Petroleum and Coal

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Facies Characterization and Outcrop Analysis of Wave-Dominated Deposits in the West Baram Delta, Sarawak: Insights into Back-Barrier Island Systems

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Received August 21, 2024; Accepted November 19, 2024

Abstract

This study presents a detailed sedimentological analysis of a back-barrier beach complex, ranging from offshore tempestite to onshore beach settings. The outcrop is located in between Sungai Rait to Jalan Bakam Road, within walking distance from Bakam Chung Hua National (C) Primary School, Miri Sarawak. This particular outcrop's accessibility is facilitated by its occupation by the brick industry. It serves as an ideal geological field trip destination, providing valuable insights into reservoir complexities and paleoenvironmental proxies. Our research identifies 24 facies, which are organized into 6 facies associations. Facies Association 1 (FA-1) is an offshore zone characterized by a thick, structureless muddy sequence with no bioturbation, featuring sand streaks and erosive-based gutter casts followed by coquinite or shell fragment deposits. Facies Association 2 (FA-2) represents the offshore transition zone, with a heterolithic composition of amalgamated swell geometrical sandstone bodies, exhibiting micro-hummock structures and increasing bioturbation upwards. Facies Association 3 (FA-3) characterizes the lower shoreface settings with thick, well-sorted sandstone bodies, oscillatory-generated structures, and moderate bioturbation featuring homogenized organism imprints. Facies Association 4 (FA-4), the middle shoreface zone, consists of heterolithic amalgamated tempestite sandstone bodies and oscillatory-generated structures, with sparse bioturbation that intensifies upward. This association also includes various soft-sediment deformation structures like ball and pillow structures, load casts, flame structures, micro faults, pseudonodules, and water escape features. Facies Association 5 (FA-5) describes the upper shoreface zone, characterized by well-sorted sandstone with oscillatory-generated structures, transitioning upward to irregular sinuous curved crests through cross-beddings. Facies Association 6 (FA-6), the foreshore-beach setting, consists of well-sorted sandstone with tabular cross-beddings adjacent to triangular and convex-shaped coarse grain sand. Facies Association 7 (FA-7) features back-barrier island-estuary settings with heavily bioturbated tidalites, followed by a scarp of erosive, well-sorted sandstone capped by carbonaceous materials. This well-sorted sandstone is overlaid by massive mudstone, transitioning into a thick sandstone body at the top of the outcrop. These comprehensive facies analysis enhances our understanding of sedimentary processes in beach complexes and their potential as geological field sites.

Keywords: *Facies analysis; Shallow marine deposits; Wave-dominated delta; Back-barrier island; Tempestite deposits.*

1. Introduction

The Baram Delta consists of fluviomarine Miocene sediments, which are widely distributed across the region and create the most prominent hydrocarbon prolific basin with a history of more than 115 years of exploration [1-2]. The sediments of the Baram Delta are mainly deposited by a wave-dominated process with the tidal influence at the distributary mouth [3-4].

The sedimentary process and its stratigraphic architectures are thoroughly discussed by [5–7]. while the research on sediment provenience has been briefly discussed by [8]. Extensive studies on exposed sediments of the Baram Delta, along with its uplift and erosion estimation have been conducted by [9]. It has also been noted that the sea level has rapidly risen in glacial periods [10]. Recently extensive paleographic farmwork has been constructed by [11-12] and the tectonostratigraphic framework has been discussed by [13–15]. Despite this, our study has presented a detailed interpretation of the outcrop we visited in the Baram Delta which technically belongs to the Miri or greater Beliat Formation.

The outcrop is located between Sungai Rait to Jalan Bakam Road, within walking distance from Bakam Chung Hua National (C) Primary School, Miri Sarawak, with coordinates of 4°14'31.0"N 113°58'04.4"E (Fig. 1B and 1C). This particular outcrop's accessibility is facilitated by its occupation by the brick industry. The outcrop exhibits an ideal location for studying wave-dominated depositional environments consisting of offshore-foreshore sediments and transitioning into lagoonal and bay head delta settings which typically reflect the Barrier Island. The sediments of these outcrops are prolific and contain a large reservoir in the subsurface of Baram Delta Province and this study may provide new insight into reservoir characteristics. The aim of this study is, i) to document the facies characteristics and sedimentology of different event beds. ii) to reconstruct the paleo depositional model which displays the observations and interpretations of the system.

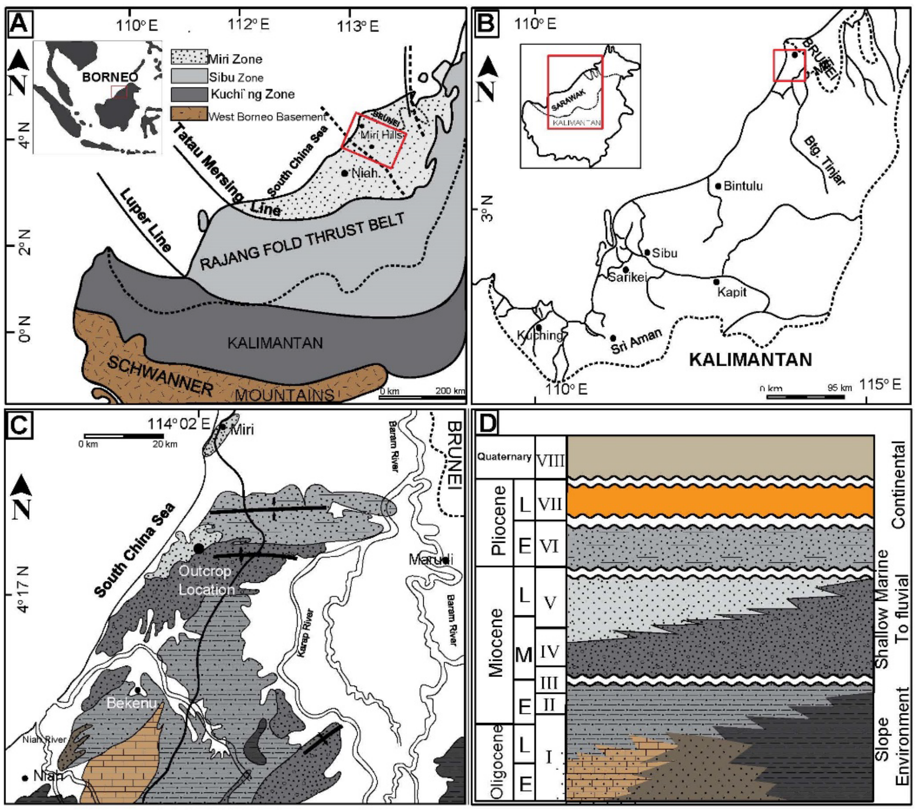

Figure 1. Geographical and stratigraphic context of the study area in the Miri Region of Borneo Island. 1A delineates four distinct zones within the Borneo region, each bounded by fault lines modified after [1]. The red triangle indicates the specific study area within the Miri Region. 1B zooms in on the study area located within the Miri Zone. 1C depicts the stratigraphic distribution and the location of outcrops within the Miri Zone modified after [91]. 1D provides detailed stratigraphic positions pertinent to the study area modified after [3].

2. Geological background

The Baram Delta, situated as the seventh geological province within the broader Neogene Sarawak foreland basin, is primarily composed of sediments dating back to the Middle Miocene period. Its formation took place over an accretionary wedge, indicative of receiving an influx of sediments from the Cretaceous to Eocene epochs during the late Miocene [16–19] (Fig. 1D). In terms of spatial coverage, it encompasses an area of approximately 7,500 square kilometers, with 2,500 square kilometers of it being onshore [20-21].

Structurally, the Baram Delta is demarcated by the West Baram Line, a significant fault zone that marks its western boundary (Fig. 1A). This fault line separates the delta from the older and more stable Balingian and Central Luconia provinces. Additionally, on the eastern margin, the Neogene Delta is bordered by the Morris Fault and Jerudong Line in Brunei, which separates the delta from the deformed Inboard Belt offshore NW Sabah [1].

In the broader Sarawak basin, sediment thickness is estimated to range from approximately 6 to 9 kilometers. These sediments are predominantly composed of coastal-to-coastal fluvio-marine sands and shales, forming the geological stratigraphy of the deltaic provinces [22]. Within the West Baram Delta, the deposition process is characterized by the formation of northward progradation sequences, commencing during the Middle Miocene period. This stratigraphic architecture comprises thick and sandy progradational shallow marine-deltaic sequences interspersed with transgressive marine shale intervals [1].

In the Sarawak Basin, [21] has established eight sedimentary cycles based on biostratigraphic zonations, spanning from the Upper Eocene to the Pleistocene. Each cycle is bounded by prominent shale layers with alternating clastic and carbonate successions. These cycles are dated and regionally correlated by planktonic foraminifers, large benthonic foraminifers as well as spora morphs (including pollen and spores).

