Bulletin of the Geological Society of Malaysia, Volume 77, May 2024, pp. 47 - 57
DOI: https://doi.org/10.7186/bgsm77202406

Tidal-influenced shoreline interpretation of Miocene Tanjong Formation in Imbak Canyon, Sabah, Malaysia

Khor Wei Chung[1], Junaidi Asis[1,*], Sanudin Tahir[2], Baba Musta[1], Kawi Bidin[1], Rezal Rahmat[3,4], Hadianshah Saleh[1]

[1]Faculty of Science & Natural Resources, Universiti Malaysia Sabah, Jalan UMS, 88450 Kota Kinabalu, Sabah, Malaysia
[2] Lorong Taman Indah Permai 22, Taman Indah Permai, 88400, Kota Kinabalu, Sabah, Malaysia
[3] Earth System Sciences, Taiwan International Graduate Program (TIGP), Academia Sinica & College of Earth Sciences, National Central University, 128, Sec. 2, Academia Road, Nankang, Taipei 11529, Taiwan
[4] Institute of Earth Sciences, Academia Sinica, 128, Sec. 2, Academia Road, Nankang, Taipei 11529, Taiwan
* Corresponding author email address: junaidi@ums.edu.my

Abstract: The Tanjong Formation of Imbak Canyon, Sabah is the Early Miocene aged shallow marine unit that crops out in the Tongod district. Tanjong Formation has previously been interpreted to have been deposited in a shallow marine environment without tidal influence. This paper reinterpreted the depositional environment with emphasis on tidal deposits through newly logged sections encountered during 2019 Imbak Canyon Expedition. Proximity-driven strike orientation correlations were employed to interrelate the logged geological sections. The eight facies recognized are 1) Mudstone Facies (M), 2) Lenticular Facies (LF), 3) Wavy Facies (WF), 4) Flaser Facies (FF), 5) Hummocky Cross-Bedded Sandstone Facies (HCS), 6) Swaley Cross-Bedded Sandstone Facies (SCS), 7) Planar Cross-Bedded Sandstone Facies (PCS), and 8) Structureless Sandstone Facies (SS). Three interpreted facies associations deduced are 1) intertidal deposits, 2) middle to lower shoreface, and 3) offshore deposits. We conclude that Tanjong Formation was deposited in a macrotidal open coast setting with significant tidal imprint signatures. The identification of tidal influence within a wave-dominated system is an infrequent occurrence, yet it holds significant potential for enhancing the refinement of shallow marine models.

Keywords: Tidal flats, tidal deposits, sedimentology, facies analysis, facies association, Tanjong Formation

INTRODUCTION

Tidal influenced shoreline deposits are rarely described from ancient records. Although Sabah has numerous shallow marine deposits, especially Neogene in age, no one has described tidal influence shoreline deposits (Lee, 1970; Tjia *et al*., 1990; cf. Tongkul, 1993; Leong, 1999; Balaguru & Nichols, 2004; Khor, 2013; Khor *et al*., 2015). The current facies models for tidally influenced shallow marine systems essentially assume macrotidal circumstances (Vakarelov *et al*., 2012). It considers only the impacts of tidal energy during fair weather and the size of the sediment on the subsequent facies successions. The difference between a supratidal and a subtidal sequence is crucial to such models. The formation of tidally forced currents, fair-weather tidal and wave energy transfer, and the predominance of heterolithic strata (tidal footprint beds) are all related to shoreline deposits. In such settings, bioturbation is intermittent and typically of lesser intensity. The lower to upper shorefaces of beaches are mostly controlled by the combination of bioturbation and event beds deposited during fair- and storm-weather. In such event beds, clay and silt sediments are winnowed and sorted according to the energy profile.

An increasing amount of study on contemporary tidal beach systems shows how increases in tidal range can have a significant impact on the shape and sediment dynamics of beaches and shorefaces. A large tidal range can refer to the significant difference between the highest water level during high tide and the lowest level during low tide. This could result in larger geomorphological features (i.e. estuaries, coastal, tidal flats, and mudflats) as well as the interaction between waves and tides. There is little doubt that tides have a considerable impact, and based on data from current tidally influenced systems, recognized suites of facies for such deposits should exist.

Previous studies have provided limited information about the Tanjong Formation, despite studies presented during the Imbak Canyon 2011 Expedition (Che Aziz Ali & Kamal Roslan Mohamad, 2011; Khairul Azlan Mustapha *et al*., 2011a; Khairul Azlan Mustapha *et al*., 2011b; Tongkul *et al*., 2011). The most comprehensive studies about lithology and type-section can be found in the study conducted by Collenette in 1965. This scarcity of information is likely due to the challenges associated with accessing Tanjong Formation outcrops, which are situated in remote and

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

preserved forest areas. The data in this study examines an example of a tide influenced deposit from the Tanjong Formation, that crops out extensively at Imbak Canyon Study Centre, Sabah. Excellent outcrop exposures allow for thorough facies observations, making it possible to assess how important tidal processes are to the sedimentary system, and should make it possible to identify analogous deposits elsewhere in Sabah.

