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Facies Analysis and Stratigraphic Succession of Early Miocene Reservoir in Temana Field, Offshore Sarawak

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Abstract

Balingian Province is a prolific hydrocarbon-producing region in Sarawak Basin which has received great interest in the past years leading to good understanding of the regional tectonic and sedimentation history. However, few studies had focus on field-scale level to address reservoir complexity associated with marginal marine setting. This study attempts to highlight on the sedimentology and stratigraphy of Cycle II (Early Miocene) reservoir interval in a mature brownfield of Temana using primarily core and well log data. The facies analysis of core reveals interbedded units of sandstone and mudstone with diverse tidal and wave sedimentary structures as well as abundant trace fossils of mixed skolithos and cruziana ichnofacies representing brackish water to open marine assemblages. Depositional model of the reservoir interval is proposed as succession of delta and estuary subjected to mixed tidal and wave energy, followed by open marine shelf resulting from marine transgression of the coastal area. Well stratal pattern of the reservoir interval depicts stratigraphic architecture that is composed of high-frequency transgressive-regressive (T-R) cycles nestled within larger retrogradationally stacked 3rd-order sequences. This study demonstrated that sedimentological and stratigraphic analysis using core and well log can provide valuable input on the reservoir lateral and vertical heterogeneity thus improving well-to-well correlation and facies prediction to support field development strategy.

Keywords: *Core; Well log; Sedimentology; Stratigraphy; Marginal marine.*

1. Introduction

Balingian geological province located within Sarawak Basin is a proven oil and gas producing region. The main reservoir targets are Cycle I to III (Oligocene to Middle Miocene) reservoirs deposited as lower coastal plain fluvial to shallow marine sands. The region had throughout Cenozoic undergone complex tectonic activities originated from the opening of South China Sea and subsequent collision with drifted microcontinent at the NW Borneo margin, exhuming orogenic belt of uplifted deepwater sediments [1]. Intense deformation that follows include extensional, compressional and wrench faulting that had large influence on the structural compartmentalization and sedimentation pattern. This led to huge challenge in optimizing oil and gas field production in the Balingian province [2].

Extensive studies have been published in the past that highlights the sedimentology, regional tectonic and stratigraphic framework utilizing information from offshore oil and gas data as well as onshore outcrops (e.g. [3-9]). This has greatly improved the understanding on the tectonic and sedimentation history of Sarawak Basin. However, there is still a need to study on a local or field-scale especially reservoir correlation, facies characterization and distribution. Therefore, this study aims to provide insight on Temana field, one of the major producing fields in East Balingian sub-province, focusing on the sedimentary and stratigraphic architecture using primarily core and well log data.

Sequence stratigraphy is a method to understand the relationship between depositional sequences and the base level changes affected by various controlling factors such as tectonics, sea level change and climate [10-11]. These can be investigated from strata stacking pattern occurring at various scale of depositional cycle from large scale first-order sequence to high-frequency 4th or 5th -order sequence. High resolution data such as outcrop, core and well log are often used to study the depositional sequence at reservoir level especially in a highly variable environment such as marginal marine setting. As such, they are very useful to examine field's reservoir zonation and heterogeneity occurring below seismic resolution [12].

Temana field which lies in offshore Sarawak just 30 km west of Bintulu town is a mature brownfield that has been producing oil since 1979 from Early to Middle Miocene reservoirs. The structure is defined by west-plunging tightly folded anticline bounded by major reverse faults on the flanks and is further dissected by numerous NE-SW trending extensional and reverse faults. Major reservoir bodies were deposited as estuarine and deltaic sands [13]. The wide range of depositional facies poses difficulty in correlating the reservoirs and predicting its lateral and vertical continuity. Facies analysis from core along with well log stratigraphic interpretation of an Early Miocene reservoir group is presented in this paper to shed light on the stratigraphic succession and paleoenvironment setting. The objectives of the study are to analyze the sedimentary facies characteristic and trace fossil assemblages, reconstruct depositional model of the reservoir and establish the stratigraphic framework from well stratal pattern.

2. Geological setting

Sarawak Basin located on the northwest margin of Borneo Island covers large part of the offshore and coastal plain of Sarawak. It is demarcated to the northeast by West Baram Line, a significant geological lineation separating it from the Baram Delta Province and Sabah Basin [14] (Figure 1). The basin formation relates to the opening of South China Sea and contemporaneous subduction beneath NW Borneo margin since Late Cretaceous [1]. This eventually resulted in a collision with drifted microcontinent during Late Eocene and caused uplift of the former deepwater Rajang Fold-Thrust Belt, an event termed as Sarawak Orogeny [15](Figure 2). Post-orogenic foreland basin developed along the margin and later evolved into passive margin as sediment source persisted from the uplifted hinterland. Stratigraphy of Sarawak basin was established by Shell workers based on seismic and well data, where it is subdivided into eight regressive sedimentary cycles bounded by transgressive surfaces, and dated using nannofossil, foraminifera and palynomorphs [3,16-17].

Balingian Province is a distinct region with complex tectonic and stratigraphic history related to the foreland basin. The province has proven petroleum system producing mainly from Cycle I-III reservoirs [18]. It is bounded by West Balingian Line to the west and Anau-Nyalau fault to the southeast, while the northern boundary gradually transitions into a carbonate dominated sediment of Central Luconia Province. It can be generally subdivided into West Balingian and East Balingian sub-provinces separated by N-S aligned thick depocenters [19]. The West Balingian sub-province is dominated by NW-SE trending structures formed by dextral fault movement of West Balingian Line. The active tectonics also led to several irregular unconformities subdividing the Cycle I-III strata. Further towards East Balingian sub-province, the tectonics were masked by marine transgression and the strata appears to be more conformable [17]. Later, series of compressive wrench tectonic related to counter-clockwise rotation of Borneo from Late Miocene to Pliocene uplifted the Balingian and Central Borneo area, creating multiple NE-SW trending anticlinal folds truncated at the crest with major angular unconformity [18].

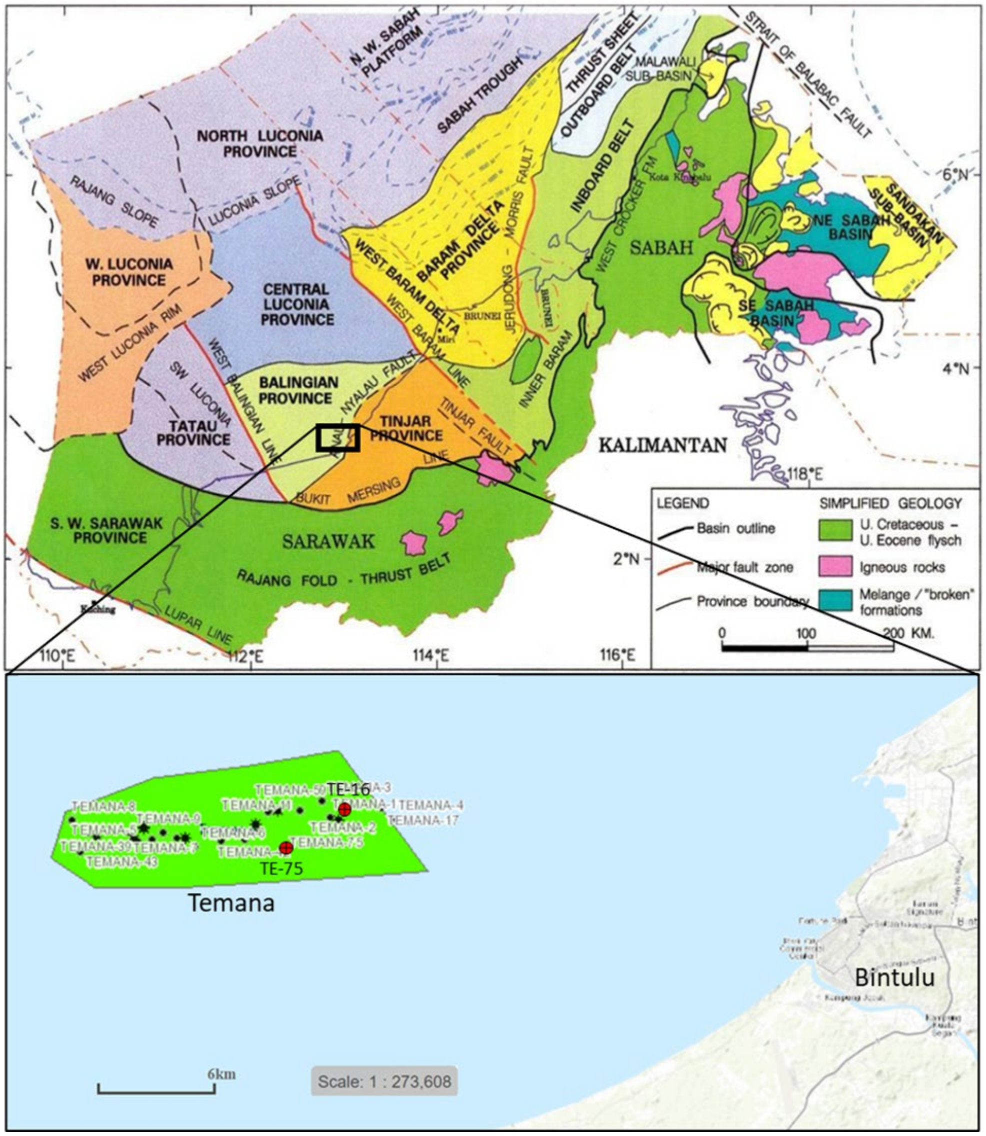


Figure 1. Top: Regional geological setting of NW Borneo and its tectono-stratigraphic provinces (after [14]). Bottom: Inset map showing location of Temana field and the two cored wells used in the study (red-filled circles)

