraphic framework of the study area

In this study area, detailed sedimentological logging of exposed Oligocene sections allowed for the identification of sedimentary facies types and their bounding discontinuities. High-resolution sequence stratigraphic principles, such as Incised Valley Floor (IVF), Regressive Erosion Surface (RES), Transgressive Erosion Surface (TES), and Marine Flooding Surface (MFS), were used to recognize these surfaces. These discontinuities are critical for understanding the stratigraphic evolution and depositional sequences within the Oligocene succession.

4.5.1. Key stratigraphic surfaces

Incised Valley Floor (IVF): The IVF is characterized by a surface formed due to erosion of underlying progradational (forward-building) sediments. This erosive truncation suggests a period of low sea level when river channels deeply incised the substrate, creating a valley floor. Above the IVF, the succession transitions into a transgressive (deepening-upward) trend, indicating that sea level subsequently rose, filling the valley with new sediment. This surface marks a shift from low sea levels and channel incision to rising sea levels, which filled the valley with finer sediment, creating the IVF [25].

Regressive Erosion Surface (RES): The RES is a surface created by erosional processes during periods when sea level dropped, leading to a shallowing-upward trend. This surface, which often truncates muddy deposits, represents a phase of relative sea-level fall, where sediment supply outpaced accommodation, resulting in erosion. Consequently, the overlying deposits typically reflect progradational sequences [26].

Transgressive Erosion Surface (TES): This surface is commonly found within valley-fill deposits formed during rising sea levels. It is typically capped by a thin layer of pebbles or sand, transitioning into finer muddy sediments. The TES reflects erosion during initial sea-level rise, marking the base of transgressive deposits within incised valleys [3]. As the sea level continued to rise, sediments filled the valley and transitioned into finer deposits, creating the TES.

Marine Flooding Surface (MFS): The MFS represents a major transgressive event and is marked by the sudden appearance of shelfal mud deposited over underlying shoreface sands. This surface signals a peak in sea-level rise, often leading to widespread deposition of mud in offshore environments, capturing the maximum extent of marine transgression over the continental shelf [27].

The study also utilizes the Transgressive-Regressive (T-R) sequence model to interpret sedimentary facies systematically, focusing on depositional trends. Six parasequence sets have been identified, classified into progradational, retrogradational and aggradational stacking patterns, and grouped into Lowstand Systems Tracts (LST), Transgressive Systems Tracts (TST), and Highstand Systems Tracts (HST), each bounded by the key stratigraphic surfaces [25].

4.5.2. Stratigraphic framework and megasequence boundaries

Within the regional eustatic sea-level context, the Barail Formation represents Megasequence 2 (MS-2), with a regressive erosional surface (RES) at the base and a transgressive surface (TES) at the top. This megasequence framework reflects major shifts from progradational (building forward) to retrogradational (backward-stepping) stacking patterns. The sedimentary record shows increased terrigenous input between 38 and 21 million years ago, as identified by Najman et al. [7], signaling the deposition of significant amounts of sediment due to tectonic uplift and climatic factors.

4.5.3. Parasequence and systems tract interpretation

Parasequence Set PS1: This set reveals progradational stacking patterns, with increasing sandstone thickness upwards, indicating a progression towards shallower conditions (Fig. 13). The base of PS1 represents a Lowstand Systems Tract (LST), marked by a regressive erosional surface that suggests sediment supply exceeded accommodation space, resulting in deposition in lower sea levels.

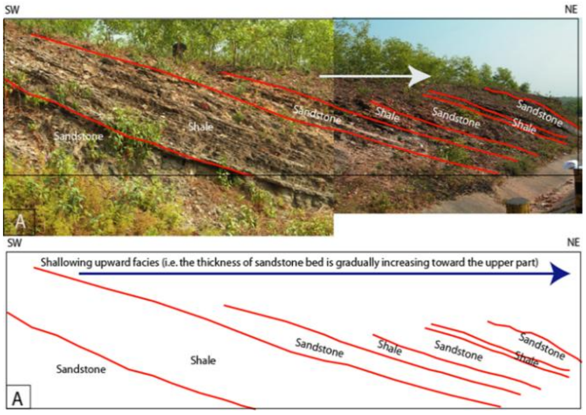

Fig. 13: The Photograph Illustrates a Shallowing-Upward Succession, with an Increase in the Thickness of the Sandstone Bed and A Corresponding Decrease in the Thickness of the Shale Bed Toward the Upper Part of the Stratigraphic Sequence.