3. Methodology

The detailed outcrop analysis is used to study different rock types during fieldwork through sedimentology in exposed sedimentary rock outcrops. It begins with fieldwork to access outcrop locations, where we carefully examine sedimentological features, such as bed geometry, texture, sedimentary structures, erosional surfaces, and fossils. We also analyze variations in sedimentary structures both vertically and horizontally to better understand how these rocks formed. We benefit from the knowledge of respected researchers in the field, like [23–25], which enhances our insights. We determine the orientation of the rock layers using Jacob's staff method with guidance from the Brunton compass and [26] principles. Afterward, we interpreted the collected sedimentological data and correlated it with established information about depositional environments. This helps us identify specific environmental systems. Our findings are meticulously documented, creating a comprehensive resource for future research and reference.

4. Facies associations and discussions

4.1. Facies association – 1: Offshore

4.1.1. Description

The facies of FA-1; offshore zone, consist of F1, F2, F3, and F4 making up to 20m thick sequence of shelf sediments (Fig. 3a). The massive mudstone is dominant (Fig. 2a) exhibiting structureless and absence in bioturbation. The elongated, bulging erosive-based gutter cast is enclaved within massive mudstone exhibiting pinch out on both sides, the internal structure was hard to observe due to accessibility and outcrop condition (Fig. 2a). It was capped by erosive-based, poorly sorted coarser grained, and bivalve shell fragment/coquinite (Fig. 2c). The sand streaks and lenses are frequently observed within this association (Fig. 2d). The detailed descriptions of Facies are given in Table 1.

4.1.2. Interpretation

The facies of FA-1 are highly suggestive with the interpretation of suspended sediments accumulated at the outer shelf zone or offshore zone, below the storm wave base. Calm water allows finer sediments i.e. mud/clay to settle down by the process of suspension [27–29]. Due to anoxic conditions in the outer shelf organisms were unable to colonize resulting in absence of bioturbation [30]. The presence of a gutter cast may suggest the bypassing of sediments to the outer shelf due to strong currents of helical vortices [31-32]. Whereas adjacent poorly sorted (coquinite/shell fragments) may have been deposited by the waning flow process [33-34]. The shell fragment also known as shell or transgressive lag is considered as an indicator of primary transgression [35].

Table 1. List of facies, its process, and interpretations.

Facies code	Facies	Structure	Process	Process interpretation
F1	Massive mudstone	Greenish Grey structureless mudstone. the bioturbation is completely absent at the lower part and gradually increases towards the top (Fig. 2a).	Accumulated due to Suspension falls out.	The suspended sediment accumulates due to calm water below the storm wave base [27-29]
F2	Coquinite/ shell fragments	Poorly sorted, erosive-based, olive grey silty mud mixed with coarse to pebble grain sediments and freshwater shell fragments (Fig. 2c).	Accumulated due to high energy flows.	The poorly sorted coarse-grained, intermingled shell fragments are also commonly called storm or transgressive lag deposits. It is often found accumulated adjacent to or on top of the gutter cast. It highly resembles the interpretation of storm-winnowed shelf deposition [33].
F3	Gutter cast	Erosive fine-grained sandstone, exhibiting Elongated, bulging with pinching out on both sides (Fig 2a).	Offshore-directed fluvial discharge due to helical flows.	Due to episodic helical vortices, the sediments have bypassed and accumulated on the outer shelf [92].
F4	Sand streak and lenses	Isolated, discontinuous sand streaks and lenses, enveloped in between mudstone (Fig. 2a and 2d).	Combined process of suspension and episodic wave and fluvial activity.	The calm energy is occasionally interrupted by high energy due to storm or fluvial activity. It is interpreted to be deposited in the subtidal zone [93]
F5	Graded silt and sandstone	Cm to a few meters thick, siltstone and very fine-grained sandstone beds, exhibit micro HCS enclaved within massive mudstone (Fig. 2b and 2e).	Continuous settlement of sediments due to wave or storm activity.	The oscillatory-generated structures in silt and sandstone are interpreted as subtidal storm deposits.
F6a	Tabular sandstone	It is homogeneous sandstone, exhibiting pinching and swell geometry, very fine- fine-grained sandstone, displaying HCS, laterally thinning and transitioning into meter-thick lenses. It often appears amalgamated (Fig. 2d and 2e).	Deposited due to wave or storm activity	The oscillatory-generated structures indicate storm deposits. It is interpreted to be deposited in a subtidal zone, near or equal to the average storm-wave base [36].
F6b	Erosive sandstone	It is heterolithic sandstone, exhibiting pinching and swell, often interbedded with silty bioturbated mudstone (Fig. 2g).	Fluvial sediments accumulated due to hyperpycnal flows.	It may represent the rapid delta aggradation, due to an increase in steepness, the erosive form of sediments has been deposited near to intertidal zone, above the storm wave base [36].
F7	Bioturbated silty mudstone	Olive gray, silty mudstone with having some concentration of sand. It is moderate to intense bioturbated with organisms and bioclasts accumulated parallel to the bedding plain (Fig. 2f).	The deposition occurs due to suspension, whereas minor may be deposited due to storm surge flows.	The bioturbated suspended sediments, mixed with silt and sand accumulated parallel to the bedding plane may suggest post-depositional bioturbation. Thus, it is interpreted that quiet water is occasionally disturbed by storm activity, whereas post-depositional bioturbation indicates the oxygenized sea floor. It is deposited near the shoreface zone but below the fair-weather wave base [94].
F8a	Interbedded Mud, sand, and silt	Interbedding of mud, silt, and, sand with the sand ratio of 0.5, exhibiting sand lenses, enclaved within mudstone (Fig. 2h and 2i).	Combination of suspension and frequent interruption of wave activity.	The quiet water environment is frequently disturbed by high-energy events. It is interpreted to be deposited

Facies code	Facies	Structure	Process	Process interpretation
				average or equal to a fair-weather wave base [36].
F8b	Interbedded HCS sandstone.	Interbedding of mud, silt, and sand with few cm thick beds of very fine grain sandstone exhibiting hummocky cross stratified (Fig. 2i and 2j).	Combine process of suspension and wave activity.	The suspended sediments are due to a quiet water environment, whereas the oscillatory-generated structure indicates high energy deposits due to wave activity. Thus, it is interpreted to be deposited above the fair-weather wave base [46].
F9a	Current rippled sandstone	The bidirectional asymmetrical rippled sandstone, has a cm thick continuous fluid-mud deposit, particularly on the lower part of HCS well-sorted sandstone (Fig. 2j).	The fluid mud may indicate the storm wave resuspended through coastal storms.	The asymmetrical ripples may represent the asymmetrical waves due to skewed with energetic wave conditions. It is commonly observed in lower shoreface settings and is well described by [51-52].
F9b	Wavy bedded sandstone	The unidirectional symmetrical ripples, altering to hummocky cross stratifications in sandstone, appear as climbing ripples (Fig. 2j and 2k).	The climbing ripples associated with HCS may represent accumulation that occurs due to weak wave intensity.	The unidirectional weak wave power may have formed a small-scale HCS pattern due to bedform migration. Thus, it is interpreted as a purely oscillatory-generated structure formed due to low wave intensity at the lower shoreface zone [27,53]
F10	Hummocky Cross Stratified Sandstone (HCS).	Well sorted very fine to fine-grained sandstone displaying hummock cross stratifications. having sparse bioturbation (Fig. 2n).	It is deposited under wave-generated unidirectional flow.	The wave oscillated structure resembles more like wave ripples, it is formed due to unidirectional flow. Thus, it is interpreted to deposit above the fair-weather wave base in the lower shoreface zone [45,50]
F11	Swaley Cross Stratified Sandstone (SCS)	Well-sorted fine-medium-grained sandstone displaying high-angle swales. Sometimes it appears as amalgamated. The bioturbation is sparse to moderate and accumulates on top of the sandstone bedding plane (Fig. 2k and 2m).	It is deposited under wave-generated unidirectional flow.	It is subordinate to HCS, exhibiting high-angle oscillated generated structures, formed due to the domination of high-energy unidirectional flows. Thus, it is interpreted that accumulation occurs above the fair-weather wave base near and below the surf zone [29,38,57].
F12	Soft Sediment Deformation (SSDS)	It is heterolithic and cryptic. Few beds represent SSDS. It includes deformed wavy beddings, which consists of major elements for recognizing SSDS such as rip-up mud clast, flame, ball, ball and pillow, and load structures. The other bed is structureless, appears muddy, or sometimes resembles deformed wavy beddings but generally, it is cryptic in nature, either due to bioturbation or could be due to SSDS. This cryptic bedding is capped by a few cm thick fine-medium-grained sandstone with some pseudonodules (Fig. 2l).	The soft sediment deformation in tempestite settings is mainly caused by liquefication. It is triggered by pore pressure induced by storm waves along with the impulsive impact of breaking waves.	The pressure difference between the trough and crest of the wave may increase the pore pressure within the floor sediments. This has caused the sediment to liquidify, resulting in a significant decrease in shear strength [59]. Thus, it is interpreted that soft deformation may occur due to the impulsive impact of the wave at the breaking zone [60]. The direct impact of breaking waves on soft-sediment deformation in proximal settings has also been documented by [95–98]