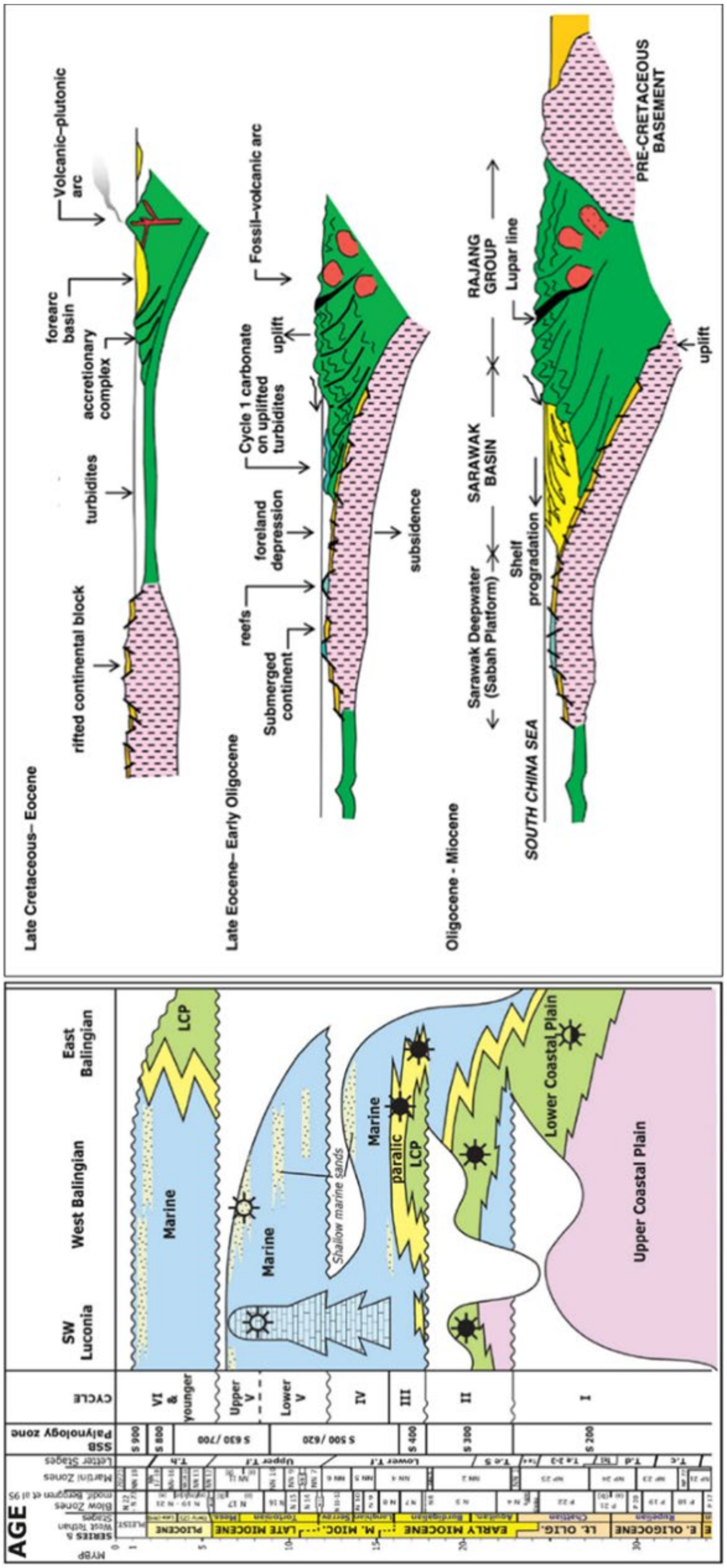


Figure 2. Left: Stratigraphic schemes of Sarawak Cycles (after [17]). Right: Schematic drawing showing tectonic evolution of Sarawak basin from Late Cretaceous to Miocene progressing from subduction to collision and formation of foreland basin which later evolved into passive margin (after [15]).

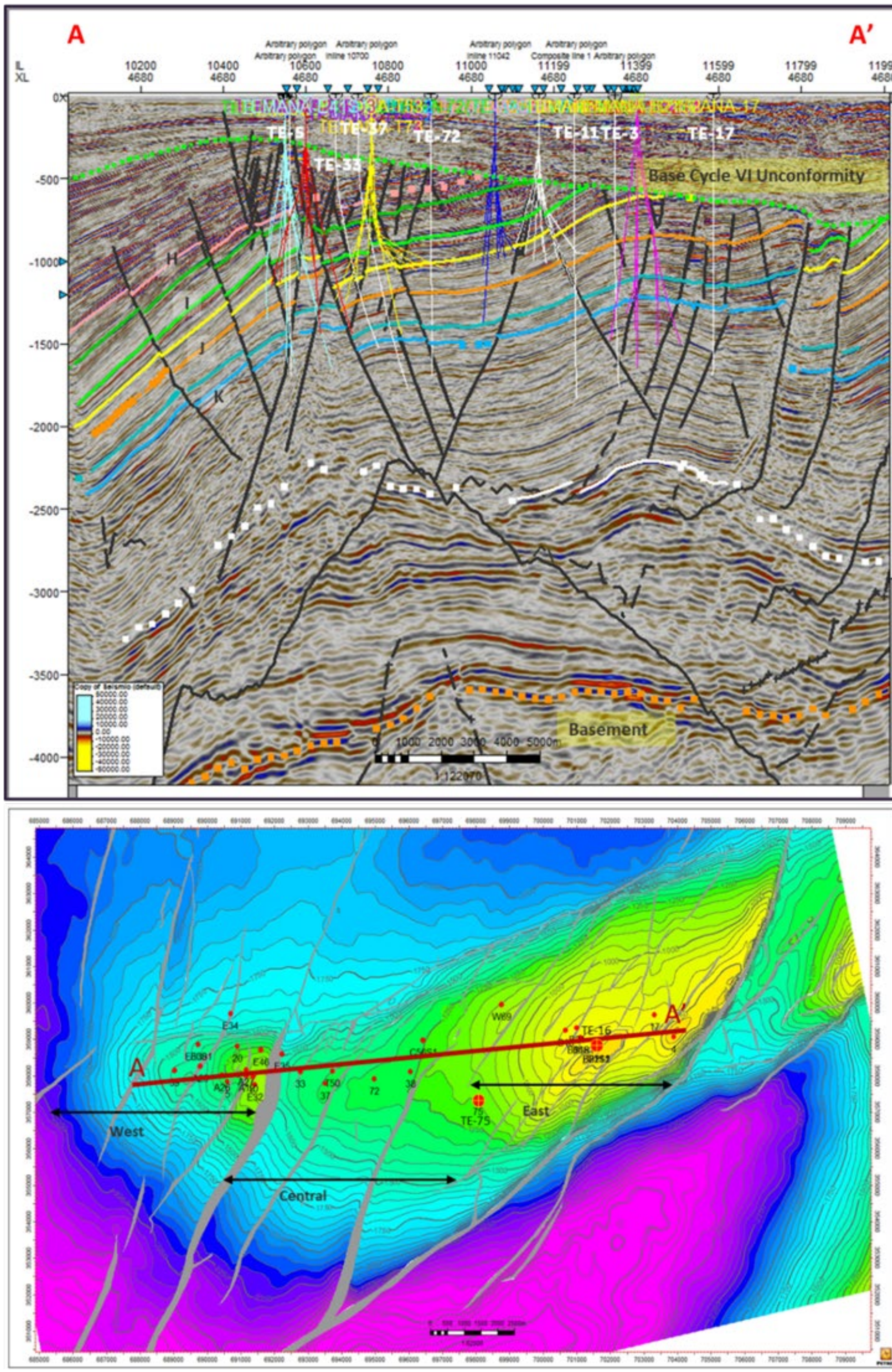


Figure 3. Top: Seismic profile across Temana highlighting the structural complexity and various style of faulting. Location of the line is shown in bottom figure. Bottom: Structural map of Temana showing the main West, Central and East compartments dissected by numerous NE-trending faults

The study area, Temana field is one of the oldest fields in East Balingian that has been producing oil for more than 40 years. Main production is coming from Early-Middle Miocene Cycle II and III reservoirs. Although hydrocarbon can be found in deeper Cycle I sand, it is considered as tight gas reservoir. Temana structure is described as an elongated E-W trending anticline bounded on both of its flanks by major reverse faults reflecting a positive flower structure. It is further complicated by numerous NNE-SSW normal and reverse faults creating highly compartmentalized structure [20] (Figure 3). Major part of the strata is seen dipping to the west whereas the crest is being truncated by an angular Late Miocene unconformity. Hence, the relatively flat-lying sediment above the unconformity overlies progressively older strata towards the east in which most of the Cycle III and upper Cycle II had been eroded. The reservoirs comprise of multi-stack heterogenous sand deposited within marginal marine setting. Despite the long production history, Temana field recovery has not been fully optimized and development remains challenging partly due to the complex reservoir architecture and correlation.