Parasequence Sets PS2 and PS3: These retrogradational parasequence sets are in the middle portion of the stratigraphic column, capped by an MFS, indicating deposition during a transgressive phase (TST). The TST exhibits low channel-to-overbank ratios, suggesting high floodplain aggradation and lower frequency of channel avulsion events, typical of transgressive settings [3].

Parasequence Sets PS4 and PS5: Forming part of the Highstand Systems Tract (HST), these sets display a high channel-to-overbank ratio, with progradational to aggradational stacking patterns. This suggests that during the highstand phase, sedimentation filled available space, creating conditions favorable for channel amalgamation and connectivity [28].

Parasequence Set PS6: The uppermost part of the stratigraphic sequence represents the LST, bounded by a sequence boundary and correlative unconformity, with a lateritic conglomerate at the top. This topmost layer reflects a shift to subaerial exposure, signaling a period when sediment supply once again outpaced accommodation, leading to the development of a regressive depositional environment. The stratigraphic surfaces and systems tracts identified in this study (Fig. 14) provide crucial insights into the depositional history of the Oligocene succession in the Surma Basin. By correlating these sequences with global sea-level fluctuations (Fig. 15), this study reveals the complex interplay of tectonics, climate, and sea-level changes that shaped the basin's sedimentary architecture. This detailed sequence stratigraphic framework enhances the reconstruction of ancient environments, particularly in understanding how eustatic changes influenced sediment deposition, accommodation space, and basin infill processes over time [17], [29]. This refined stratigraphic interpretation not only deepens our understanding of the Barail Formation's depositional environment but also contributes to broader sedimentological and sequence stratigraphic models applicable to similar foreland basin settings worldwide.

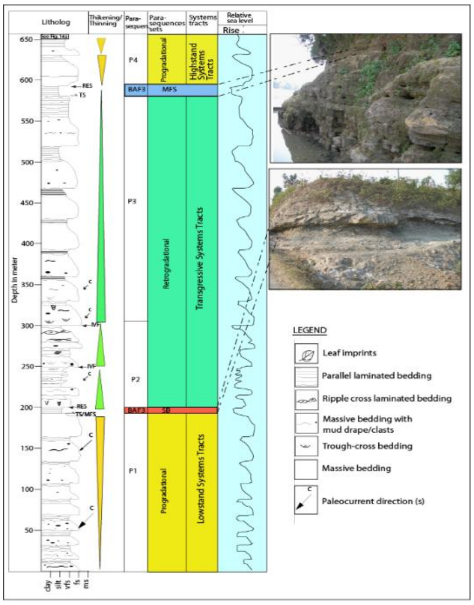

Fig. 14: The Composite Sequence of the Barail Litho-Succession Displays the Lowstand Systems Tract (LST), Transgressive Systems Tract (TST), and Highstand Systems Tract (HST), Along with the Corresponding Sequence Stratigraphic Surfaces and Parasequence Sets (Continued in Fig. 14a).

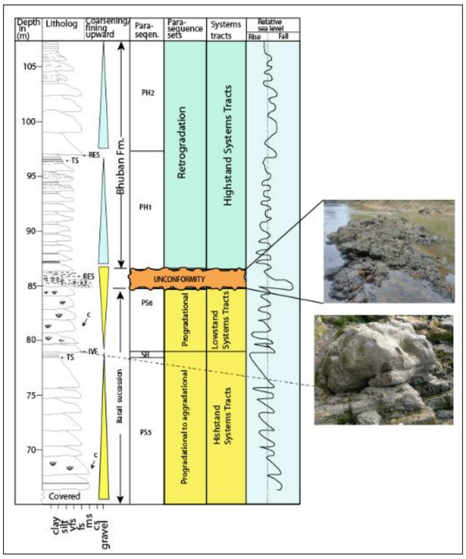

Fig. 14: A) Composite Sequence of the Barail Litho-Succession Showing LST, TST, and HST Along with Various Sequence Stratigraphic Surfaces and Parasequence Sets.

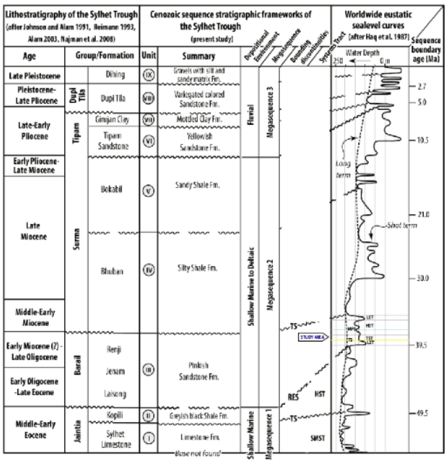

Fig. 15: The Correlation of Lowstand (LST), Transgressive (TST), and Highstand (HST) Systems Tracts with the Global Eustatic Curve, Adapted from Khanam [29].