Geological and stratigraphical settings

Shallow marine deposit outcrops in Sabah are limited and mostly Neogene aged, to name but a few, Meligan Formation, Bongaya Formation and Belait Formation. The term "Tanjong Formation" was first introduced by Roothaan & Wenk in an unpublished report and later used by Collenette (1965). Similarly related termed "Tanjung Formation" is reported by Witts *et al*. (2012) in Barito Basin, Kalimantan, Indonesia, but should not be confused with these two formations as they differ in age.

The western Neogene deposits of Sabah are understood to be underlain by mélanges, which are complex mixtures consisting of mud-dominated olistostromes and fragmented tuffaceous strata resulting from slumping (Leong, 1999). These formations are known as the Kuamut and Garinono Formations. Like other Miocene aged shallow marine clastics, (e.g., Meligan Formation, Tabanak Formation, Sandakan Formation and Kapilit Formation), these formations are constrained by separated NE and SE circular depo-centres (Tongkul, 1991; Khor *et al*., 2015). The inception of the Tertiary sub-basins, specifically the Sandakan and Tarakan sub-basins can be attributed to a series of significant NW-SE deformation events (Tongkul, 1993; Satyana *et al*., 1999). These 3 distinct deformations encompass the i) Deep Regional Unconformity (DRU) of the late Early Miocene-early Middle Miocene age, ii) Upper Miocene deformation which uplifted the region and the subsequent iii) NW-SE Pliocene deformation which form topography of present Sabah. The provenance of these Neogene depo-centres derived mainly from older Rajang Fold-Thrust Belts (RFTB) units such as Crocker Formation and Trusmadi Formation (Fitch, 1958; Staufer & Lee, 1972; Khor, 2013).

Tanjong Formation is reported to be Neogene (Early Miocene) aged shallow marine unit at Tongod (Kuamut and Imbak Canyon Conservation Area), Persiangan and Kinabatangan districts. This formation is also reported to occur in the Maliau Basin, extending from the upper part of the Kuamut River to the Pinangah River, with the proposed type-section located in the Maliau Basin as identified by Collenette (1965). Tanjong Formation is defined by the occurrence of sandstone, siltstone and mudstone with subordinate occurrence of conglomerate. Tanjong Formation is mentioned to be divided into two sections which are i) mudstone and siltstone-dominated, and ii) mudstone and sandstone-dominated. It is estimated to be 2800 m in thickness (Collenette, 1965).

The general stratigraphy framework of Imbak Canyon is proposed by Tongkul *et al*. (2011). The authors suggest that Tanjong Formation shares lithological similarities with the overlaying Kapilit Formation, with exception for the presence of andesitic volcanic rocks in the form of sill (Figure 2). Despite the absence of radiometric dating, this perspective posits that these andesitic sills likely date back to the Early-Middle Miocene volcanic activity, potentially arising from the north-westward subduction of Celebes Sea oceanic lithosphere in the eastern Sabah region (Rangin, 1989). Kapilit Formation is described to consist of 3 lithological units which are i) Mudstone Unit, ii) Sandstone and Mudstone Unit, and iii) Upper Sandstone Unit that extend from Maliau Basin located south-westward

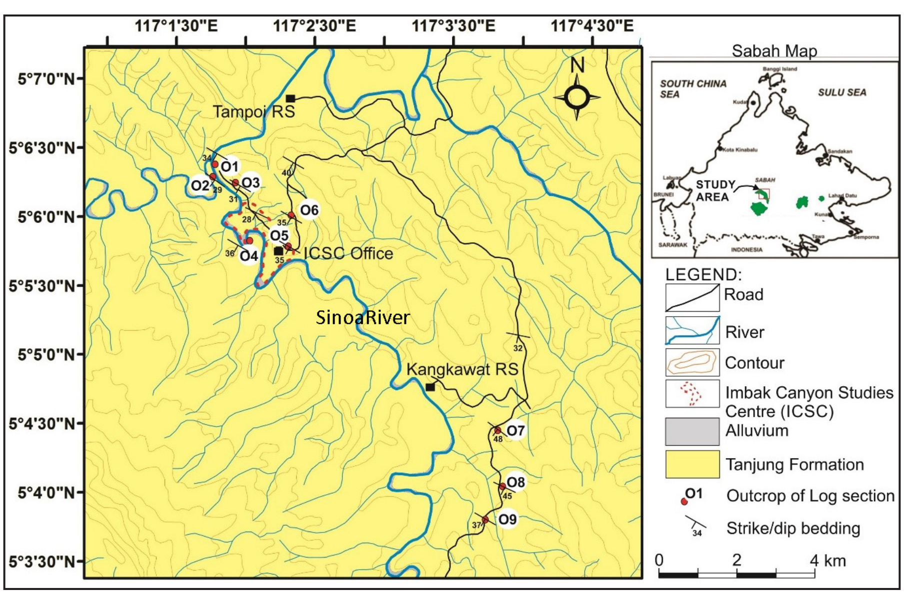


Figure 1: Geological map of study area, Imbak Canyon, Sabah, Borneo.