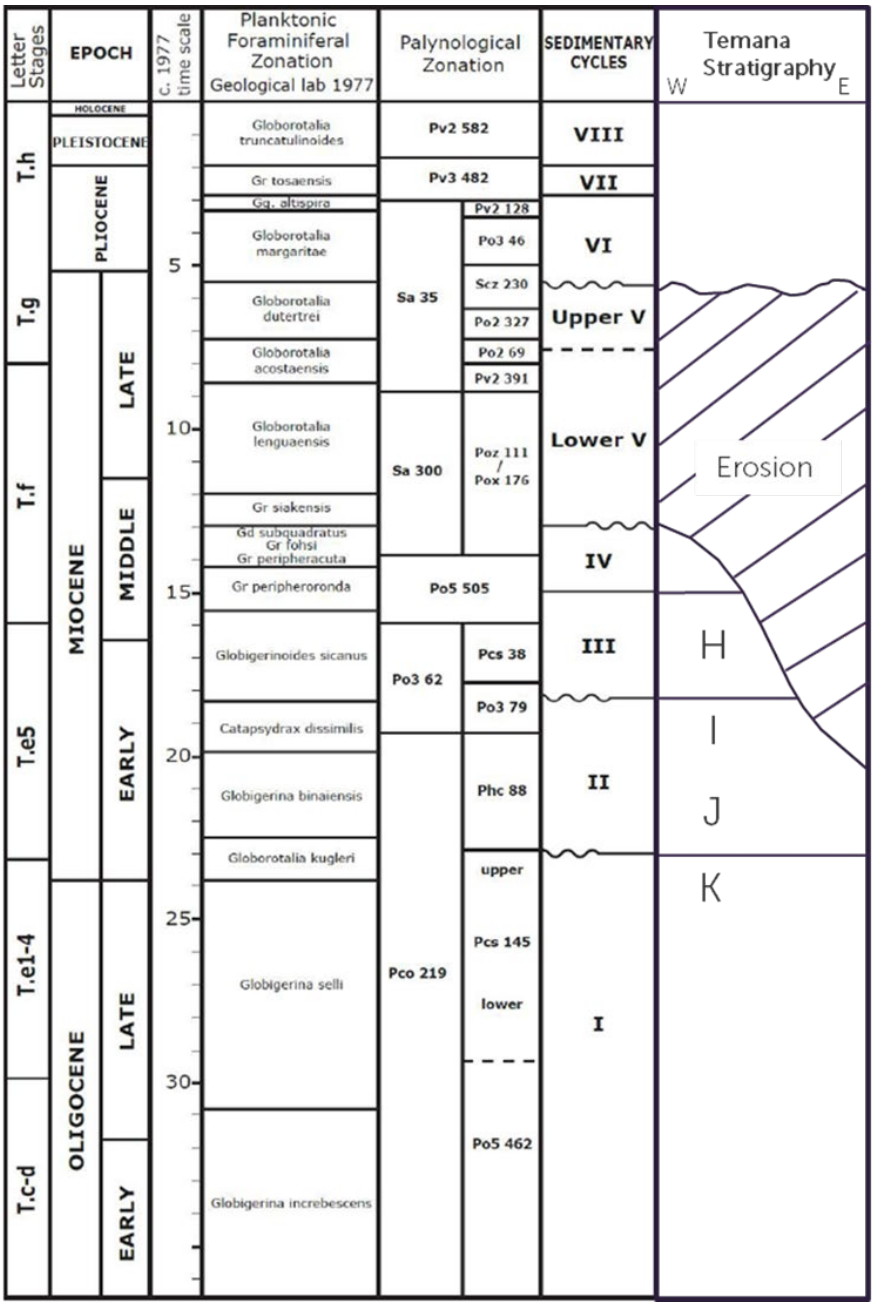


Figure 4. Generalized stratigraphy of Temana reservoir in comparison to Sarawak Cycles and Shell bio-stratigraphic zonations (modified from [16-17])

The stratigraphy of Temana reservoir is segregated from young to old into H, I, J and K-series reservoir groups. H-series comprises of alternating fining and coarsening upward sequences of interbedded sand, shale and thinly-bedded coals followed by major thick and coarsening upward sands towards the top deposited within fluvio-deltaic setting [21]. The age is dated as Early-Middle Miocene and broadly equivalent to Cycle III. I-series is generally mud-dominated strata with major channelized sand at the base followed by coarsening upward sequence. Several well-developed coal markers can be recognized. The reservoir can be correlated to Upper Cycle II stratigraphy dated as Early Miocene. J-series reservoir is characterized by overall retrogradational sequence of repeated coarsening and fining upward sequences. Coals are rare and only present in localized area. The age is placed at basal Early Miocene and correlatable to Lower Cycle II stratigraphy. Lastly, the K-series consists of predominantly thick and well-developed, albeit tight sand with alternating coarsening and fining upward sequence. It is equivalent to Cycle I or Upper Oligocene age. Summarized stratigraphic chart is as shown in Figure 4. This study focuses on J-series due to the availability of core and well log data and its good reservoir potential that is still being under-developed.

3. Data and methodology

In this study, core samples from TE-16 and TE-75 spanning a length of 29 m and 69 m respectively within J-series interval were investigated for sedimentology, trace fossil assemblage and facies association. TE-16 is located at the eastern side of Temana while TE-75 is situated slightly towards the center. The cores were logged whereby sedimentary facies were described based on lithology, texture, primary sedimentary structures and degree of bioturbation. Bioturbation index is scaled from 0 to 6 with 0 being absent while 6 is completely bioturbated and homogenized sediment [22-24]. The lithofacies were then grouped into facies associations which represent depositional environments. Trace fossil assemblages were also used to support paleoenvironment interpretation based on archetypal ichnofacies [25].

Well log data that are responsive to lithology such as gamma ray (GR), resistivity (Res) and neutron-density (Neu-Den) were utilized to characterize the log motif for each of the interpreted depositional facies. This allows for extrapolation to non-cored intervals and analysis of well log stacking pattern over greater intervals. Well correlation panel focusing on J-series reservoir is also presented to show the stratigraphic interpretation and lateral facies variation in depositional-dip direction. These results were incorporated into depositional model and stratigraphic framework of Temana reservoir.

4. Results and discussion

4.1. Facies description

The sedimentary facies were described from TE-16 and TE-75 cores based on the lithology, grain size, color, sorting, primary sedimentary structures and degree of bioturbation. Selected photographs of the core depicting the facies and trace fossils (ichnogenera) are shown in Figure 5-6. There are nine lithofacies identified: 1) S1, massive to faintly laminated sandstone; 2) S2, rippled and cross-bedded sandstone; 3) S3, planar-laminated sandstone; 4) S4, low-angle to hummocky cross-stratified sandstone; 5) S5, bioturbated sandstone; 6) H1, heterolithic flaser-to-wavy bedded sandstone; 7) H2, heterolithic lenticular mudstone; 8) M1, laminated mudstone; and 9) M2, bioturbated mudstone.

1) S1: Massive to faintly laminated sandstone

This facies is characterized by fine to medium and occasionally coarse-grained, light to dark brown and poor to moderately sorted sand. The sandstone thickness ranges from tens of centimeters to few meters and generally appear as massive due to lack of internal structures, but faint laminations and cross beddings could be seen in places. Angular to subrounded rip-up mud clasts and carbonaceous materials are commonly present. The sand is typically sharp or erosive base and transitions upward into finer grains with ripple laminations or heterolithic flaser-to-wavy bedded sand, which may occur alternately in some intervals. Bioturbation is rare, but when present in finer sand it may contains *skolithos* and *ophiomorpha* ichnogenera.

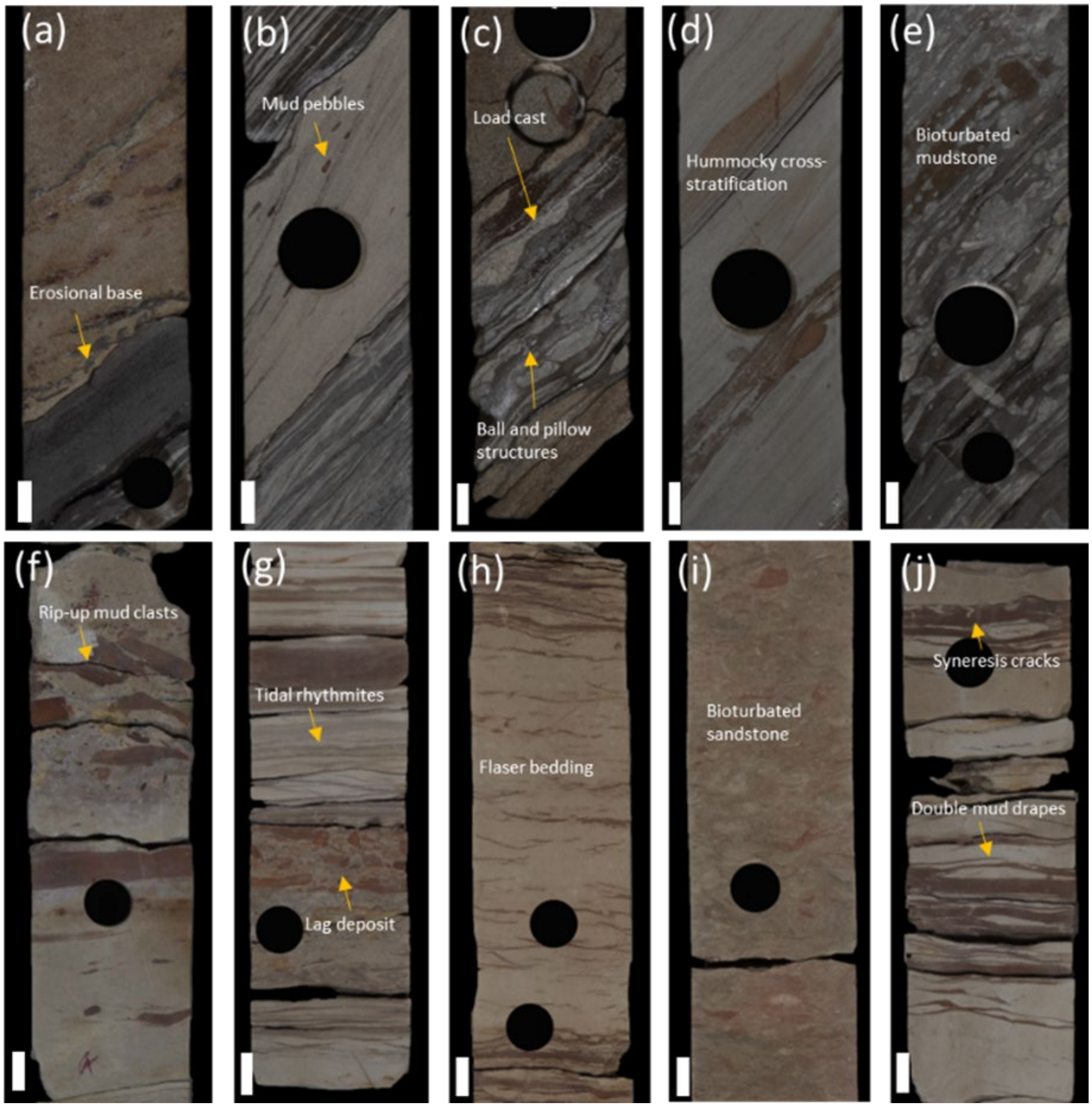


Figure 5. Photographs of selected core samples from TE-75 (a-e) and TE-16 (f-j). **(a)** Erosional-based massive to faintly laminated sand, S1, typical of channel deposit overlying dark-grey laminated mudstone, M1. **(b)** Cross-bedded sandstone, S2, with mud drapes and pebbles along the lineations are indicative of tidal-influenced process. **(c)** Soft-sediment deformation that includes load cast and ball and pillow structures due to differential loading in heterolithic mudstone, H2. **(d)** Well-sorted clean sandstone with low angle to hummocky cross-stratification structures, S4, dominated by wave and storm processes, interpreted as shoreface sand. **(e)** Highly bioturbated mudstone, M2, with visible planar laminations, reflecting calm environment and low-sedimentation input in the offshore zone. **(f)** Rip-up mud clasts commonly found in massive sandstone, S1, formed by scouring activity of tidal channel. **(g)** Tidal rhythmites in planar-laminated sandstone, S3, overlying thin lag deposit layer possibly representing ravinement surface. **(h)** Rippled sandstone, S2, with mud flasers over the trough suggesting alternating current flow in high sediment input setting such as mouthbar facies. **(i)** Intensely bioturbated sandstone, S5, associated with lower shoreface setting appears to be homogenized and poorly distinguishable trace fossils. **(j)** Sand-dominated heterolithic unit, H1, displaying syneresis cracks and double mud drapes believed to be deposited under fluctuating water salinity and flow such as tidal bar or tidal flat. Scale bar is 2 cm long