Facies code	Facies	Structure	Process	Process interpretation
F13	Silty Sandstone	It appears as a wavy heterolithic mixed succession of sand, silt, and mudstone. it is intensively bioturbated with destroyed laminations. In some places, it also appears as mud draped (Fig. 2l, 2m, and 2n).	It formed due to rapid deposition during storms. The soft sediment deposition appearance is possibly derived from storm-induced liquefication. The mud and clay drapes are possibly due to hypopycnal bouyant mud plumes and rapid clay flocculation.	The heterolithic succession is formed due to the interruption of flood-ebb tidal currents intervening in the suspended sediments. Therefore, it indicates a minor tidal influence [99].
F14	Trough cross-bedded sandstone	The sandstone displays trough cross beddings with irregular, multidirectional crests. the sinuous crest forest truncated to an erosive surface (Fig. 2n, 2o, and 2p).	It is formed due to 2D and 3D migration dunes.	A multidirectional, irregular sinuous crest strongly suggests highly sinuous crest sand bars. It is interpreted that it may have been accumulated by nearshore currents in the surf zone [61].
F15	Amalgamated tabular cross-bedded sandstone	The sandstone beds appear flat or amalgamated with an internal structure of massive or low-angle plane tabular cross beddings. The basal part is often interbedding with trough cross-stratified sandstone (Fig. 2o, 2p, and 2q).	It is formed due to high energy sheet flows.	The horizontally bedded amalgamation with low-angle tabular cross stratifications suggests high-energy sheet flows. This, it is highly resembling the interpretation of the surf-swash transition zone [64].
F16	Tabular cross-bedded sandstone	The fine-medium-grained, very well-sorted sandstone has an internal wedge-type planer-tabular cross-bedded sandstone structure. the cross-bedded crests are straight as compared to the trough cross-bedded sandstone (Fig. 2p, 2q, 2s, and 2v).	It is formed due to the 2D migration of crested dunes.	The straight crest and very well-sorted sandstone may highly suggest the 2D migration of crested dunes and are interpreted to be accumulated in the surf zone [100].
F17	Parallel laminated beddings	The sandstone exhibits parallel laminations at the top part of wedge-type cross-bedded sandstone (Fig. 2q, 2r, 2t, and 2v).	It is formed due to the continuous deposition of sediments in horizontal beds under upper-plane bed flow.	The parallel laminations on top of the planner-tabular bedded sandstone are highly indicative of the accumulation of sheet flow in the swash zone or a beach environment [65,68,101].
F18	White unconsolidated sand	It appears featureless, and impresistant, unconsolidated white sand, having a sharp base, displays a triangular or convex shape, and is accumulated adjacent to parallel laminated sandstone. It is capped by carbonaceous-rich materials (Fig. 2q, 2s, and 2v).	It is highly resembling the accumulation of early-stage beach ridges due to the eolian process.	The featureless white sand and convex shape adjacent to the foreshore deposits highly suggest the accumulation of foredunes. It is relatively small-ler a few cm thick indicating an early stage of dune development. It is also commonly termed an 'embryo or frontal dune' [90]. Thus, it is interpreted that eolian accumulation occurs in the backshore environment [89].
F19	Coastal calcarenite sand	Yellowish, mm to few cm thin, conglomeratic in nature, it is poorly sorted fine to medium-grained calcarenite sandstone consisting of coral debris, terrestrial material, and micaceous sand (Fig. 2q, 2s, 2u, and 2v).	It formed due to over washing process	The conglomeratic micaceous, calcarenite sandstone could have been accumulated due to storm-induced waves transporting sediments over top of dunes and interpreted as over-

Facies code	Facies	Structure	Process	Process interpretation
				washing deposits at back-shore depositional environments in the intertidal zone [102-103].
F20	Carbonate tidalites	It is muddy carbonate sequence, appears as structureless due to organic activities (Fig. 2q, 2s, 2u, 2w, and 2x).	It is formed due to the combination of tidal, biogenic, chemical, and diagenetic processes.	The combination of carbonates and silicates may have formed due to an arid or humid environment, possibly in a back-barrier island. Thus, it is interpreted as accumulation occurring in a subtidal lagoon environment and is least affected by tidal activities due to weak ebb tidal currents. It can also be known as back barrier tidal flats [74–76].
F21	Cross-bedded sandstone	It is cm-m thick very well-sorted fine to medium-grained sandstone exhibiting hummock, swale, and wedge type cross beddings. The basal part is sharp and erosive and may contain isolated pebbles. It is covered by carbonaceous materials (Fig. 2x and 2y).	Eolian dunes are formed due to wind activity	The wedge type very well-sorted sandstone overlying on top of carbonate tidalites is suggestive of the accumulation of coastal dunes in back-barrier beach settings [104]. It is also known as back-barrier wind flats [105-106], often caped by intertidal salt marshes [79].
F22	Muddy sand	Mudstone consisting of wavy bedding of sand beds (50:50) (Fig. 2x).	It is formed due combined process of ebb and flood, and suspension in the back-barrier island.	Mudstone is episodically deposited due to suspension in lagoon environment in back-barrier settings. Sandstone exhibiting wavy beddings represents the ebb and flood deposits. Thus, it is interpreted as the accumulation of mixed tidal flats in a subtidal lagoon environment [79].
F23	Clayish mudstone	Clayish mudstone consisting of lenticular beddings and thin lenses of sand, 75 to 95% of mud content whereas mud cracks are commonly observed within these facies (Fig. 2x).	It is formed due combined process of ebb and flow and suspension in an estuary setting. Whereas mud cracks are the product of persistent dissection and contraction of muddy sediments.	Mudstone is accumulated due to suspension in the lagoon, whereas minor sand content suggests ebb and flow deposition due to neap and spring tides. The presence of mud cracks may possibly indicate the drying up of lagoons which causes persistent dissection and contraction of muddy sediments [79–81].
F24	Mudstone	Mudstone exhibits a few cm thick continuous sandstone beds which have also been identified by [108] along with a dominant feature of elongated sandstone body enclaved within mudstone. It is more resembling to F1 facies. The sandstone beds are pinching out on both sides and displaying a sharp erosive base (Fig. 2y).	Mud is a product of suspension, whereas an enclaved sharp base suggests either subaqueous channels or tidal creaks in lagoon settings.	The massive appearance of mudstone may suggest the lagoonal self-mud or mud flats whereas enveloped sandstone bodies indicate channel-like features which could be either subaqueous channels or tidal creaks in lagoon settings [79,107].