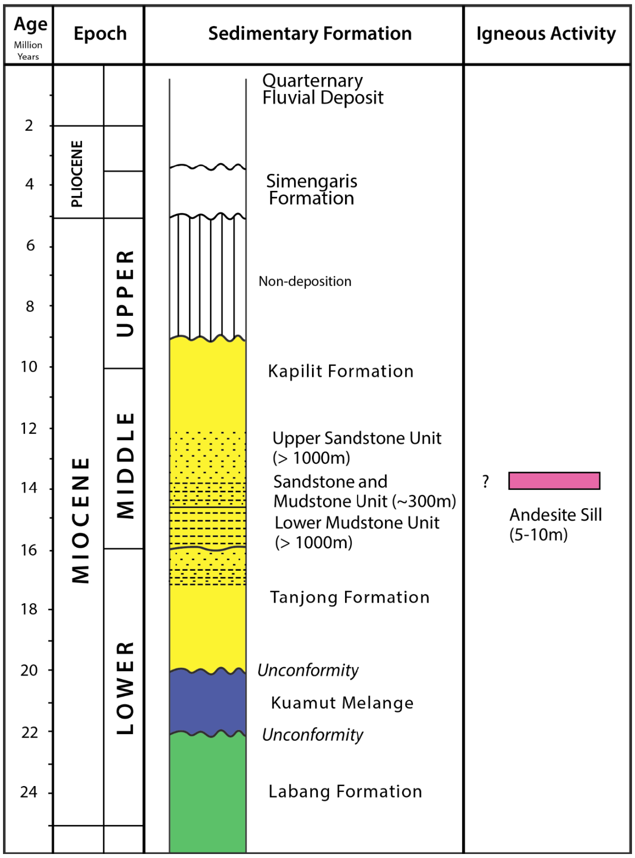


Figure 2: Proposed stratigraphy of Imbak Canyon by Tongkul *et al*. (2011).

(cf. Tongkul, 2010; Tongkul *et al*., 2010). The sedimentary logs reported comprise mudstone-dominated with thickly bedded, massive mudstone with subordinate thin layers of siltstone and sandstone. Additionally, the mudstone beds are noted for their rich iron concretion and thin coal lenses (Che Aziz Ali, 2011; Tongkul *et al*., 2011).

Methods

The outcrops in Imbak Canyon are primarily found along the Imbak River and its distributary. During the traverse along these rivers, nine loggable outcrops were encountered, labeled as Outcrops O1, O2, O3, O4, O5, O6, O7, O8 and O9. The traverse area is defined by latitude range of 5° 3' 30" N to 5° 6' 30" N and the longitude range of 117° 0" 30" E to 117° 4' 30" E (refer Figure 1). Features like lithology, bedding and stratification, grain size, sedimentary structures and fossils were logged based on Tucker (2011). The development of facies for limiting likely depositional conditions is made possible by detailed sedimentological data. The outcrops' superficial weathering prevents a close analysis of thinly interbedded sandstone and mudstone components where most of these outcrops effectively display these geological characteristics. Examining the stratigraphic interval enables in-depth facies studies in areas of succession where sandstone and mudstone predominate through facies analysis. The stratigraphic positioning and gaps between the outcrops were then calculated based on the strike-orientation readings to generate a continuous log, as shown in Figure 3. Facies associations are established using the continuous sections of the 8 identified facies listed below, providing representations of different sub-depositional environments. This study uses the idealized conceptual model of tidal influenced wave-dominated environments by Clifton (2006) and Vakarelov *et al*. (2012).

RESULTS

Sedimentology

A total of 9 outcrops were logged, producing a cumulative thickness of 58 meters in sedimentary logs. Field observation revealed that the beds generally coarsen upward from a thick homogenous mudstone with thin laminated layers in the bottom section to heterolithic (wavy bedding, flaser bedding, lenticular bedding), mudstone- and siltstone-dominated middle section to a sandstone-dominated upper portion (Figure 4 and Figure 5). This coarsening upward sequence is overlain by unborrowed and clean sandy and silty mudstone. The lower interval's base, which is dominated by mudstone, is not exposed in the outcrop. Non-fossiliferous sandstones that transition into burrowed mudstones abruptly overlie the sand-dominated heterolithic interval. The sandstones in this heterolithic interval display ripple cross bedding. The entire coarsening-upward succession is composed primarily of sandstone and mudstone beds with copious amounts of carbonaceous detritus. Carbonaceous laminae beds are common but form locally. This coarsening upward succession can be characterized into 8 facies (Table1).

Facies analysis

Facies are characterized based on sedimentological descriptions (thickness range, lithology, grain size, physical sedimentary structures, ichnology, and lithologic accessories; Table 1). The measured sections are as displayed in Figure 3. The eight facies recognized are 1) Mudstone Facies (M), 2) Lenticular Facies (LF), 3) Wavy Facies (WF), 4) Flaser Facies (FF), 5) Hummocky Cross-Bedded Sandstone Facies (HCS), 6) Swaley Cross-Bedded Sandstone Facies (SCS), 7) Planar Cross-Bedded Sandstone Facies (PCS), and 8) Structureless Sandstone Facies (SS).