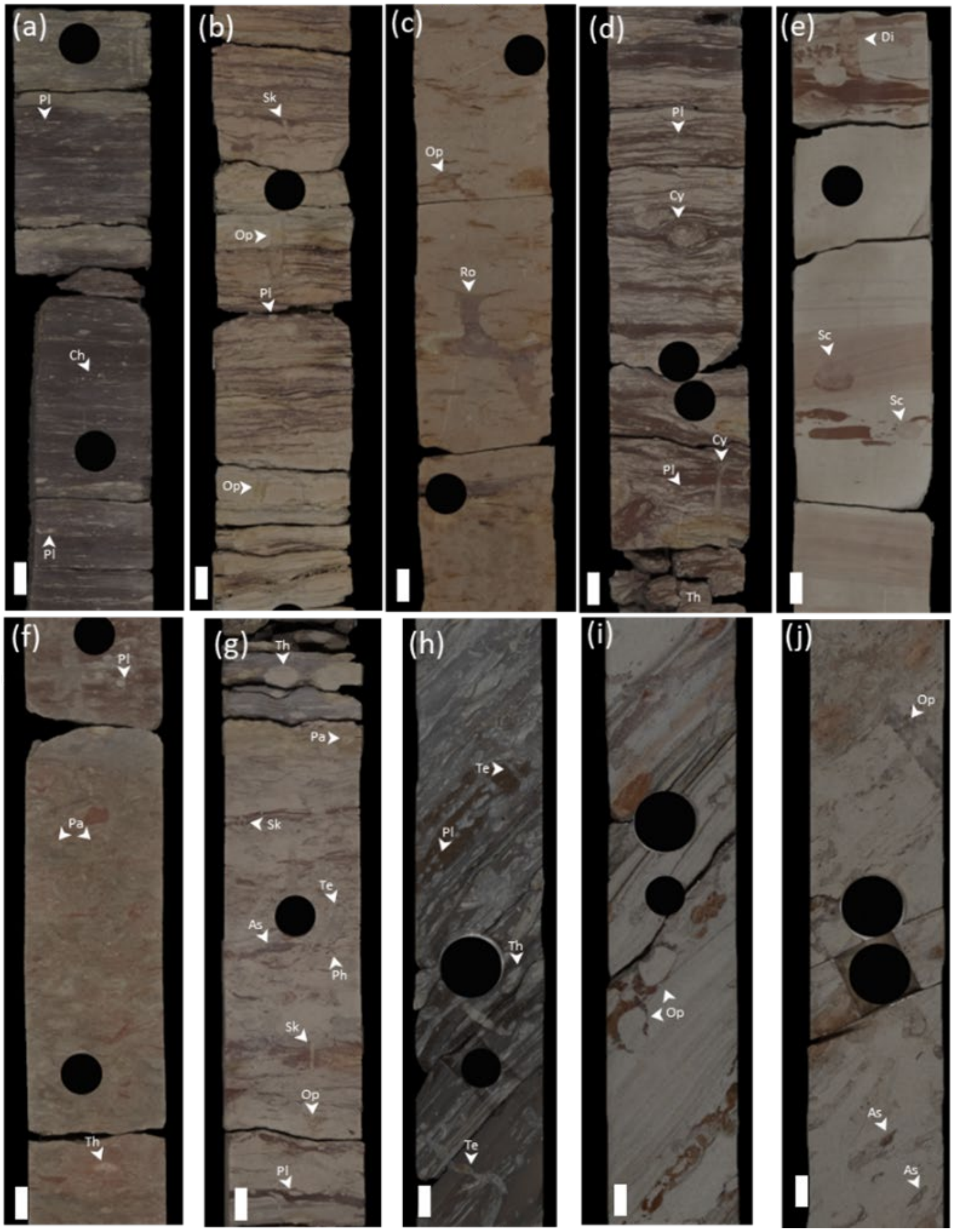


Figure 6. Core photographs of identified trace fossils in different lithofacies. **(a-b)** Heterolithic units characterized by *planolites* (Pl) and *chondrites* (Ch) in mud-dominated zone and *skolithos* (Sk) and *ophiomorpha* (Op) in sand-dominated zone. **(c)** *Ophiomorpha* (Op)and *rosselia* (Ro) in moderately bioturbated flaser-bedded sandstone interpreted as distal mouthbar deposit. **(d)** Heterolithic sandstone unit in strong tidal setting dominated with *planolites* (Pl) and *cylindrichnus* (Cy) belonging to impoverished cruziana ichnofacies. **(e)** *Diplocraterion* (Di) and *scolicia* (Sc) in upper shoreface planar-laminated to low-angle cross stratified sandstone. **(f-g)** Heavily bioturbated sandstone with diverse trace fossil assemblage such as *palaeophycus* (Pa), *thalassinoides* (Th), *asterosoma* (As), *phycosiphon* (Ph) and *teichichnus* (Te) indicating open marine influence. **(h)** Bioturbated mudstone characterized by cruziana ichnofacies which includes *teichichnus* (Te), *planolites* (Pl) and *thalassinoides* (Th). **(i-j)** Well-sorted sandstones with moderate bioturbation interpreted as upper shoreface deposit are dominated by *ophiomorpha* (Op) and occasional *asterosoma* (As). Scale bar is 2 cm long

Interpretation: The massive and vaguely laminated sandstone is believed to be formed by rapid deposition. The fining upward succession with sharp erosive base is indicative of channel fill with waning current energy towards the top which could be vertically stacked. Presence of carbonaceous plant material and rip-up mud clasts indicate tidal-influence distributary channel or bayhead delta within estuary.

2) S2: Rippled and cross-bedded sandstone

This sandstone consists of light grey to medium brown, silty and very fine to medium-grained sand. The main sedimentary structure is dominated by wave- and current-ripple cross-laminations with common flaser beddings and carbonaceous materials. The individual bed thickness may vary from tens of centimeters up to 2 meters. Thin beds (less than 1 meter) of trough cross-bedding occur in few horizons showing clay-draped foreset laminae and lineated sideritic pebbles. Current ripples are usually found to occur above planar-laminated and massive sand while wave-rippled cross-lamination is frequently observed in blocky to coarsening upward clean sandstone. Bioturbation degree is low around 1-2 consisting of *skolithos*, *ophiomorpha* and *thalassinoides* ichnogenera.

Interpretation: The deposition is dominated by bedload transport in lower flow regime energy. Current ripple cross-laminations are produced by unidirectional flow while symmetrical ripples correspond to oscillatory action of wave or bidirectional flow. Cross-beddings are generated by migrating sand dune or bar. Flaser bedding and frequent clay drapes suggests tidal origin which was deposited over the sandy rippled surface during quiescence period of alternating tidal current. Possible environments include tidal distributary channel, tidal bar, delta front and shoreface depending on facies association and stratigraphic succession.

3) S3: Planar-laminated sandstone

Planar-laminated sandstone is well distributed throughout the cores and occurs in variety of sand such as light grey, silty to fine-grained sandstone or sharp-based, fine to medium grained, well-sorted sandstone with parallel to wavy laminations. The thickness ranges from 0.1 m to 1.5 m. Thinly laminated mm-scale mudstone and carbonaceous materials occur alternately with the silty sandstone which may form mud couplets and tidal rhythmites in places, while sideritic mud clasts and layers are abundant in the sharp-based well-sorted sandstone. Thin lag deposits (2-4 cm) comprising of small rounded sideritic pebbles is observed in both TE-75 and TE-16 cores. Bioturbation is mostly low but locally could be moderate (1-3) characterized by *skolithos, ophiomorpha*, *thalassinoides* and *palaeophycus* trace fossils.

Interpretation: The planar lamination is primarily deposited by traction transport in upper flow regime condition subjected to high-energy wave or strong tidal current. However, intermittent flow depositing fine-grained particles during low-energy may produce thin laminations of silt and mud. The thin sideritic pebble lag layers possibly represent transgressive lag deposit. This facies could occur in various environments such as distributary channel, tidal flat, tidal inlet and barrier bar to shoreface deposits.

4) S4: Low-angle to hummocky cross-stratified sandstone

The facies is characterized by well-sorted clean sandstone, light to medium brown and very fine to fine-grained sand. The sedimentary structure is dominated by low-angle cross lamination that could appear to represent hummocky or swaley cross-stratification. It usually occurs sharply interbedded with well-sorted planar-laminated sand and wave-rippled cross-lamination structures with bed thickness ranging from 0.2 m to 0.7 m. Interbedded sideritic mudstone layers are also common. In the core sections, it typically transitions upward into bioturbated sandstone and mudstone. Bioturbation is generally low to moderate which includes ichnogenera such as *skolithos*, *ophiomorpha*, *diplocraterion* and *scolicia.*

Interpretation: The sharp-based low-angle to hummocky cross-stratification indicates high energy deposition dominated by oscillatory wave or storm action. Constant reworking and sorting of sediments produce the clean and well-sorted sandstone. Sideritic mud layers are early diagenetic feature typically associated with reducing non-marine to marine condition [26].

The storm-dominated sediments are most likely preserved below fair weather wave-base in lower shoreface to offshore transition setting. The association with bioturbated sandstone and mudstone also supports marine shelf environment.

5) S5: Bioturbated sandstone

Bioturbated sandstone comprises of light to medium grey, silty to very fine-grained sand. The sedimentary structures are mostly affected by pervasive bioturbation activity, but remnant planar to wavy laminations can be seen in few horizons. Individual sand thickness ranges from tens of centimeters to a maximum of 2.5 m. It is typically observed in upper section of cores overlying clean planar-laminated and low angle cross-stratified sandstone which then grades upward into bioturbated mudstone. Locally in TE-16 core, moderate bioturbation also occurs within top part of coarsening-upward rippled and flaser-bedded sandstone suggesting infauna colonization following high-energy sand deposition. The bioturbation is moderate to high (4-6) with rather diverse and sometimes indistinct marine trace fossils which includes *ophiomorpha*, *thalassinoides*, *palaeophycus*, *asterosoma* and *rosselia*.