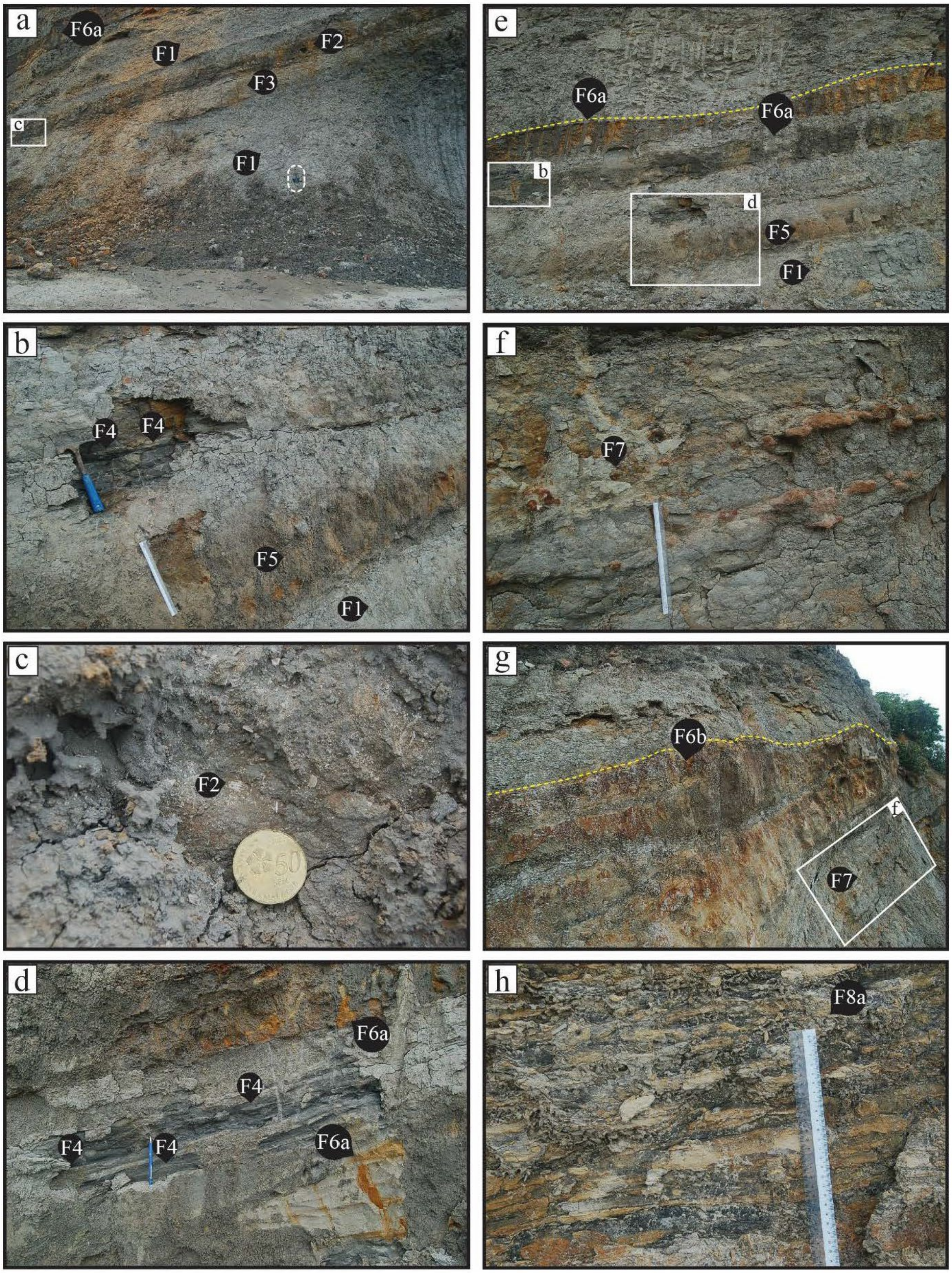

Figure 2. Various facies within a white rectangle, showcasing image locations.

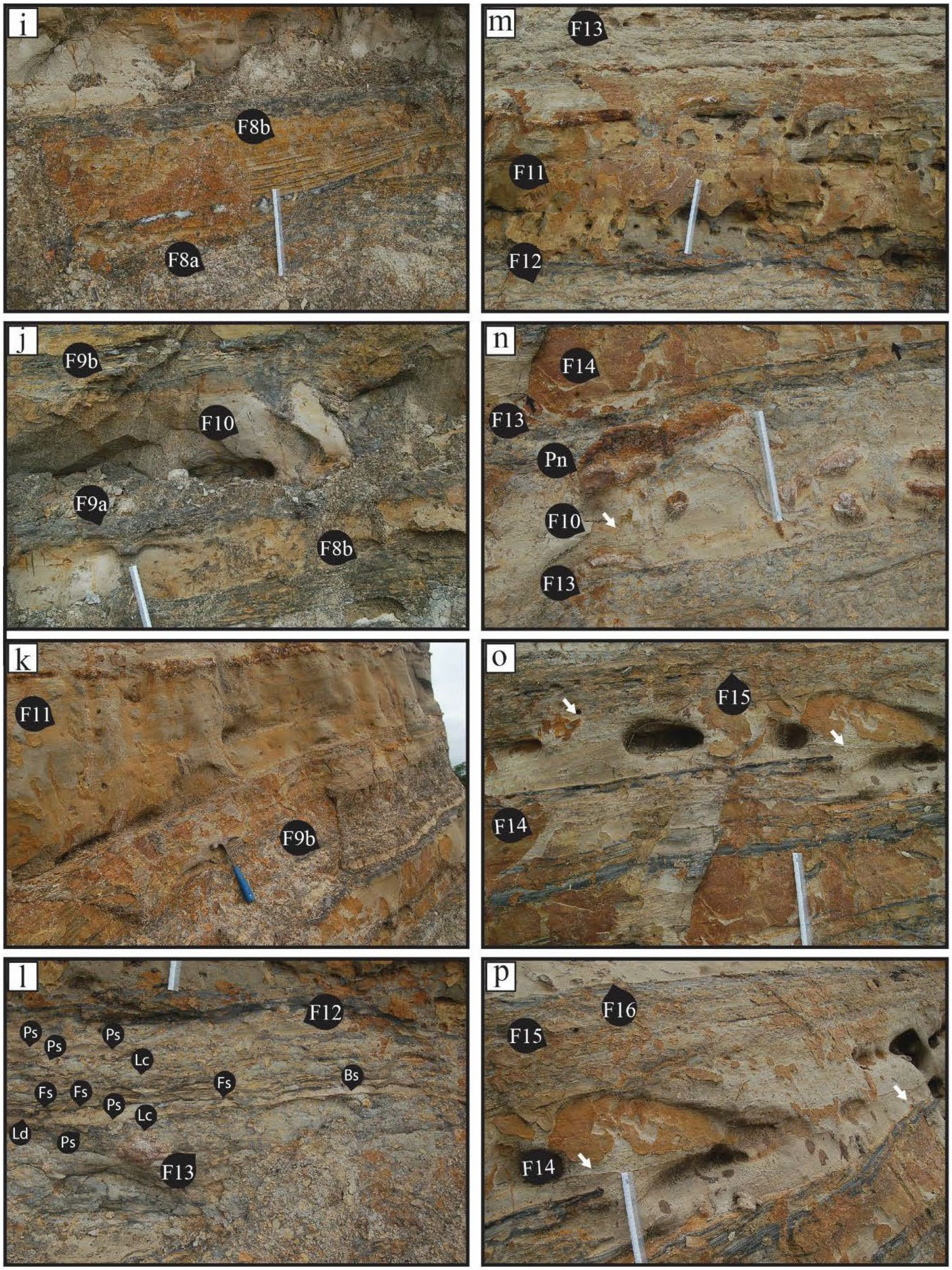

Figure 2. Various facies within a white rectangle, showcasing image locations. In Figure 2k, the following structures are displayed: Pb (Ball and Pillow structure), Bs (Ball structure), Lc (Load casts), Fs (Flame structure), Ld (Load structure), and Ps (Pillow structure). Figure 2n features pseudonodules, labeled as Pn, while Figure 2y highlights a tidal creek, denoted as Tc.

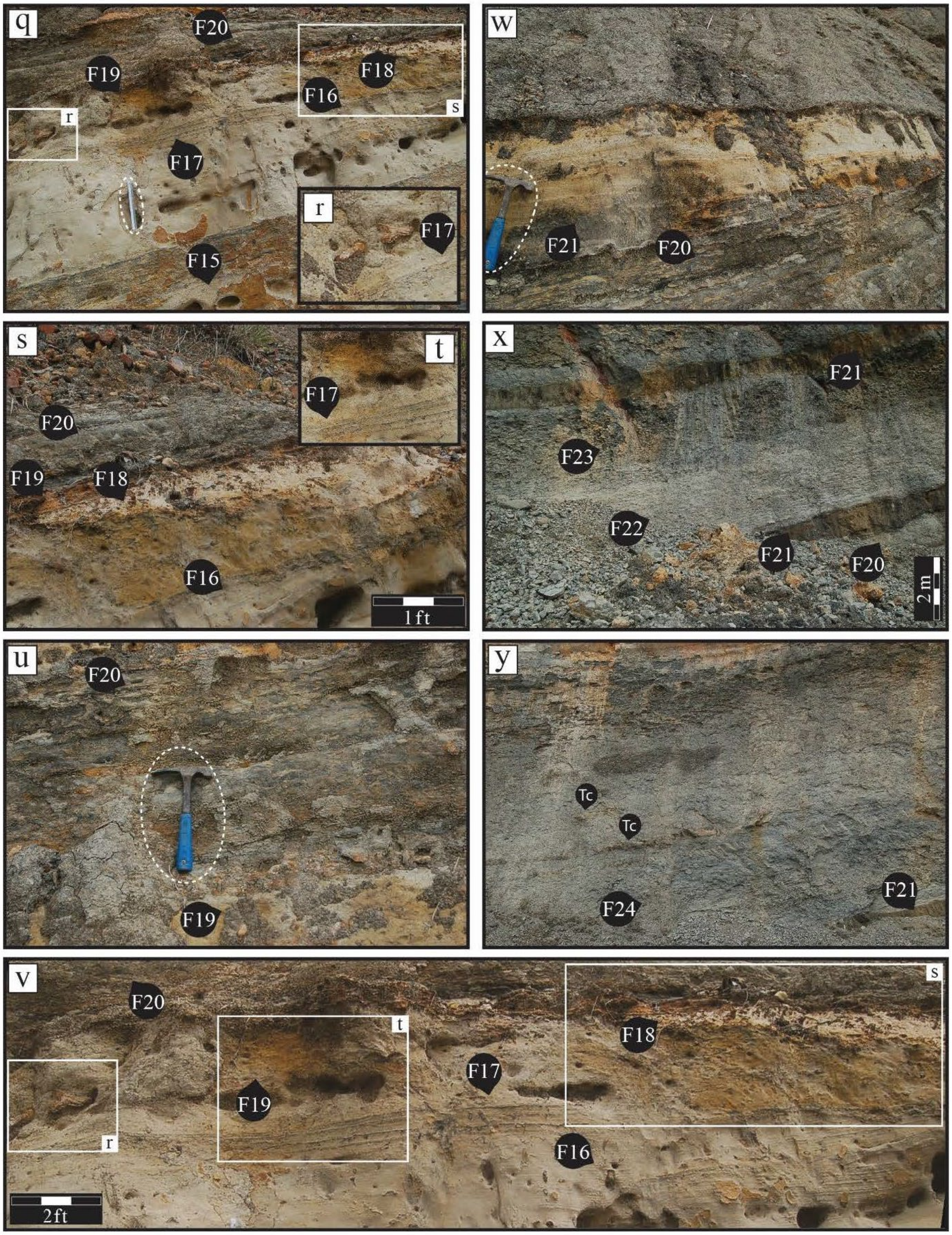

Figure 2. Various facies within a white rectangle, showcasing image locations.