Mudstone Facies (M) is characterized by weakly to non-burrowed mudstone beds with thin silty stripes and ranges up to meters in thickness. Lenticular Facies (LF) and Wavy Facies (WF) are mudstone-dominated with mudstone ranging from mm- to cm-scale thick and defining characteristics of wavy and lenticular bedding. The mudstones in these two facies (LF and WF) are distinguished by differences from scarcely to extensively bioturbated silty mudstone, to thick, fissile, and heavily burrowed mudstones. The Flaser Facies (FF) is defined with sandstone-dominated beds with sinusoidal wavy bedding. Sandstone beds in Hummocky Cross-Stratified Facies (HCS)

Table 1: Summary of facies identified in Imbak Canyon.

Facies	Structure	Lithology	Bed Thickness	Contact	Interpretation
Mudstone Facies (M)	Fissile, thin parallel interlaminae of silt and sand.	Mudstone with sandstone strips. Weakly burrowed.	1 – 100 cm	Mudstone irregular top	Suspension deposit, laminar flow
Lenticular Facies (LF)	Lenticular, low angle planar, parallel, thin parallel interlaminae of silt and sand	Mudstone–dominated. Mudstone – gray, silty and unborrowed. Sandstone – lenticular, fine- to very fine- grained	1 – 10 cm	Sharp and gradational top, sharp base	Suspension deposit with short-wavelength oscillation ripples during the slack water period
Wavy Facies (WF)	Wavy, lenticular	Equal mud to sand ratio. Intercalated sand and mud. Bioturbated. Fine- to very fine sandstone.	1 – 10 cm	Sharp and gradational top and base	Oscillation ripple with suspension deposit – two direction current movement
Flaser Facies (FF)	Flaser	Fine- to very fine grained.	1 – 10 cm	Sharp and gradational top and base	Oscillation ripple / current during mean low tide
Hummocky Cross-Bedded Sandstone Facies (HCS)	Hummocky, amalgamation	Sandstone – medium- to fine-grained sandstone, moderately to well-sorted	10 – 100 cm	Sharp and undulatory to small-scale scour	Wave deposit, high regime, variety of wave orbital unidirectional current velocity and availability of sand towards the lower beach profile during storm activity
Swaley Cross-Bedded Sandstone Facies (SCS)	Swaley	Sandstone – medium- to fine-grained, well-sorted	~ 2 m	Undulatory base	Wave deposit, high regime
Planar Cross-Bedded Sandstone Facies (PCS)	Planar	Sandstone with thin layer of mud	40 – 50 cm	Sharp base	2D bedform migration, high energy current, straight migration of ripples during wave activity
Structureless Sandstone Facies(SS)	Structureless	Medium- to coarse-grained	1 – 200 cm	Sharp top and base	Rapid deposition, high to very high regime