Interpretation: The high bioturbation activity points toward relatively calm and quiet period following high-energy deposition in which marine organisms may thrive on the sandy substrate of shallow marine or abandoned delta lobe. Highly abundant and diverse trace fossil supports low sedimentation in marine environment such as distal delta front or lower shoreface to offshore transition sand.

6) H1: Heterolithic flaser-to-wavy bedded sandstone

The heterolithic facies is observed frequently throughout the cores dominated by sand with interbedded silt and mud. The sandstone is typically light grey to brown, poor to moderately sorted, silty to fine grained with dominant flaser to wavy bedded sedimentary structures. Overall thickness may be up to 6 m with individual bed within tens of centimeters thick. Abundant mud couplets and tidal rhythmites occur as well as soft sediment deformations such as load cast. Syneresis cracks can be found locally between sharp-based sand and mud layers. The facies usually occurs in association with lenticular mudstone or rippled and cross-bedded sandstone facies. Bioturbation is low to moderate (2-4) dominated by low diversity vertical and horizontal burrows such as *cylindrichnus, thalassinoides*, *planolites* and *teichichnus*.

Interpretation: The flaser-to-wavy bedded structures suggests constant supply of sand and mud under fluctuating hydraulic condition giving the distinct heterolithic feature. This is typically formed under tidal-influence setting while the occurrence of tidal rhythmites could records the spring and neap tidal cycles [27]. Soft sediment deformation and syneresis cracks indicate rapid deposition and freshwater input in marginal marine environment possibly deposited as tidal channel, tidal flat or tidal mouthbar.

7) H2: Heterolithic lenticular mudstone

This facies is generally thick (1-5 m) mud-dominated unit intercalated with lenses and streaks of silty sand. The mudstone appears as light to medium grey and is gradational with heterolithic sand. Load casts and ball and pillow structures are abundant as well as symmetrical starved ripples which may show internal unidirectional cross-laminations (combined-flow ripples). Sideritic mudstone layers and syneresis cracks occurs locally. Bioturbation is moderate (2-4) with small burrows such as *planolites*, *chondrites*, *cylindrichnus*, *teichichnus* and *gyrolithes*.

Interpretation: The facies was formed under similar condition as heterolithic sand marked by generally low-energy deposition interrupted with episodic high current flow as represented by the abundant starved ripples. Load casts and ball and pillow structures were formed due to differential loading of sand over fluidized mud attributed to high rate of sedimentation. Sideritic mudstone is common in brackish water environment while syneresis cracks are attributed to salinity fluctuation due to occasional freshwater input [28]. The facies can be interpreted to be deposited in distal delta front, tidal mud flat or interdistributary bay/lagoon.

8) M1: Laminated mudstone

This mudstone facies is composed of medium to dark grey mud with thin mm to cm-scale silty laminae. The bed thickness ranges from tens of centimeters to few meters. It may also appear massive as observed at bottom part of TE-75 core. It typically grades into lenticular mudstone and is also found interbedded with bioturbated mudstone in certain intervals. Sideritic brown mudstone layers are occasionally presents. Bioturbation is generally low (1-2) characterized by *planolites* and *chondrites*.

Interpretation: The laminated mudstone was formed predominantly by the settling of suspended fine grain particles in low energy environment. The occurrence with bioturbated mudstone also suggests low sedimentation rate that supports biogenic activity such as marine shelf below storm wave-base depth. It occurs in relatively low sediment input environment such as bay/lagoon, prodelta and offshore deposits.

9) M2: Bioturbated mudstone

This facies is mud-dominated unit with moderate to high bioturbation activity (3-5). The mudstone is light to dark grey while the burrows are commonly filled with silty sand giving lighter appearance. Relatively diverse horizontal and vertical burrows are abundantly present including *planolites*, *chondrites*, *schaubcylindrichnus*, *phycosiphon* and *teichichnus.* Remnant sedimentary structures such as parallel lamination can be observed locally. The mudstone forms distinctive unit in the upper part of cores interbedded with bioturbated sandstone with thickness ranging from tens of centimeters to around 2 meters.

Interpretation: The bioturbation activity in muddy sediments indicates deposition in low sedimentation rate, quiet and well-oxygenated environment conducive to support biogenic activity. The diverse trace fossils and close association with bioturbated sandstone and laminated mudstone also suggest open marine condition below fairweather wave-base. It is interpreted to be deposited in offshore or prodelta setting.

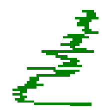
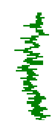
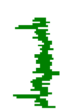
4.2. Facies association

Lithofacies gives information on the depositional processes that form the sedimentary rocks. These can then be further grouped into facies associations and along with identified trace fossil assemblages, relate to the possible depositional environment. There are five major facies associations distinguishable from the cores which are: 1) Mouthbar-delta front (MDF); 2) Fluvial-tidal channel (FTC); 3) Bay or lagoon (BL); 4) Barrier-shoreface (BSF); and 5) Offshore or prodelta (OP). Figures 7-8 depict the vertical succession of the facies from well TE-16 and TE-75. Table 1 summarizes the facies associations and their characteristics. Depositional facies are also calibrated with wireline log especially gamma ray to permit depositional interpretation in non-cored wells and interval.

1) Mouthbar-delta front (MDF)

The mouthbar-delta front facies represents prograding delta as sediments carried by fluvial are dispersed towards the shoreline. During normal regression, as the rate of sedimentation increases greater than rate of sea level rise, deltaic sediments are accreted resulting in seaward movement and shallowing upward succession. In Temana cores, the facies consists of heterolithic lenticular mudstone (H1) and flaser-to-wavy bedded sandstone (H2) at the base, grading upward into rippled and cross-bedded sandstone at the top (S2). The trace fossil assemblage belongs to mixed skolithos and cruziana ichnofacies comprising of simple horizontal and vertical burrows suggesting sublittoral zone [25]. In both TE-16 and TE-75, the facies can be found at the basal part of the cores. The log motif typically appears as funnel shape or coarsening upward.

Table 1. Summary of facies associations identified from TE-16 and TE-75 cores and its characteristics

Facies Associations	Lithofacies	Bioturbation	GR Profile	Occurrence
Mouthbar-Delta front (MDF)	Coarsening upward from lenticular mudstone (**H2**) through heterolithic sandstone (**H1**) and rippled and cross-bedded sandstone (**S2**) with carbonaceous materials and mud drapes.	Low-moderate (1-3) Generally low but moderate bioturbation observed locally at top of coarsening upward sand in TE-16 with skolithos ichnofacies.	Funnel-shaped 	Represents prograding delta during highstand system tract.
Fluvial-tidal channel (FTC)	Fining upward from massive to faintly laminated sandstone with sharp erosive base (**S1**), to rippled and cossbedded sandstone (**S2**) and heterolithic sandstone (**H1**) with flaser and wavy bedding. Rip-up mud clasts are common.	Rare to moderate (0-3) Occasional burrows in rippled and cross-bedded sandstone and heterolithic sandstone. Skolithos ichnofacies.	Bell-shaped or blocky 	Developed as fluvial channel fill during lowstand system tract and rapidly overlain by estuarine tidal channel deposit during early transgression.
Bay or lagoon (BL)	Predominantly lenticular mudstone (**H2**), intercalated with heterolithic sandstone (**H1**) and occasionally laminated mudstone (**M1**).	Moderate (3-4) impoverished cruziana ichnofacies (low diversity and presence of monospecific suite).	Serrated high GR 	Mud-dominated estuarine lagoon facies or interdistributary bay interfingering with tidal flat deposit.
Barrier-Shoreface (BSF)	Well-sorted planar-laminated sandstone (**S3**) interbedded with low-angle cross-stratified sandstone (**S4**). Bioturbated sandstone (**S5**) at the top part.	Low to High (1-5) Diverse cruziana ichnofacies in highly bioturbated sandstone.	Funnel-shaped to blocky 	Transgressive barrier bar and marine shelf deposits or prograding shoreface.
Offshore or prodelta (OP)	Bioturbated mudstone (**M2**) interbedded with laminated mudstone (**M1**)	Low to High (2-5) Archetypical cruziana ichnofacies in bioturbated mudstone.	High GR 	Hemipelagic mud in open marine setting with occasional storm deposit, represents marine flooding surface.

2) Fluvial-tidal channel (FTC)

The fluvial-tidal channel is a rapidly deposited facies that typically consists of massive to faintly laminated sandstone with sharp or erosional base (S1) and gradually fining upward into rippled and cross-bedded sandstone (S2) and heterolithic flaser-bedded sandstone (H1). Tidal influence is evident from abundant mud drapes, carboniferous debris, and rip-up mud clasts indicating estuarine setting. It usually overlies previous highstand delta plain or shoreface deposit as channel incision was formed during subsequent sea level drop. The incised valley was quickly drowned and filled with estuarine sediments as sea level start to rise. The FTC can thus be regarded as distributary channel of bayhead delta situated at the inner part of estuary [29]. Trace fossils are generally rare except in heterolithic sandstone unit belonging to skolithos ichnofacies. The gamma ray (GR) log shows bell shape pattern.