4.2. Facies association – 2: Offshore Transitions

4.2.1. Description

The offshore transition zone; FA-2 is heterolithic consisting of facies F1, F4, F5, F6a, F6b, F7, F8a, and F8b making up to 15 m thick succession of offshore transition (Fig. 3B, 3C, and 3D). The F1 is getting siltier and more abundant with bioturbation at the upper part of this association (F7) (Fig. 2g), as well as followed by isolated sand streaks and lenses (Fig. 2d). The other peculiar feature in this association has been observed is two wavy or pinching and swell geometrical amalgamated sandstone bodies F6a (Fig. 2d, e) and F6b (Fig. 2f). Both are laterally continuous, thinning and forming a meter-thick sandstone lens. The F6a is homogeneous and sharp based, whereas F6b is heterolithic, bioturbated, and erosive based, sometimes it resembles gutter cast features. The F6b is generally interbedding with bioturbated siltier mudstone F7. In this association, the silt and sandstone beds are commonly observed exhibiting micro hummocky cross stratifications. Whilst, the top part of this association is dominant with interbedded mud and sand (50:50) and sometimes with cm thick sand beds exhibiting hummock cross stratifications.

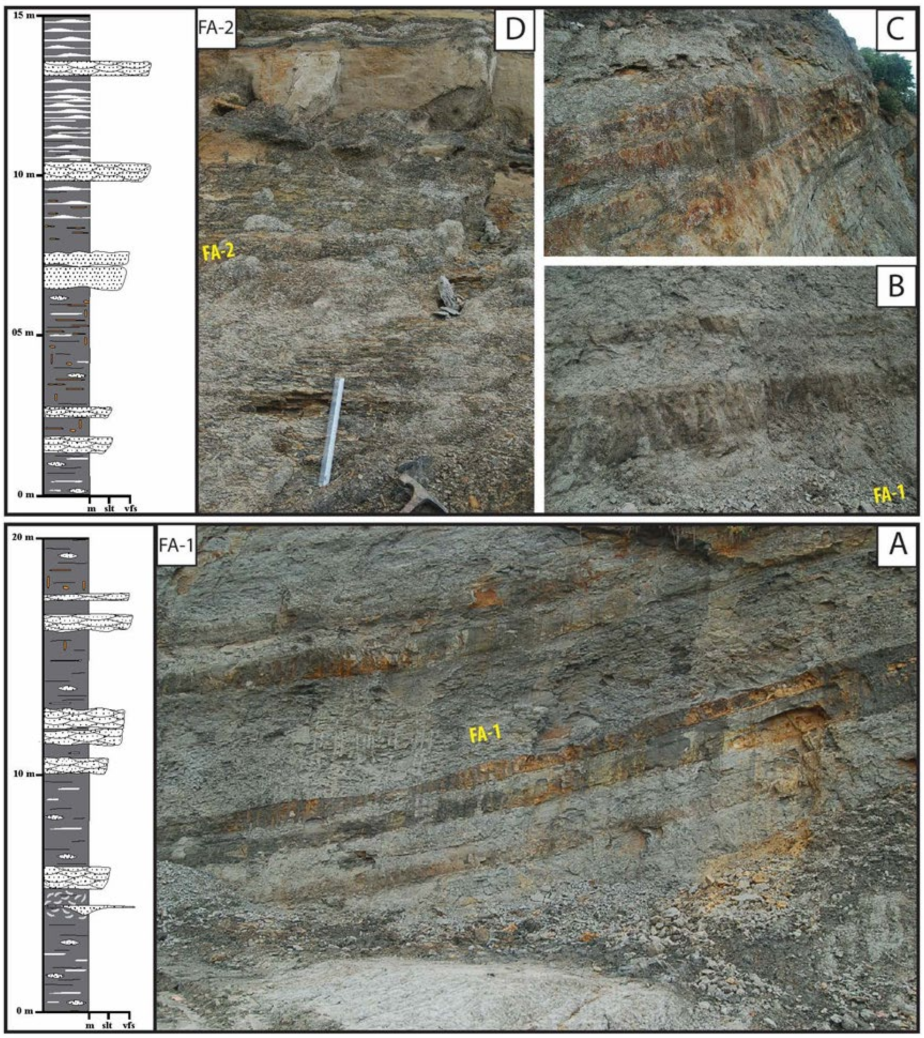

Figure 3. Facies associations and their distribution within the outcrop. FA-1 corresponds to the offshore zone, FA-2 to the offshore transition zone, FA-3 to the lower shoreface, FA-4 to the middle shoreface, FA-5 to the upper shoreface, FA-6 to the foreshore-beach complex, and FA-7 to the back barrier island-estuary settings.

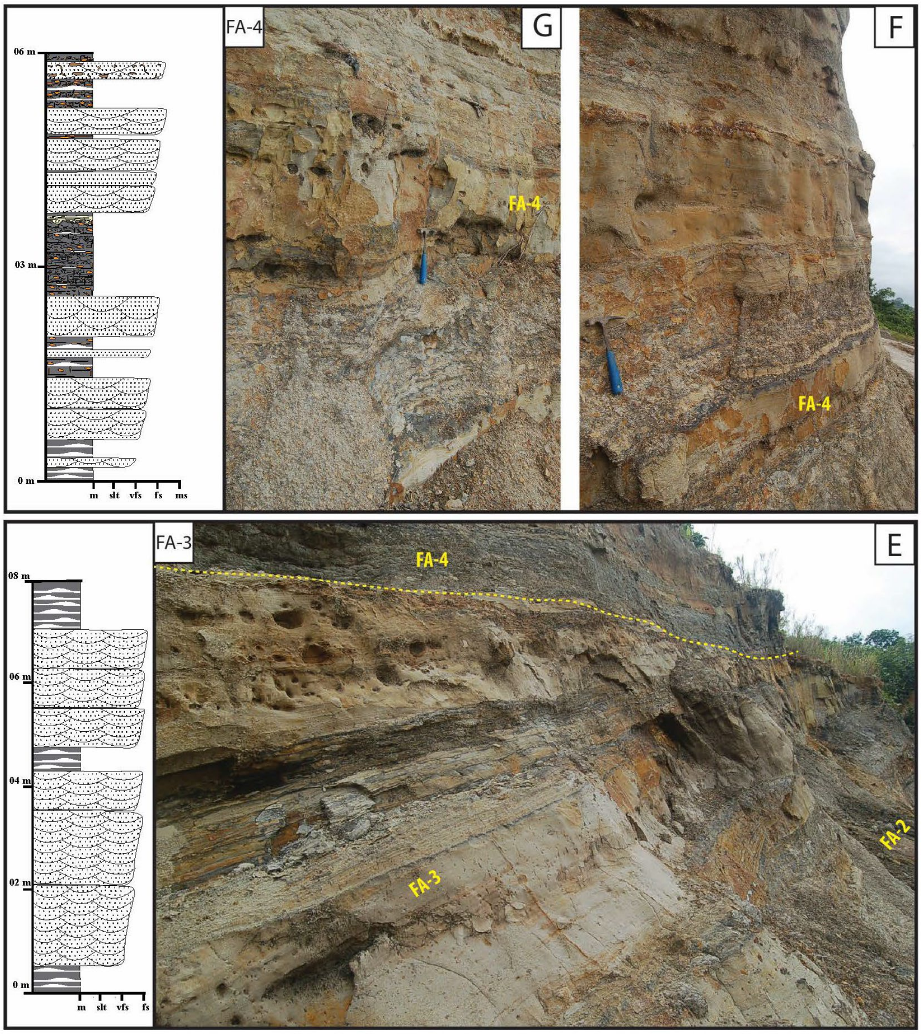

Figure 3. Facies associations and their distribution within the outcrop. FA-1 corresponds to the offshore zone, FA-2 to the offshore transition zone, FA-3 to the lower shoreface, FA-4 to the middle shoreface, FA-5 to the upper shoreface, FA-6 to the foreshore-beach complex, and FA-7 to the back barrier island-estuary settings.