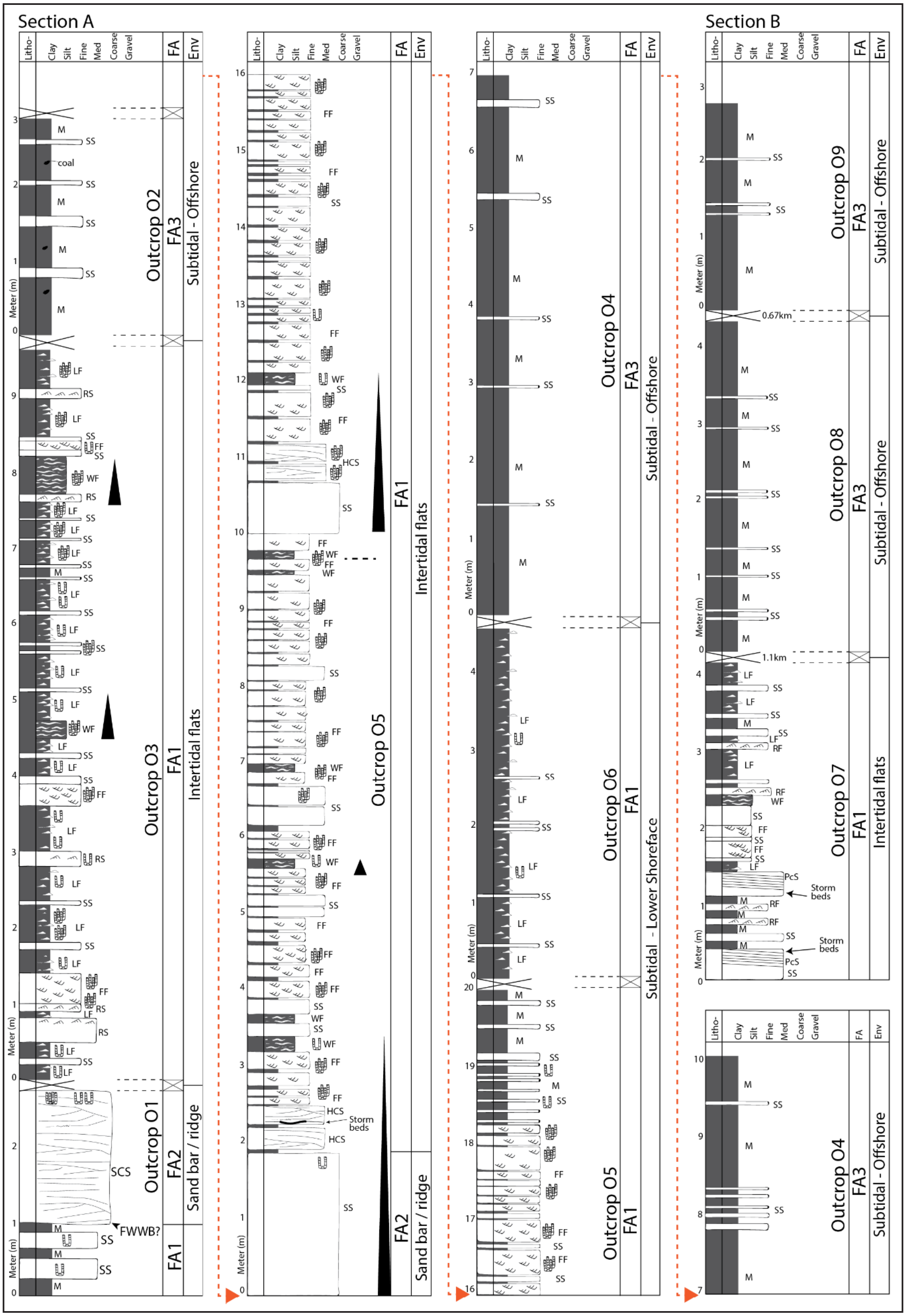


Figure 3: Correlated sedimentary logs of Tanjong Formation at Imbak Canyon, Tongod, Sabah.