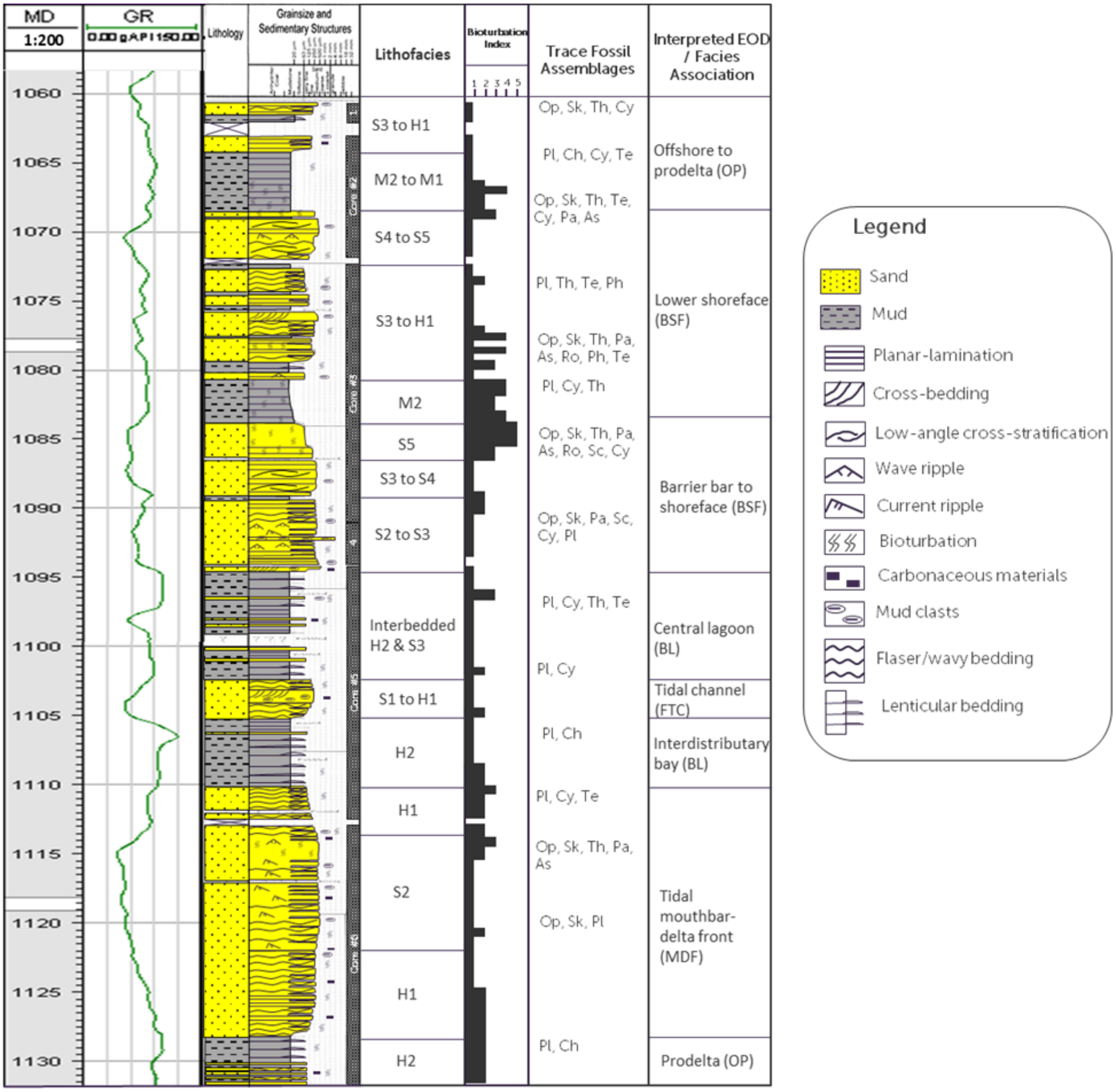


Figure 7. Summarized sedimentary log of cored interval in TE-16 well accompanied with GR curve, litho-facies, bioturbation index, trace fossil assemblages and depositional facies interpretation. MD- measured depth, GR- gamma ray, Pl- *planolites*, Ch- *chondrites*, Op- *ophiomorpha*, Sk- *skolithos*, Th- *thalassinoides*, Pa- *palaeophycus*, As- *asterosoma*, Cy- *cylindrichnus*, Te- *teichichnus*, Sc- *scolicia*, Ro- *rosselia*, Ph- *phycosiphon,* Gy- *gyrolithes*, Sch- *schaubcylindrichnus*, Co- *conichnus*. Refer to text for abbreviations on lithofacies and facies association.

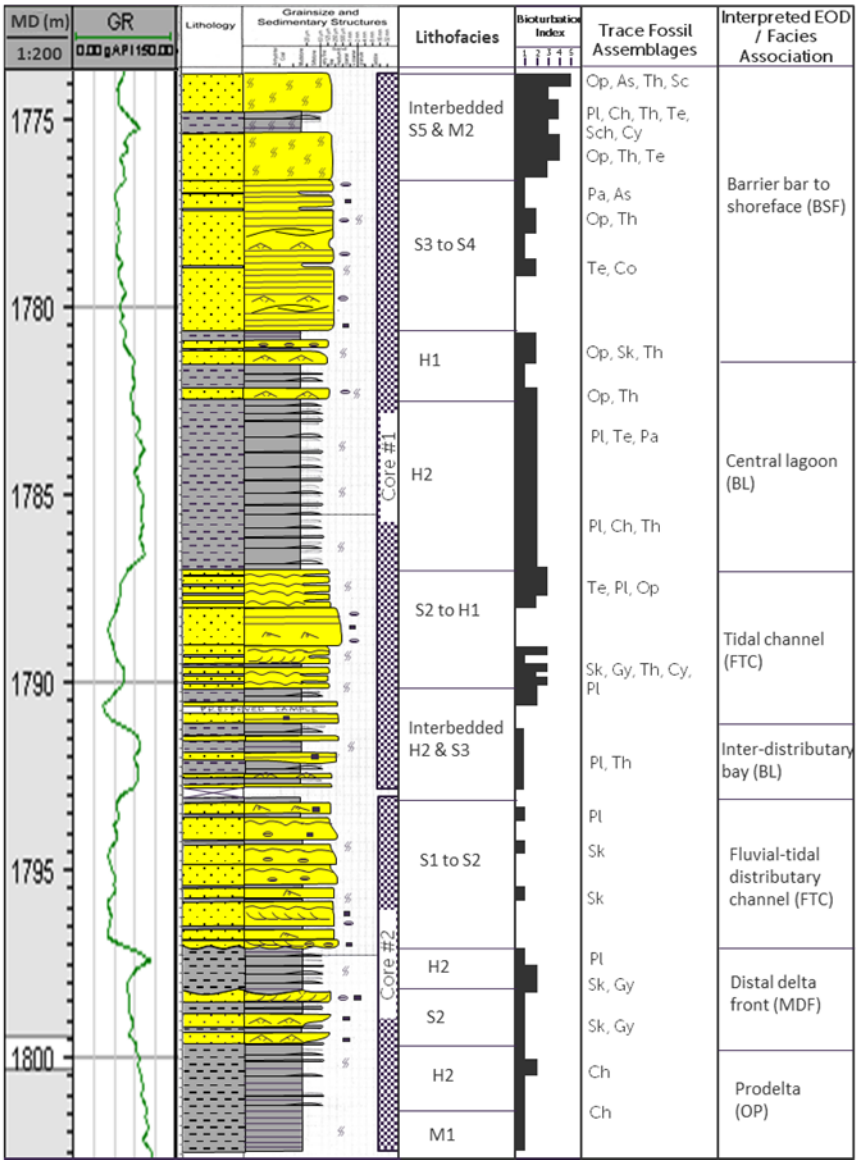


Figure 8. Summarized sedimentary log of cored interval in TE-75 well accompanied with GR curve, lithofacies, bioturbation index, trace fossil assemblages and depositional facies interpretation. Refer to Figure 7 for legend and abbreviations.

3) Bay or lagoon (BL)

Bay or lagoon is defined as low-energy shallow water body that is partially restricted from open marine between deltaic lobes or by barrier bar sand. This creates a distinctive brackish water condition due to mixture from freshwater and seawater. The facies is dominated by heterolithic mudstone and sandstone unit (H1-H2) and planar-laminated silty sandstone. Syneresis cracks and tidal rhythmites are also common features attributed to high fluctuation of water salinity and strong tidal activity. The mud-rich facies was formed as central lagoon in estuary during transgression or interdistributary bay delta plain deposits. The identified trace fossils belong to impoverished cruziana ichnofacies characterized by dimunitive form and presence of local monospecific suite indicative of stressed paleoenvironment [30]. The log motif typically shows high GR values with serrated character.

4) Barrier-shoreface (BSF)

Barrier bar and shoreface depositional facies are highly influenced by marine processes and constantly reworked by wave and storm. The barrier bar complex formed at the outer part of estuary which may include beach barrier, tidal inlet delta and washover fan that partially connects the central lagoon to open marine condition. The well-sorted and sharp-based sandstone bed is distinctly associated with planar to wavy laminations and low-angle to hummocky cross-stratified sandstone (S3-S4), which is typically overlain by bioturbated sandstone and mudstone unit (S5-M2). This suggests continuous deepening of sea level and landward facies shift resulting in a composite barrier bar to shoreface succession. Thin pebble lag deposit layer observed within the facies probably represents tidal inlet channel or transgressive ravinement surface [27]. Trace fossil is characterized by rare skolithos ichnofacies in the high energy planar-laminated and low-angle cross-stratified sandstone before being replaced with more diverse and abundant cruziana ichnofacies in the highly bioturbated zone, further supporting marine shelf environment interpretation [25]. The GR log profile usually displays blocky to funnel-shape characteristics.

5) Offshore or prodelta (OP)

This depositional facies include mud-rich offshore and prodelta facies that were deposited in distal marine environment below the fairweather wave-base depth. The fine-grained sediments mostly accumulated via suspension settling in low-energy environment with occasional silty sand deposition from storm or delta current. The facies primarily consists of interbedded laminated mudstone (M1) and bioturbated mudstone (M2) that grades upward into heterolithic lenticular mudstone (H2). The bioturbated and laminated mudstones are typically found overlying barrier bar-to-shoreface facies in transgressive succession and thus, would represent marine flooding surface. The trace fossil assemblage belongs to diverse cruziana ichnofacies characteristic of open marine setting. The shaly zone is represented by high GR log with clear separation of neutron-density.

4.3. Depositional model

The core description and facies association present strong evidence of tidal activity in the sedimentary record exemplified by the abundant occurrence of flaser to wavy beddings as well as clay drape laminations, rip-up mud clasts, syneresis cracks and tidal rhythmites. In addition, influence of wave and storm actions are also visible especially in the upper part of the core samples characterized by wave-ripple cross-laminations and low-angle to hummocky cross-stratification structures. The vertical profile of the facies associations exhibits succession from mixed wave- and tidal-dominated delta to estuarine channel fill and transgressive open shelf deposit marking a marine flooding event (Figure 7-8). Similar core succession was recognized in Dunvegan Formation, Alberta, Canada showing erosive estuarine channel fill overlying prograding wave-dominated shoreface followed by brackish and marine mudstone [31]. Locally in Balingian Province, repetitive cycles of tidal-dominated to wave-dominated environments in Early Miocene sediment had been demonstrated suggesting a prominent role of tidal and wave energy on NW Borneo coastal deposit [32]. Figure 9 shows the conceptual depositional model during regressive phase, transgressive phase and marine flooding surface.