4.2.2. Interpretations

The facies of FA-2 highly resemble with interpretation of the offshore transition zone accumulated below the storm wave base but closer to the nearshore environment [36–38]. It is more heterolithic and peculiar than the standard setting of offshore transition zones due to pinching and swelling geometrical and amalgamated sandstone bodies. This type of facies has repeatedly been observed in offshore transition zone and discussed by several authors such as [28,36,39,40]. [39] has interpreted that tabular type wavy homogeneous sandstone bodies (F6a) have been accumulated due to cyclic process of deposition such as tides. Whilst, it is been interpreted as storm beds deposited due to waning combine flow events due to storms [28]. The heterolithic F6b erosive-based sandstone bodies have previously been interpreted by [41-42] to be a product of falling sea levels and bypassing of sediments as erosive based is more resembling gutter casts. Whereas, [39] have interpreted it as a lobe feeding subaqueous channels, and somewhat it is also been agreed by [36,43]. The isolated sand and silt streaks enclaved in suspended sediment suggest the periodic influx of sediment input due to the intensity of wave or fluvial activities [44]. The oscillatory-generated structure in silt and sandstone indicates the deposition influence by unidirectional flow due to wave currents [38]. The interbedded sequence of the upper part is interpreted that suspended sediments are frequently been disturbed by high-energy events such as waves or storms, and the associated sandstone beds exhibiting oscillatory generated structures also support this interpretation [38]. Thus. F8a and b may be deposited in between storm wave and fair-weather wave base [36,45,46]. Further, decreases in siltstone and increases in sandstone beds upwards with increases in bioturbation intensity also support this interpretation [47-48]. The increase in bioturbation may indicate that shelf flows could have played a vital role in delivering nutrients and oxygen to the water collum that facilitates organisms to colonize [49].

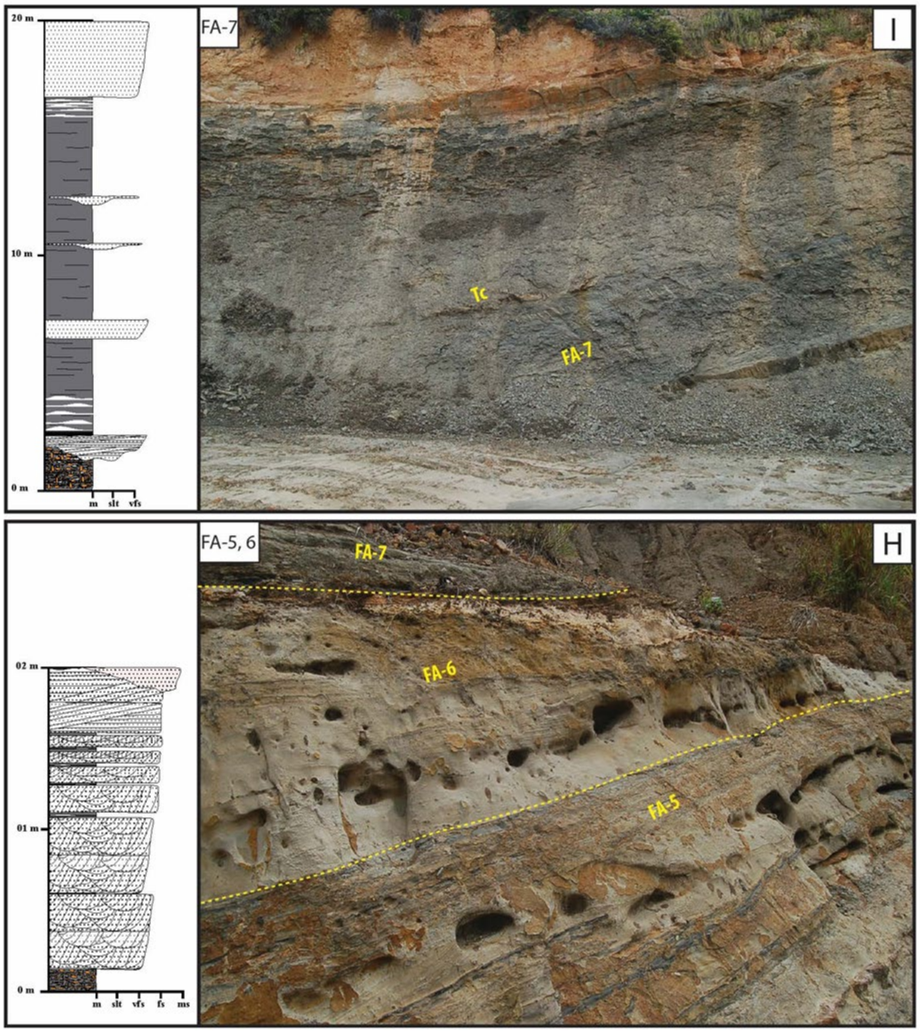

Figure 3. Facies associations and their distribution within the outcrop. FA-1 corresponds to the offshore zone, FA-2 to the offshore transition zone, FA-3 to the lower shoreface, FA-4 to the middle shoreface, FA-5 to the upper shoreface, FA-6 to the foreshore-beach complex, and FA-7 to the back barrier island-estuary settings.

4.3. Facies Association – 3: Lower Shoreface

4.3.1. Description

The lower shoreface zone FA-3; consists of F9a, F9b, F10, and minor F11 facies making up to 6 to 8 meters thick succession (Fig. 3E). It is mostly dominated by very fine-fine-grained few cm to meters thick sandstone beds exhibiting hummock and swale cross stratifications. The basal part of this association is followed by mud draped bidirectional asymmetrical ripples

(F9a) and unidirectional symmetrical ripples (F9b) are enclaved within well-sorted sandstone beds. The upper part of this association often displays amalgamations and swales cross stratifications. The bioturbation intensity in this association is moderate with homogenized organisms.

4.3.2. Interpretation

The facies of FA-3 are highly indicative of accumulation occurring in the lower shoreface zone below the fair-weather wave base [45,50]. The asymmetrical mud draped ripples at the base of this association indicate the fluid mud resuspended through coastal storms and bidirectional structures are formed due to high energy wave skewness [51-52]. Whereas, wavy bedded symmetrical ripples are purely a product of unidirectional oscillatory flow and formed under weak wave intensity [27,53]. The unidirectional oscillated generated structure is gradually increasing upward F10 and F11 with increasing bed thickness suggesting the coarsening upward trend and deposited in distal to proximal setting in the lower shoreface zone [54-55].

4.4. Facies association – 4: Middle shoreface

4.4.1. Description

The Middle shoreface zone consists of F9a, F9b, F10, F11, F12, and F13 facies making up to 6 meters thick succession possessing very fine-fine-grained well sorted sandstone beds, mostly appearing as heterolithic (Fig. 3F and 3G). Similarly, like FA-3, the basal part consists of asymmetrical and symmetrical mud-draped ripples followed by amalgamated Swaley cross-stratified sandstone upwards. The uppermost part FA-4 is mostly dominated by soft sediment-deformed structures. Three beds in this association indicate soft-sediment deformation, one is deformed wave-rippled sandstone (F12) exhibiting Ball and Plow structure (Pb), Ball structure (Bs), Load casts (Lc), Flame structure (Fs), Load structure (Ld), and Plow structure (Ps), and also displays some micro faults (Mf) (Fig. 2l). Second is a deformed sandier mudstone bed (F13) consisting of Load clast (Ls), the internal structure is almost destroyed by either bioturbation or liquidization (Fig. 2m). Third is a moderately bioturbated sandstone bed consisting of pseudonodules (Pn) and water escape (We) like features (Fig. 2n). The overall bioturbation intensity is increasing upwards, usually sparse to moderate bioturbation has been observed within sandstone whereas, bioturbation along the bedding plane was moderate and it is intense within muddy sediments.

4.4.2. Interpretation

The facies of FA-4 represent that accumulation occurs within the middle shoreface zone in between fair-weather wave base and near the surf zone [56]. It is also sometimes known as the middle or proximal lower shoreface [39]. The asymmetrical mud draped rippled suggests the fluid mud accumulation due to wave skewness. Whereas, symmetrical wave ripples are formed due to weak wave intensity [51-52]. The hummocky (HCS) and swaley (SCS) cross-stratified sandstone indicate the unidirectional oscillatory flow deposition by waves or storms [45,57]. The sparse bioturbation within sandstone beds suggests the wave energy was higher which creates a non-favorable condition for small organisms to colonize, evidencing a big form [56]. The tempestite bed amalgamation represents the moderate energy interrupted by high energy leading to an erosion of the bed surface most likely due to storm/high wave activities as previously described by [58]. The silty sandstone along with intense bioturbation indicates a weak wave period which has led finer sediment to accumulate and seafloor oxic conditions facilitated organisms to colonize [56]. In this association, the soft sediment deformation may represent the impulsiveness of wave crest and trough in the breaker zone which may have caused changes in pore pressure within the floor sediments, and a decrease in shear strength had led sediments to liquidify [59-60].