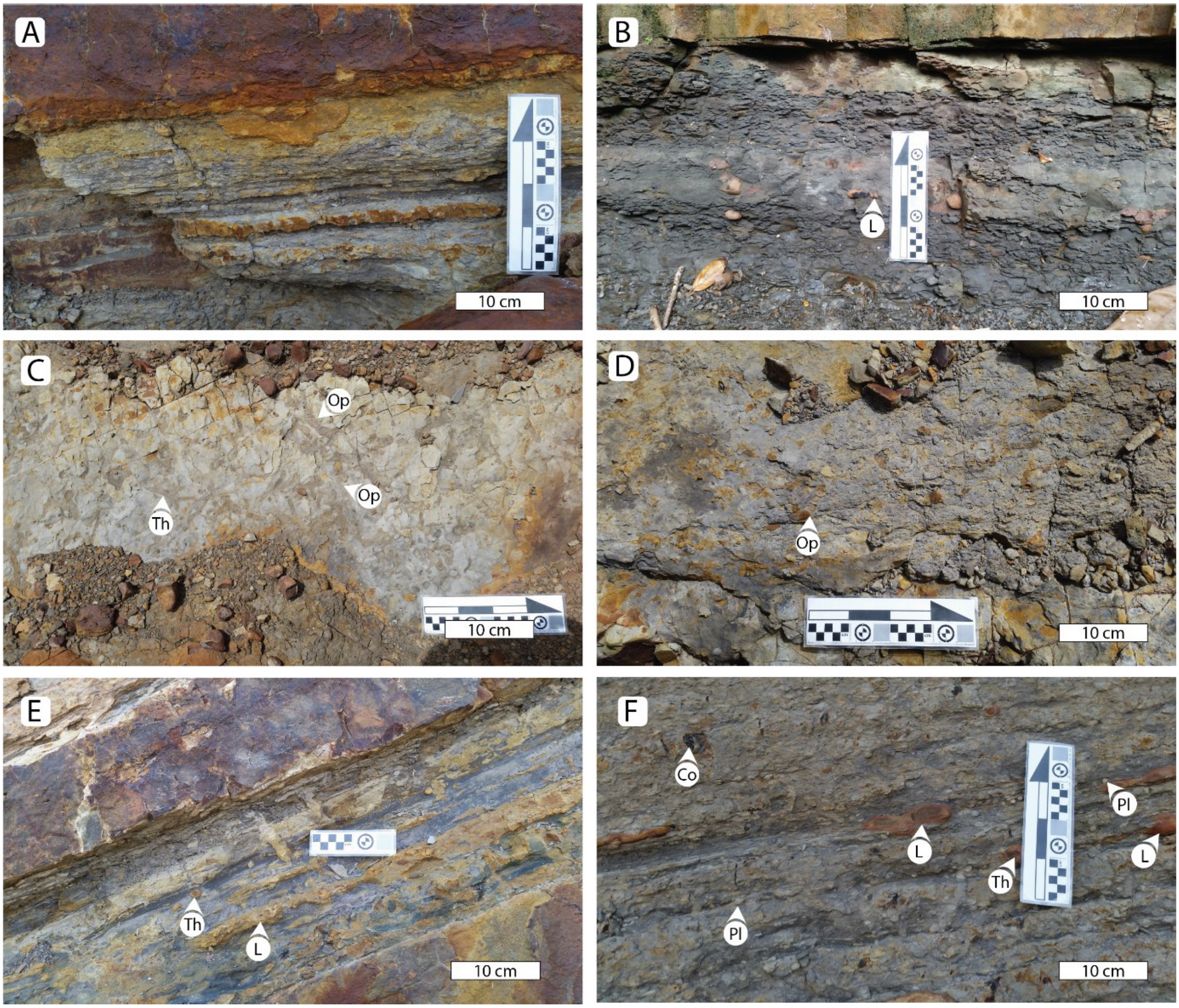


Figure 4: A) Lenticular facies (LF facies) with bioturbated texture; B) sandstone bed overlaying mudstone with tidal lenses and concretions; C) bedding-plane view of bioturbated sandstone; D) bioturbated mudstone with *Ophiomorpha*; E) sandstone bed encased within intercalated mudstone and sandstone wavy bedding (WF facies); F) Lenticular facies with coal fragment (L = Sand Lenses, Co = Coal, Pl = *Planolites*, Th = *Thalassinoides*, Op = *Ophiomorpha*).

and Swaley Cross-Bedded Sandstone Facies (SCS) display low angle, plan-oriented cross-stratification with scouring bases, commonly truncating the underlying beds. Planar Cross-Bedded Sandstone Facies (PCS) is subordinate, ranges 40 – 50 cm in thickness and was only observed in Outcrop O7 overlying structureless coarse sandstone facies (SS).

DISCUSSION

Facies Association / Discussion

The relationship and arrangement between the 8 facies throughout the sedimentary logs were studied. Three facies associations were identified in measured sections. Facies Association 1 (FA1) and Facies Association 3 (FA3) exhibit mud-dominated sequences, which are interpreted to represent intertidal flat and offshore deposits. A distinguishing observation between FA1 and FA3 is the bioturbation rate. FA1 exhibits high bioturbation, while FA3 shows no bioturbation recorded. Facies Association 2 (FA2) shows sand-dominated sequences, which indicate a high-energy wave environment situated above SWWB (Storm Weather Wave Base). The interpreted depositional environments are Facies Association 1 (FA1) Intertidal flat (alternating sandstone and mudstone), Facies Association 2 (FA2) sand / shoal bar, and Facies Association 3 (FA3) offshore. Table 2 provides a summary of facies associations' characteristics.

Facies Association 1 (FA1): Intertidal flat (alternating sandstone and mudstone)

FA1 records mud- and sand- dominated heterolithics. It contains Mudstone Facies (M), rippled sandstone facies,

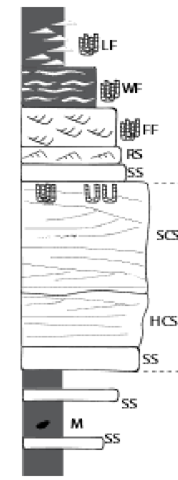
Figure 5: A) Cross bedded sandstone with scouring base (Outcrop O1); B) Thinly bedded sandstone at the edge of a waterfall (Outcrop O1); C) Lenticular facies (LF) (Outcrop O2); D) Flaser bedding facies (FF) (Outcrop O5); E) LF facies dominated outcrop (Outcrop O6); F) Mudstone facies (M) of Outcrop O4.

structureless sandstone facies (SS), wavy facies (WF), Flaser Facies (FF) and hummocky cross-bedded sandstone facies (HCS). Planar Cross-Bedded Sandstone Facies (PCS) is subordinate and observed to overlay SS facies. This facies association is well exposed at Outcrop O3, O5 and O6. The mudstones are characterized by the variation from scarcely to extensively bioturbated silty mudstones, fissile, greyish, thickness, moderately bioturbated with presence of tidal structures (lenticular, wavy and flaser) and locally siderite cemented. Cementation of siderite is locally present in sandstone lens and form immature nodules. Mudstone layers average approximately 50 cm and can range up to 1 m in thickness. Mudstone with carbonaceous materials (wood fragments) and alternating with sandstone beds are observed at outcrop O2. Thicker sandstone (~50 cm) with low angle-stratification and planar stratification are present. Bed-scale stratification is commonly observed in the upper section of the interval. In Outcrop O5, the outcrop exhibits gradual changes from flaser bedding to lenticular bedding with common occurrence of trace fossil (*Ophiomorpha*).