Estuary is conventionally classified into two end members of tide- and wave-dominated regime which can be characterized by the relative importance of fluvial, tidal and wave processes on the corresponding facies distribution [29]. The studied core interval appears to preserve distinctive wave-dominated estuary succession comprising of inner bayhead delta, central mud-rich lagoon and outer barrier bar-to-shoreface deposits. Fluvial energy is characteristically high in the inner part carried by distributary channels which then disperse to form bayhead delta into low-energy sediments in the central lagoon. Marine influence increase towards the outer estuarine zone comprising of barrier bar, tidal inlet delta and shoreface sediments subjected to higher tidal and wave energy [29,33]. Meanwhile, as fluvial sedimentation rate increases during regressive phase, the estuary would gradually give way to prograding delta characterized by tide-dominated channel and mouthbar and wave-influence deposition in distal delta front facies.

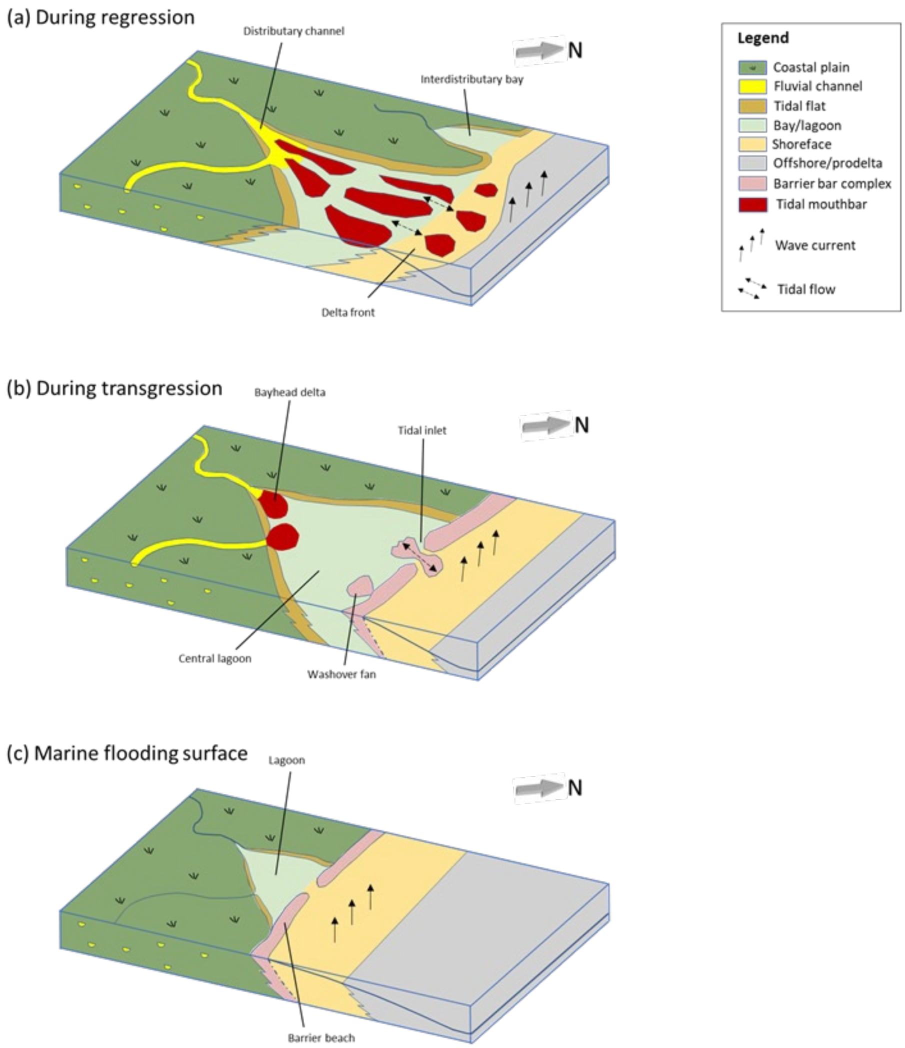


Figure 9. Conceptual depositional model of Temana derived from core analysis.
(a) Regression phase comprising of prograding delta and shoreline with mixed tidal and wave energy.
(b) Wave-dominated estuary with barrier bar and tidal inlet formed during transgressive phase.
(c) Marine flooding surface leading to coastal inundation and sediment reworking by wave and storm energy

Trace fossils identification further supports the depositional environment interpretation based on animal behavior towards physio-chemical factors such as substrate type, oxygen concentration, hydrodynamic energy and salinity [25, 34]. Brackish water system is defined by reduced water salinity that induces stressed paleoenvironmental condition for organisms and is typically characterized by marine-derived ichnotaxa that can thrive in diverse environmental conditions, relatively dimunitive form compared to marine counterpart, lower diversity assemblage and presence of monospecific suite among others [30,35]. In Temana core records, the estuarine facies is dominated by mixed skolithos and impoverished cruziana ichnofacies including *planolites*, *cylindrichnus*, *teichicnus*, *thalassinoides*, *skolithos*, *ophiomorpha* and *palaeophycus* and occurrence of monospecific suites at certain intervals. It is sharply replaced by moderate to highly bioturbated sandstone and mudstone towards the upper part of the core intervals with more diverse cruziana ichnofacies and occurrence of indicative marine trace fossils such as *rosselia*, *asterosoma, phycosiphon* and *scolicia*. This suggests marine incursion over the estuarine deposit marked by landward shift in facies from central lagoon to shoreface and offshore.

Extensive regional studies of Cycle I-II sediment in Balingian Province and equivalent onshore Nyalau Formation have shown that the Oligocene to Early Miocene sediment were deposited within an embayment with regional paleocoastline oriented in NW-SE direction [5-7, 16, 36]. Sediment provenance during Early Miocene was derived primarily from East Malaya/Indochina to the west and later from Central Borneo to the south as demonstrated by recent study on nearby outcrops utilizing light and heavy mineral assemblages and zircon-age population [37]. Temana field would likely have developed as localized bay receiving sediment input from western and southern rivers which was then reworked by mixed tidal and wave depositional processes. The modern analogue for Temana depositional environment would be the present-day Inner Brunei Bay located to the northeast along the same NW Borneo coastline with similar depositional setting and climate. It is described as micro-mesotidal estuary fed by multiple rivers and protected from the open sea by barrier spit and island [38]. The estuary is roughly V-shaped that passes into broader Brunei Bay with varying fluvial-, tidal- and wave-dominated coastal morphologies (Figure 10). The estuary extends approximately 22 km long which is comparable to Temana field while the deepest depth is 13 m at the mouth and gradually shallows landward [38].

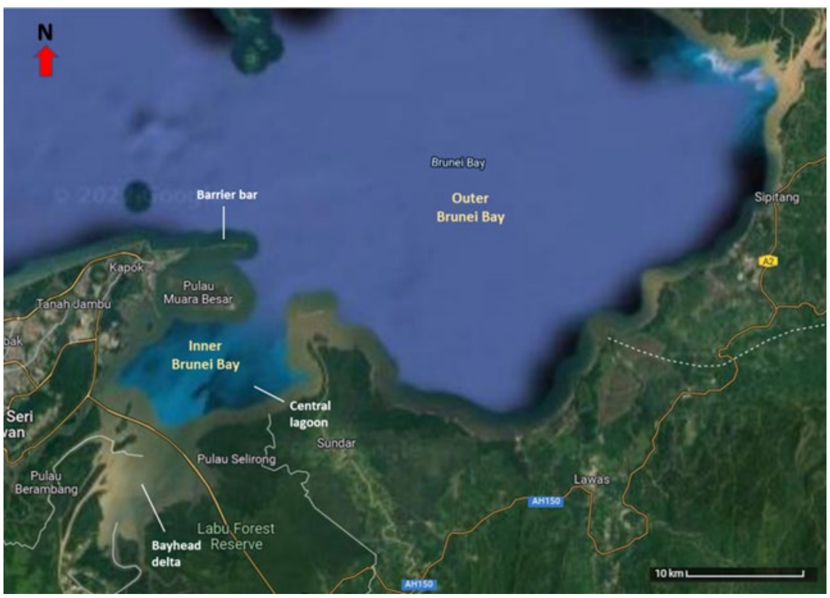


Figure 10. A modern analogue of Inner Brunei Bay estuary located within broader embayment of Brunei Bay (from Google Maps satellite image). Note the distinct morphologies of wave-dominated estuary consisting of bayhead delta, central lagoon and barrier bar, comparable to Temana conceptual depositional model

4.4. Stratal pattern and stratigraphic succession

Vertical stacking pattern of non-marine to marine facies reflects the change in shoreline which corresponds to interplay between sediment supply rate and accommodation space created. As rate of sedimentation surpasses the accommodation space being created, shoreline progradation will ensue while a relative sea level rise would cause transgression and landward shift in facies [39]. Following Walther's Law, where the vertical succession of facies in a strata could also be visualized in adjacent lateral facies changes, the facies stacking pattern from core and well log would give insight on the relative sea level fluctuation and corresponding system tracts under which the depositional facies were formed [11].

In both TE-16 and TE-75 studied cores, the basal part is characterized by shallowing upward sequence from offshore or prodelta mudstone to fine-grained sand with wave-ripple cross-lamination and mud-draped cross-bedding. This represents a prograding mixed wave- and tidal-dominated delta developed during highstand sea level as sediment supply grows. The unit is then overlain by erosional or sharp-base fluvial-tidal distributary channel consisting of medium to coarse grained sand with rip-up mud clasts indicating initial estuarine deposit of drowned river valley. The channel deposit is characterized by fining upward sequence of rather massive sandstone grading into ripple and cross-bedded sandstone and flaser-to-wavy bedded heterolithic sandstone. The estuary was then continuously being filled by marine transgression, evident from the vertical succession change into mud-rich lagoonal facies. This is followed by sharp-based and well-sorted planar-laminated to low-angle cross-stratified sandstone deposited under strong wave and storm influence, indicating backstepping barrier bar to upper shoreface sand before being capped by bioturbated sandstone and mudstone unit typical of lower shoreface to offshore deposits. Overall, the core stacking pattern exhibit small-scale regressive to transgressive depositional cycle within a marginal to shallow marine setting.