4.5. Facies association – 5: Upper Shoreface

4.5.1. Description

The facies of FA-5 consist of F14, and F15 facies and makes up to 2 to 3 meters of a thick succession of upper shoreface settings (Fig. 3H). The dominant features in this association include trough to low angle planner-parallel cross-beddings and some cryptic laminations (Fig. 2o and p). The foresets of trough cross beddings are irregular and display sinuous to strongly curved crests often with muddy laminations truncated to wadge-type erosive surface (Fig. 2p). The trough cross-bedded sandstone transitioning upward to horizontal-parallel muddy laminated isolated sandstone (F15) few cm thick erosive base beds appearing as amalgamating. The overall bioturbation intensity is lower and sparse (Fig. 2p).

4.5.2.Interpretation

The facies of FA5 are interpreted to be the deposition of the upper shoreface regime accumulated in between the oscillatory and breaking wave zone [61-62]. In this zone, the current of shoaling waves is dominant, resulting in the accumulation of well-moderately sorted fine-medium grain sandstone [63]. The multidirectional irregular crest trough cross-stratification typically truncated to the erosive base suggests the migration of highly sinuous crest sandbars by nearshore currents in the surf zone [46,64-65]. The horizontal-parallel laminated flat bedded sandstone capping trough cross-bedding sandstone with a lack of wedge type or trough cross-beddings is interpreted as surf-swash transition deposits [64]. The lower intensity of bioturbation and medium-grained sandstone suggest a shallowing upward trend and the presence of higher wave energy created an unstable condition for organisms to colonize [50,64,66].

4.6. Facies association – 6: Foreshore – beach complex

4.6.1. Description

The FA-6 consists of F16, F17, F18, and F19 facies and makes up to 1.5-2 meters of a thick succession of foreshore-beach settings (Fig. 3H). The tabular cross-bedded sandstone is dominant in this association, possessing wedge-type cross-beddings of clean and well-sorted fine-medium-grained sandstone. The cross-bedding foreset appears planner and parallel laminated with an absence of irregular crests as compared to trough cross-stratified sandstone in FA5 (Fig. 2q, v). The tabular cross-stratified sandstone is followed by low-angle – parallel and horizontal lamination upwards and capped by impersistent micaceous sand and sandy calcarenites and conglomerates F19 (Fig. 2v). The white coarse-grained, convex-triangular shaped unconsolidated dune-like sand (F18) has been observed adjacent to F19 facies and is mostly capped by carbonaceous materials. The internal structures of F18 were hard to observe due to outcrop conditions and accessibility. Overall, the bioturbation intensity of FA-6 is comparatively lower and sparse than FA-5.

4.6.2. Interpretation

The facies of FA6 are interpreted to be the deposition of foreshore–beach complexes accumulated in the intertidal zone by the swash and backwash process [65,67-68]. Mostly this association is found on the landward side of a wave-dominated shoreface delta, with mostly uniformed and well-sorted sediments. The tabular-wedge type cross beddings with parallel-planner laminations are believed to be formed by the swash deposits. Whereas, the horizontal laminations are interpreted to be formed by sheet flow in a swash zone or beach environment [65,68-69]. The curving structure of sandstone may represent well-developed beach cusps on the foreshore [70-71]. The triangular and convex-shaped white coarse-grain sand is interpreted as Eolian dunes formed by wind activities [72]. Adjacent to the dune facies, impersistent laminar stratified, rich in heavy minerals and bioclasts are interpreted as overwash deposits [71].

4.7. Facies Association –7: Back Barrier Island - Estuary settings

4.7.1. Descriptions

The FA7 consists of F20, F21, F22, F23, and F24 facies making up to more than 20 meters of a thick sequence of estuary settings with having range of environments including back barrier island and lagoonal settings (Fig. 3I). It is mostly dominated by mudstone facies, F18 and F19 of FA6 are capped by heavily bioturbated carbonate tidalites (F20) (Fig. 2u), appearing as structureless due to organic activity. The fine-medium grained very well-sorted sandstone is capping F20 facies, displaying hummock and swaley cross-stratifications, laterally it is thinning and have scarp erosive based and topped by a carbonaceous sheet (Fig. 2w). Two beds of cross-bedded sandstone have been observed sandwiching mudstone facies F22 and F23. Mudstone on top of F21 facies consists wavy beddings of sand (50:50) (Fig 2x), and F23 appears as clayish and consists of minor sand and is mostly dominated with mud cracks and capped by F21 facies (Fig 2x). The F24 more resembles F1 facies and appears as massive mudstone consisting of thin cm sandstone beds along with elongated sharp-based pinched sandstone bodies (Fig. 2x, y). The top part of this outcrop was not accessible and it is not been documented as per facies. But one can easily observe the sequences. The mudstone (F24) is transitioning upwards to mixed sand and shale sequence 50:50 and is finally covered by thick sandstone bodies. Overall bioturbation in this association was intense in F20 facies but it gets sparse or minor bioturbation in other facies.

4.7.2. Interpretation

The facies of FA7 are believed that deposition may occur in a back-barrier island-estuary setting. Which range of sub-environments may include such as barrier islands, back-barrier flood tidal delta, and estuary basins. The other environments may have included bay head delta and alluvial sediments which have not been evaluated deeply due to outcrop accessibility. These settings highly resemble the idealized model of [73] of the wave and tide-influenced barrier-beach system. The carbonate tidalites may indicate the accumulation occurs in subtidal lagoons under humid and arid environments and it is least affected by tidal intensity [74–76]. The capping well-sorted hummocky-swaley cross-bedded sandstone bodies are interpreted as sand shoals [77]. Sand shoals are mainly composed of either local biota which has winnowed from the adjacent subtidal environment or the chemical precipitation of ooids under higher energy shoaling conditions [78]. The muddy sand is interpreted as a product of ebb-flood deposits [79] and interpreted sub tidal flat. Clayish mudstone having a dominant feature of mud cracks may exhibit drying up of lagoons which has caused dissection and contraction of muddy sediments [80-81]. The thick mudstone sequence is interpreted as suspended sediments in the estuary basin [82] (Fig. 5). The elongated enclosed sandstone bodies within mudstone are interpreted as subaqueous distributary channels [83]. Whereas the sand shale interbedded sequence capping the mudstone facies is interpreted as a bay head delta and also a transition zone of marine and fluvial depositional environment [84]. The thick sandstone body capping on top of the Bay Head delta may be the deposition of sandy tidal deposits within the delta plain environment [85]. Thus, the facies in this association are good examples of studying back–barriers to estuary settings.

5. Depositional model, facies process, and shoreline evaluation

The vertical succession of outcrop comprises 24 facies and is divided into seven zones exhibiting different environments of shallow marine siliciclastic deposits of wave-dominated offshore-shoreface and coastal settings (Fig. 4). It highly resembles the model [86] of the transgressive sediment supply deficit of the back-barrier island. In the shoreface system, sediments are accumulated under the influence of storm and fair-weather wave bases by both unidirectional and bidirectional oscillatory flow, and the upper part is influenced by surf and swash deposits. In the back barrier settings, it is a combined accumulation of flood and tidal processes. The offshore zone of the shoreface system is dominated by suspended sediments accumulated below the storm wave base, with a complete absence of seafloor colonization/bioturbation possibly due to anoxic conditions and lack of nutrient supply [87-88]. Gutter casts and a cap of erosive-based poorly sorted coquinite /shell fragments within suspended sediments are indicative of episodic coastal helical vortices which have caused coastal erosion and led sediment bypassing to the outer shelf by hyperpycnal flows and capping by winning flow deposits [31–34].

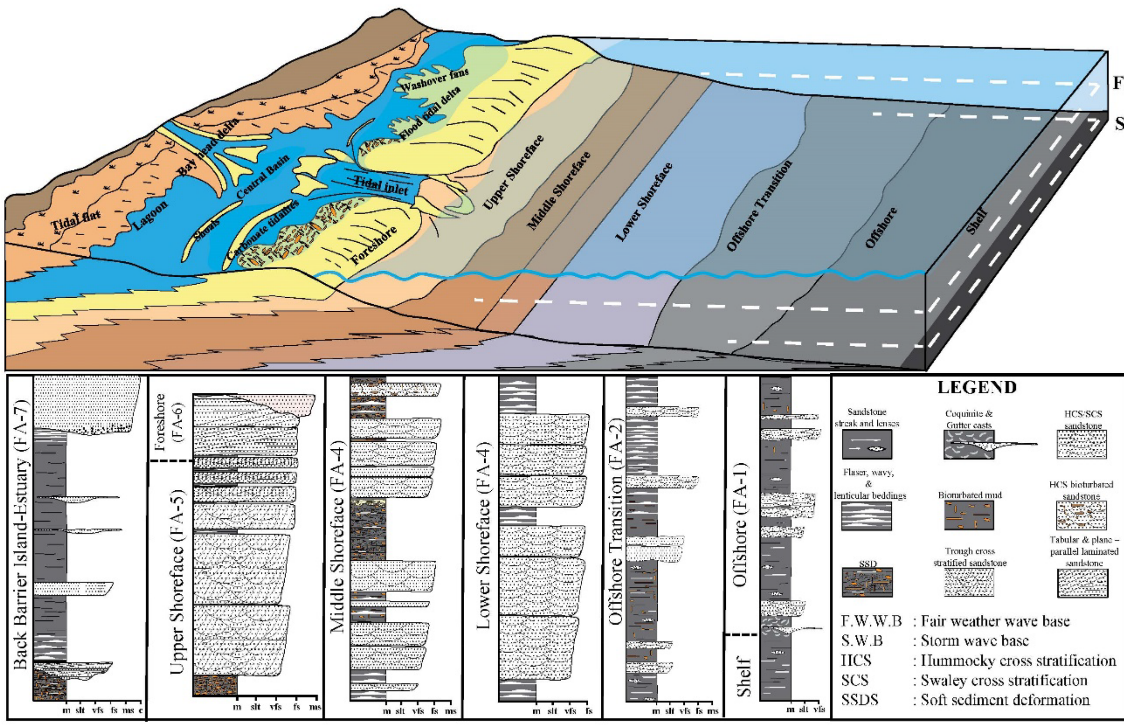

Figure 4. Schematic Paleo-depositional model.