Interpretation

The upwards increase in sandstone / mudstone ratio is not observed continuously but recorded in other shoreface profiles (Nordfjord *et al*., 2009; Dashtgard *et al*., 2012; Vakarelov *et al*., 2012). Sandstone beds with low angle stratification resemble ripple-scale hummocky cross-stratification and short-wavelength undulating ripples. The sandstone beds with HCS in these intervals suggest deposition by storm currents. While the carbonaceous detritus rich

Table 2: Summary table of facies association recognized at Tanjong Formation, Imbak Canyon, Sabah.

Facies Association	Log	Facies	Description	Interpretation
FA1: Alternating sand-stone and mudstone		M, RS, LF, SS, WF, FF & HCS	-alternating bioturbated mudstone and tidal imprinted sandstone beds (WF, FF, LF). -mud-, sand- and equally dominated sequences. -trace fossils – *Planolites*, *Ophio-morpha*, *Thalassinoides*, *Rosselia*	Intertidal zone Tide-dominated
FA2: Middle to lower shoreface		SS, HCS, SCS	-thick sandstones with HCS / SCS or structureless. -trace fossils are uncommon.	Subtidal zone Wave- domi-nated
FA3: Mud-dominated interval		M & SS	-thick mud with thin strips of silt / very fine sand. -trace fossils are rare.	Lower offshore

intervals likely represent waning currents after storms where deposition was not completely eroded away by subsequent storm currents (Vakarelov *et al*., 2012). Abundance of wavy, flaser and lenticular bedding indicate strong influence of tides that occur at intertidal flats. However, flaser bedding (FF) at the bottom and sandwiched wavy bedding (WF) with overlying lenticular bedding (LF) was not observed to occur in an ideal fining upward sequence (cf. Fan, 2013). Frequent occurrence of trace fossils also suggests slow deposition, which in this case, possibly represents the hiatus between two high tidal range (high water spring and high water neap tides). Such hiatuses enable biological activities by burrowing organisms, and in some cases, they serve as feeding grounds for scavenging organisms, such as birds and decapods. These hiatuses suggest periods of reduced energy or quiescent conditions, which is further supported by the occurrence of thinly layered mudstones in between the sandstone beds with tidal signatures. The ebb and flow of tides not only directly control the processes of material transportation, dispersion and deposition but also play a crucial role in eroding and reworking sediments within the intertidal zone (Li, 2012). Intertidal deposits are less likely to be preserved in geological records due to these dynamic processes. The presence of Planar Stratified Sandstone Facies (PCS) can represent to the basal section of overall coarsening upward, shallowing upward and progradational shoreface succession. FA 1 is interpreted to have been deposited in a tide-dominated setting, chiefly intertidal zone.

Facies Association 2 (FA2): Middle to lower shoreface

Facies Association 2 (FA2) comprises thick medium to coarse grained, structureless and hummocky cross-stratified sandstone (HCS and SS facies). Sandstone beds are 1.8 m to 2.0 m thick, erosional amalgamated and moderately well- to well-sorted. The scour at the base of the sandstone occurs on a decimeter (dm) scale in width and centimeter (cm) in depth. Unidirectional ripple-scale cross-lamination has been observed at Outcrop O5. However, the occurrence of ripple cross-lamination in the entire interval is, nonetheless, low. These beds are separated by centimeter thick mudstones. *Ophiomorpha* trace fossil is observed at the top of the sandstone beds but uncommon in FA1.

Interpretation

FA2 suggests a high-energy, wave-dominated, oscillatory, and high sediment input of deposition which is reflected by HCS and SS facies. The scour or sharp erosional surface at the base of FA2 may just reflect oscillatory current (cf. Clifton, 2006). Facies models often show the passing of swaley or hummocky cross-stratification into low-angle to parallel stratified in thicker sandstone intervals (cf. Longhitano *et al*., 2012), which, in this case, is not observed. The possibility above suggests part of progradation, coarsening and shallowing of marginal succession and are only observed in thinner sandstone beds (~50 cm) in FA2 otherwise eroded by subsequence transgression or regression. The presence of rippled cross beds being topped with mudstone represents the waning condition of storm currents. The type of bioturbation consists of low numbers of ichnogenera such as *Ophiomorpha* and *Rossalia* which are typical of early adaptable colonization of the sandy bedrocks in marine setting. These ichnofossils are also common in high energy environments, which in this case, wave-dominated environment. We interpret this facies association as having been deposited in a storm-dominated middle to lower shoreface environment.

Facies Association 3 (FA3): Offshore (Mud-dominated interval)

This facies association exhibits a mudstone-dominated sequence with thin strips of siltstone and fine sandstone. It is represented by mudstone facies (M) and structureless sandstone facies (SS). Mudstones are characterized by variations from silty mudstones, to dense, fissile, and largely unburrowed mudstones. FA3 is exposed at outcrop O4, O8 and O9 (Figure 2). The thin sandstone strips are millimeter to centimeter thick and unburrowed while mudstones are thick (~1 – 2 m). Carbonaceous detritus such as wood fragments is commonly observed throughout the mudstones and locally occur along bedding planes. Bioturbations and occurrence of trace fossils are rare in FA3.