5. Conclusion

The Oligocene Barail Formation in the Surma Basin offers valuable insights into the region's sedimentary evolution, shaped by tectonic, climatic, and eustatic sea-level changes. This study identifies the Barail Formation as part of Megasequence 2 (MS-2), with a regressive erosional surface (RES) at its base and a transgressive surface (TES) at its top. The stratigraphic sequence shows a clear shift from progradational to retrogradational stacking patterns, which reflects significant variations in sea level and accommodation space during the Oligocene period.

The analysis reveals an increase in terrigenous sediment input between 38 and 21 million years ago, likely caused by tectonic uplift and climate shifts. This period marks a time of intensified sedimentation, which contributed to the formation's depositional characteristics. The study also highlights the deposition of parasequence sets in different systems tracts, starting with lowstand conditions at the base, where sediment supply outpaced accommodation space. This is followed by a transgressive phase (TST), characterized by high floodplain aggradation and reduced channel avulsion, reflecting a rise in sea level. The highstand phase (HST) shows progradational to aggradational patterns with higher channel-to-overbank ratios, suggesting the filling of accommodation space and the formation of more interconnected channels.

This detailed sequence stratigraphic framework enhances our understanding of the Barail Formation's complex depositional history. It underscores the dynamic interactions between tectonics, climate, and sea-level changes that have influenced sediment deposition and accommodation space over time. Additionally, the study contributes to broader sedimentological and sequence stratigraphic models, offering valuable insights applicable to other foreland basin settings worldwide.

Acknowledgements

The authors sincerely thank the Department of Geology and Mining, University of Rajshahi, Bangladesh, for providing access to geological field equipment crucial for conducting our field survey. We are grateful to the administrative authorities for their support in organizing accommodation and ensuring the safety of the research team. Additionally, we deeply appreciate the warm hospitality and cooperation extended by the local community, which significantly contributed to the success of this study.

References

[1] M. Alam, M.M. Alam, J.R. Curray, M.L.R. Chowdhury, M.R. Gani, An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history, Sedimentary Geology 155(3-4) (2003) 179-208. https://doi.org/10.1016/S0037-0738(02)00180-X.

[2] R.G. Walker, N.P. James, Facies Models: Response to Sea Level Change, Geological Association of Canada, 1992.

[3] O. Catuneanu, Principles of Sequence Stratigraphy, Elsevier, 2006.

[4] A.D. Miall, The Geology of Stratigraphic Sequences, 2nd Edition, Springer, 2010. https://doi.org/10.1007/978-3-642-05027-5.

[5] L. Yang, W. Xiao, M.J.J. Rahman, B.F. Windley, K. Schulmann, S. Ao, J.E. Zhang, Z. Chen, M.S. Hossain, Y. Dong, Indo–Burma passive amalgamation along the Kaladan Fault: Insights from zircon provenance in the Chittagong-Tripura Fold Belt (Bangladesh). GSA Bull 132(9–10) (2020) 1953–1968. https://doi.org/10.1130/B35429.1.

[6] S. Biswas, B. Grasemann, Quantitative morphotectonics of the southern Shillong plateau (Bangladesh/India). Aust J Earth Sci 97 (2005) 82–93.

[7] Y. Najman , M. Bickle, M. B. Fadel, A.C.E. Garzanti, M. Paul, J. Wijbrans, E. Willett, G. Oliver, R. Parrish, S.H. Akhter, R. Allen, S. Ando, E. Chisty, L. Reisberg, G. Vezzoli, The Paleogene record of Himalayan erosion: Bengal Basin, Bangladesh, Earth and Planetary Science Letters 273 (2008) 1–14. https://doi.org/10.1016/j.epsl.2008.04.028.

[8] P. Evans Tertiary succession in Assam. Trans Min GeolInst India 27(1932), 155–260.

[9] J. Holtrop, J. Keizer, Some aspects of the stratigraphy and correlation of the Surma Basin wells, East Pakistan, ECAFE Miner Resour Dev Ser 36 (1970), 143-154.