Comparatively, the offshore transition zone is more heterolithic and accumulated on average and equal to storm and fair-weather wave base [36,45-46]. It is getting coarser and bioturbated upwards with a decrease in siltstone beds and an increase in sandstone beds exhibiting hummock and swale cross-stratification. In the offshore transition zone, two facies F6a and F6b very essential to document as they can hardly be noted in the core logs. F6a is more homogeneous whereas F6b possesses heterogeneous characteristics, both are amalgamating with distinguishing features of erosive and sharp basal boundaries. Similar facies in offshore transition zones have also been documented and discussed briefly by [36,39–42]. The increase in colonization/bioturbation strongly suggests a well-oxygenized sea floor water columns have led organisms to colonize [49].

The lower shoreface zone is sandier with a fine grain of sandstone beds exhibiting oscillated generated structures accumulated above the fair-weather wave base [45,50]. The basal part of the lower shoreface is dominated by mud-draped asymmetrical ripples which are mainly caused by bi-directional flow due to wave skewness [51,54]. The symmetrical ripples are documented on most of the basal part of sandstone beds representing weak wave periods [27]. The sediments in the middle shoreface zone occur above the fair-weather wave base but below the surf zone. It is more heterolithic than the lower shoreface and consists of soft sediment deformation beds which may have occurred due to impulsiveness of wave crest and trough in the breaker zone [59-60]. The sandstone beds exhibit high-angle swales and low bioturbation intensity indicating high energy creating a non-favorable situation for small organisms to colonize [56]. Most bioturbations are found parallel and along the bedding plane of some sandstone beds. The upper part is muddier and most bioturbated within the shoreface system, which may represent the weak wave period resulting in the deposition of mud due to the suspension and colonization of organisms due to a well-oxygenized water column. The muddier part may also represent the transition zone of the middle and upper shoreface setting.

The sediments of the upper shoreface zone accumulated near the surf or breaker zone where shoaling waves are dominant. Resulting in the deposition of irregular sinuous crested sandbars, typically exhibiting trough cross stratifications [64]. The trough cross-stratified unit is capped by horizontal tabular cross bedded sandstone strata, individual beds are either amalgamated or bounded by muddy laminations, representing a surf-swash transition deposit [64]. The transition deposits are capped by clean well-sorted wedge-type tabular cross-bedded sandstone which is the most landward part of shoreface settings in the foreshore zone exhibiting well-developed beach cups and parallel laminations at the upper part [70-71]. The parallel lamination and wedge-type tabular cross-bedded sandstone are capped by poorly sorted coastal micaceous calcarenite sand consisting of coral and terrestrial debris suggesting overwash deposits of backshore settings. It is also truncated to convex triangular-shaped featureless embryo foredune capped by carbonaceous materials suggesting local vegetation [89-90]. Due to the enclosed back-barrier island system only over wash and embryo foredunes have been documented in the backshore environment, capped by back-barrier carbonate tidalites.

The sediments in back-barrier islands may be further divided into 3 zones as per the conceptual model of [82] (Fig. 5). The carbonate tidalites, precipitated shoals, mud, and tidal flats are more marine-dominated in the zone of flood tidal delta. Whereas, estuary mud, erosive and elongated channelized enclosed sandstone bodies are accumulated within a central basin. The top part of estuary mud is capped by an interbedded sequence consisting of shale and sand which is probably a transition zone (bay head delta) of the estuary central basin to the alluvial valley environment [84].

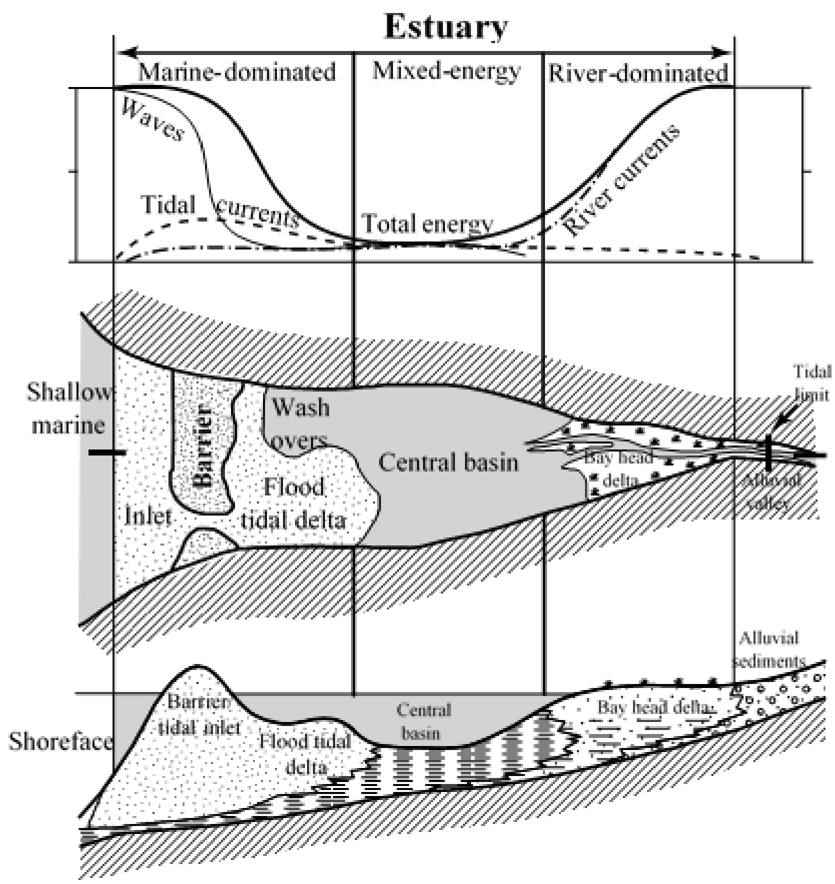

Figure 5. Schematic model of wave-dominated estuary (modified after [82]).

6. Conclusion

The sedimentological analysis of the vertical succession comprising 24 facies reveals a complex interplay of depositional environments within a shallow marine siliciclastic setting. The study identifies seven distinct zones ranging from wave-dominated offshore-shoreface to coastal back-barrier island environments, aligning closely with the transgressive sediment supply deficit model proposed by Flemming [86].

In the shoreface system, the sediments exhibit characteristics indicative of storm and fair-weather wave influence, with notable variations in energy conditions and bioturbation intensity. The offshore zone, dominated by suspended sediments and characterized by anoxic conditions, contrasts sharply with the more heterolithic and bioturbated offshore transition zone, where the presence of facies F6a and F6b provides critical insights into the depositional processes that are difficult to discern in core logs.

The shoreface zones, from lower to upper, display a gradation in sediment texture and structure, reflecting the dynamic processes of wave action, surf, and swash. The lower shoreface is marked by oscillation-generated structures, while the middle shoreface shows evidence of soft sediment deformation and reduced bioturbation due to high-energy conditions. The upper shoreface, dominated by shoaling waves, culminates in the formation of sandbars and surf-swash transition deposits, transitioning landward into well-sorted foreshore sandstones and backshore overwash deposits.

In the back-barrier island environment, the sediments further divide into zones consistent with Dalrymple *et al.* [82] (Fig. 5) conceptual model, transitioning from marine-dominated flood tidal delta deposits to more terrestrial influences within the central basin and bay head delta. The presence of carbonate tidalites, precipitated shoals, and estuarine mud highlights the intricate relationship between marine and terrestrial processes in shaping the back-barrier island system.

Overall, this study underscores the significance of integrating facies analysis with established sedimentological models to interpret complex depositional environments, providing valuable insights into the sedimentary dynamics of wave-dominated coastal systems.

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