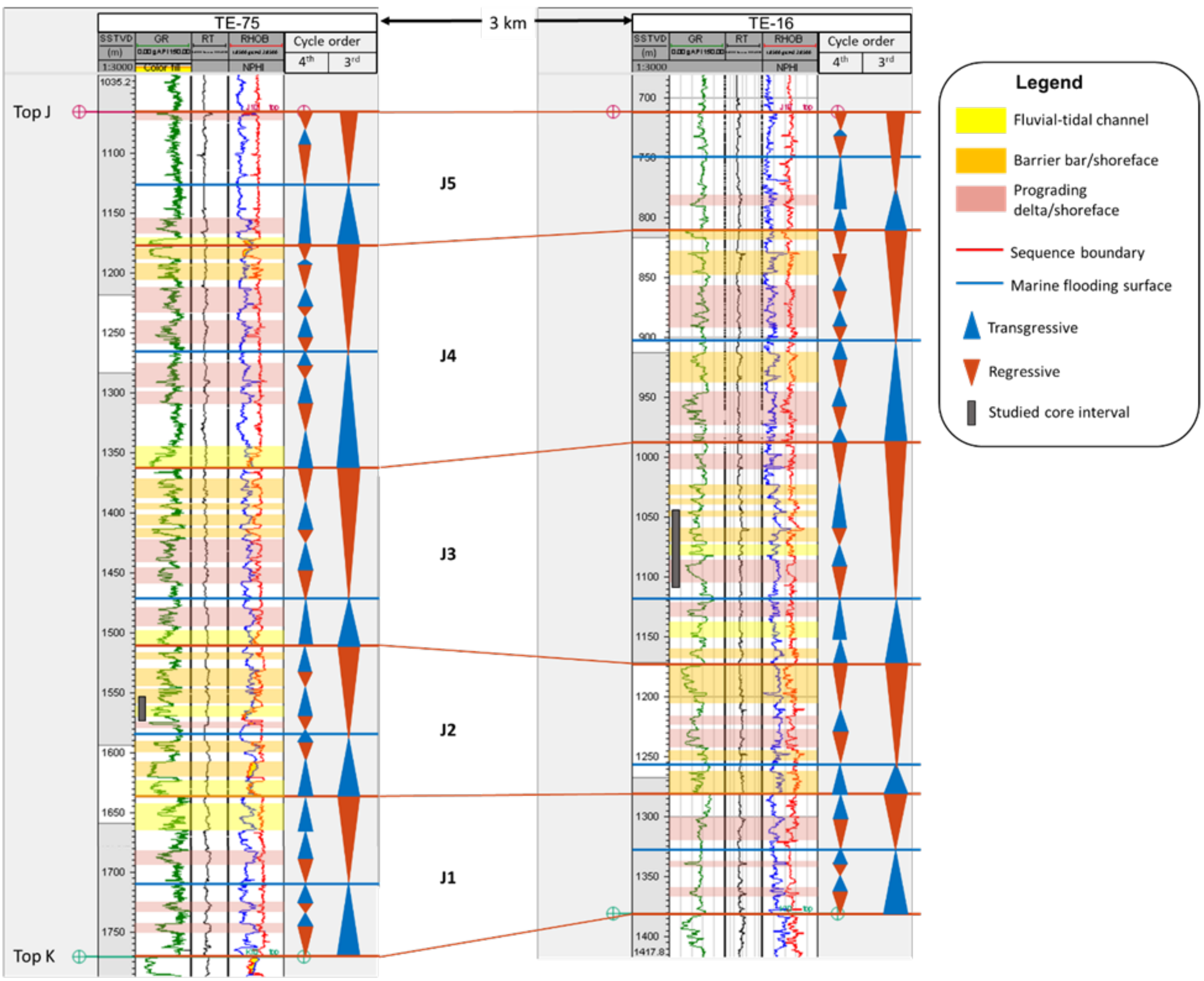


Figure 11. Well log correlation of TE-75 and TE-16 illustrating depositional facies interpretation calibrated from core analysis (only reservoir bodies are interpreted for simplification). Stratigraphic correlation reveals five depositional sequences over the J-series interval superimposed with smaller scale transgressive-regressive cycles. Dark grey bars represent core intervals

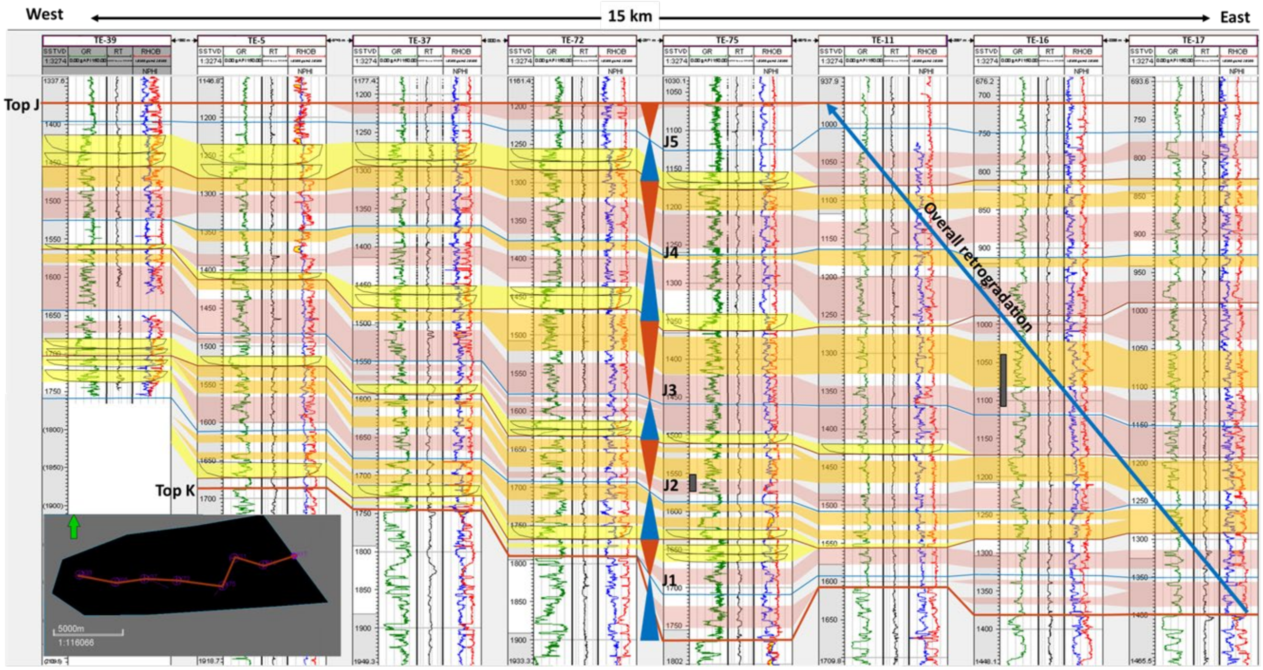


Figure 12. Depositional-dip well transect across Temana from west to east showing interpreted sequences and depositional facies. The sequences are stacked in overall retrogradational trend. Western and central parts are proximal to sediment source shown by more fluvial log character while the eastern side is dominated by delta front and shoreface facies denoting general basinward direction to the east. Refer to Figure 10 for legend

The well log data offers greater depth coverage albeit at lower resolution as compared to core data. By calibrating the depositional facies to log motif and extrapolating it to non-cored intervals, vertical succession can be analyzed over larger interval through identifying stratigraphic sequences and key stratal surfaces. Well log correlation of J-series reservoir reveals five major depositional sequences- J1 to J5- bounded by unconformity surfaces interpreted at the base of major fining upward profile indicating fluvial-tidal distributary channel (Figure 11-12). Meanwhile, major flooding surfaces are marked by high gamma ray peak separating transgressive and regressive phase within the sequence. Depositional-dip well transect illustrated in Figure 12 suggests lateral variation of proximal to distal facies from west to east. The western and central areas up to TE-75 well contains dominant fluvial channel character probably reflecting multiple rivers input from west and south of Temana. Whereas the eastern wells regularly feature funnel-shaped profile typical of barrier bar-shoreface or prograding mouthbar and delta front, thus indicate general basinward direction to the east.

Small-scale transgressive-regressive (T-R) cycles were also be observed nestled within the major 3rd- order depositional sequence that reflects shoreline movement affected by short-term sea level fluctuation (Figure 11). High-resolution stratigraphy has been recognized in many basins across the globe and proved to be crucial aspect of reservoir development especially in marginal marine setting [13,28,40]. In Southeast Asia, high-resolution biostratigraphic sequences have been interpreted and correlated across Malay Basin, West Natuna Basin, NW Borneo and Vietnam shelf [41-42]. This suggests a regional sea level control believed to be related to glacio-eustacy climatic changes driven by Milankovitch orbital cycles. Based on study of carbon and oxygen isotope records, the global eustatic sea level changes during Oligocene to Early Miocene appeared to correspond to Antarctic polar glaciation occurring at roughly 100 kyr and 400 kyr cycles that were essentially driven by eccentricity orbital forcing [42-43]. These timeframes fall within 4th- to 5th -order stratigraphic sequences occurring below seismic resolution [12]. The facies succession interpreted from core could therefore reflects the small-scale depositional sequences controlled by high-frequency sea level changes. This in turn was superimposed on overall retrogradationally stacked sequences associated with longer period of sea level rise and foreland basin subsidence (Figure 12).

5. Conclusion

Facies analysis of the cored interval within Temana Cycle II J-series reservoir reveals wide range of tidal and wave sedimentary structures including flaser-to-wavy bedding, tidal rhythmites, wave-ripple lamination and hummocky cross-stratification. Various trace fossils were identified belonging to mixed skolithos and cruziana ichnofacies that show characteristics of brackish water and open marine assemblages. The sedimentary unit can be broadly classified into five major facies associations related to depositional facies within marginal to shallow marine setting. The resulting depositional model of Temana reservoir was proposed as succession of mixed tidal- and wave-energy delta during regression phase, followed by estuary fill in early transgression, and culminating into open marine shelf which reflect control of sea level changes on sediment distribution. Stratigraphic architecture interpreted from well stratal pattern of the reservoir is composed of high-frequency transgressive-regressive (T-R) cycles nestled within larger 3rd-order sequences that are stacked in overall retrogradational trend.

The outcome of this study has demonstrated that the application of core and well log data can provide valuable input in interpreting the sedimentology and stratigraphy of hydrocarbon-bearing reservoir. Specifically in marginal marine setting, the sand development is affected by various interacting forces such as fluvial, tidal and wave which resulted in highly heterogenous facies and small-scale high-frequency sequences. The reconstructed depositional model and stratigraphic framework would help to predict reservoir lateral and vertical heterogeneity, improve well-to-well correlation and support development strategy in a mature brownfield.

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