[10] F. Khanam, M.J.J. Rahman, M.M. Alam, R. Abdullah, Sedimentology and basin-fill history of the Cenozoic succession of the Sylhet Trough, Bengal Basin, Bangladesh, International Journal of Earth Sciences 110 (2020), 193–212. https://doi.org/10.1007/s00531-020-01946-1.

[11] S.Y. Johnson, A.M.N Alam, Sedimentation and tectonics of the Sylhet trough, Bangladesh, Geological Society of America Bulletin 103 (1991), 1513–1527. https://doi.org/10.1130/0016-7606(1991)103<1513:SATOTS>2.3.CO;2.

[12] K.U. Reimann, Geology of Bangladesh, Gebruder Borntraeger, Berlin (1993).

[13] M. Alam, M.M. Rahman, M.Y. Gazi, J.H. Lupin, M.N. Zaman, Depositional environment and reservoir prospect analysis of Barail sandstone exposed in the northeastern part of Bangladesh, The Dhaka University Journal of Earth and Environmental Sciences 12 (1) (2023), 1–15. https://doi.org/10.3329/dujees.v12i1.70557.

[14] M. Alam, M.M. Alam, J.R. Curray, M.L.R. Chowdhury, M.R. Gani, An overview of the sedimentary geology of the Bengal Basin in relation to the regional tectonic framework and basin-fill history, Sedimentary Geology 155 (2003), 179–208. https://doi.org/10.1016/S0037-0738(02)00180-X.

[15] A. Maltman, The geological deformation of sediments, Springer, New York (2012).

[16] A.D. Miall, The geology of stratigraphic sequences. Springer, New York (2010). https://doi.org/10.1007/978-3-642-05027-5.

[17] F. Khanam, M.J.J. Rahman, M.M. Alam, R. Abdullah, Sedimentology and basin-fill history of the Cenozoic succession of the Sylhet Trough, Bengal Basin, Bangladesh, International Journal of Earth Sciences 110 (2020), 193–212. https://doi.org/10.1007/s00531-020-01946-1.

[18] A.D. Miall, Lithofacies types and vertical profile models in braided river deposits: a summary, Geological Survey of Canada Paper 78-27 (1977), 1–18.

[19] J.D. Collinson, H.G. Reading, Sedimentary environments: processes, facies and stratigraphy. Alluvial Sediments. Blackwell Scientific Publications, Oxford, pp 37-82. (1996).

[20] R.W. Dalrymple, Facies models 4. Tidal depositional systems. Geological Society of Canada, pp 201–231 (2010).

[21] A.K.M.E. Haque, W.S. Downey, M.M. Alam, M.A. Islam, M.O. Faruk, R. Islam, Eocene-Miocene stratigraphy of the Surma Trough, Bengal basin: a sequence stratigraphic approach, Petroleum and Coal 61(3) (2019), 490-507.

[22] H.E. Reineck, F. Wunderlich, Classification and origin of flaser and lenticular bedding, Sedimentology 11(1-2) (1968), 99-104. https://doi.org/10.1111/j.1365-3091.1968.tb00843.x.

[23] G. Nichols, Sedimentology and Stratigraphy, Wiley-Blackwell, Oxford (2009), 419 pp.

[24] H.G. Reading, Sedimentary Environments: Processes, Facies and Stratigraphy, 3rd ed., Blackwell Science (1996).

[25] O. Catuneanu, V. Abreu, J.P. Bhattacharya, M.D. Blum, R.W. Dalrymple, B.A. Eriksson, C.R. Fielding, W.L. Fisher, W.E. Galloway, M.R. Gibling, et al., "Sequence stratigraphy: methodology and nomenclature," Newsletters on Stratigraphy 44 (3) (2011), 173-245. https://doi.org/10.1127/0078-0421/2011/0011.

[26] H.W. Posamentier, P.R. Vail, "Eustatic controls on clastic deposition II—sequence and systems tract models," Sea Level Changes: An Integrated Approach 42 (1988), 125-154. https://doi.org/10.2110/pec.88.01.0125.

[27] D. Emery, H.F. Myers, Sequence Stratigraphy: An Introduction, W.H. Freeman and Company, 1996. https://doi.org/10.1002/9781444313710.

[28] Bristow, C.S., Best, J.L., The influence of sediment supply on the dynamics of high-energy, gravel-bed rivers: Insights from the River Wye, UK, Sedimentology 40(6) (1993), 1123–1145.

[29] B.U. Haq, J. Hardenbol, P.R. Vail, Chronology of fluctuating sea levels since the Triassic, Science 235(4793) (1987), 1156–1167. https://doi.org/10.1126/science.235.4793.1156.