Interpretation

Rapid mud accumulation suggests association with the distal portion of a retrograding shoreface sequence. The largely non-fossiliferous, structureless and dark mudstone drapes suggest fast and continuous deposition of fine sediments through suspension. Thin strips of siltstones and fine sandstones represent the winnowed and dissipated deposits of seasonal storm currents. Carbonaceous detritus could be mixed during the storm and could indicate seaward transportation (Steel *et al*., 2018). The geometry of these offshore deposited beds is usually continuous and relatively uniform, leading to well-defined horizontal bedding. FA3 is interpreted to occur below Storm Weather Wave Base and Fair Weather Wave Base (Pemberton *et al*., 2012). Such setting is unlikely to be affected by waves and tidal currents though thin layers of silt and fine sand beds could occur occasionally due to dissipation of storm currents.

Depositional environment model

Three main intertidal-flat deposits criteria recognized from the sedimentary sequence are 1) regular changes vertically between tidal beddings (wavy bedding, flaser bedding and lenticular bedding), 2) fining upwards sequence from sand / shoal bar, and 3) rhythmic alternations of storm and tidal deposition (Mangano & Buatois, 2004; Desjardins *et al*., 2012). Contrast of wave- to tide-dominated settings differs in their facies and facies association arrangement. Fining-upward sequence with thick sandstone deposition (FA2) at the base, topped by intertidal muddy deposits (FA1) suggest a prograding tidal flat system (Figure 6).

FA3 features thick, unburrowed and fissile mudstone sequence with thin, sharp and structureless sandstone. Though the similarities with lagoonal sequence in terms of thickness, FA3 mudstones are not bioturbated, fissile and not laminated. Moreover, lagoon or estuary deposit is characterized by silty-shaly and upward fining sequence with abundant tidal structures, laminations and marine bioclasts (Hayes, 1975; Wright & Mason, 1990; Palmer *et al*., 2020; Sebok *et al*., 2020). Thick sequences of alternating sandstone and mudstone with tidal imprints (FA1) suggest a macrotidal setting. Classification of macrotidal shorelines is defined by > 4 m tidal range. Likewise, microtidal is < 2 m and mesotidal is 2 m to 4 m in tidal range (Davies, 1980). The abundance of rippled sandstones (RF facies) in FA2 could indicate a back barrier tidal flat setting. Tides enter the systems through tidal inlets and rapidly diminish landward. Such settings are often low or absent in waves. With large tidal flat areas bordered to the seaward by subtidal sandbar complexes, the Tanjong Formation records deposition in a macrotidal open-coast and shallow marine environment.

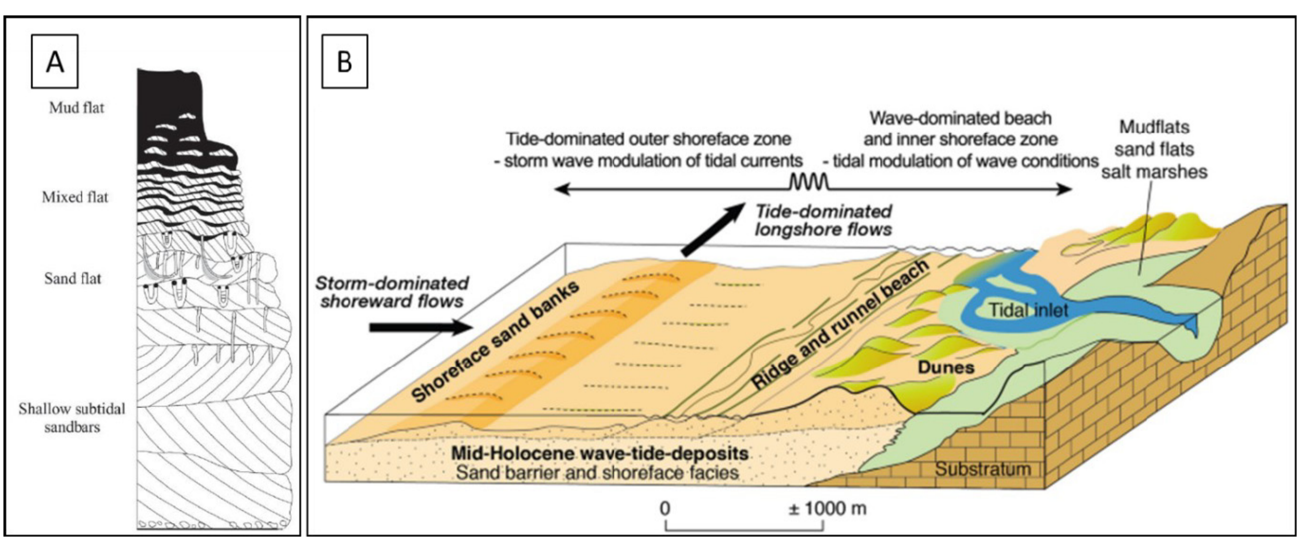


Figure 6: Proposed conceptual depositional model for Tanjong Formation. A) Fining-upward tidal-flat parasequence of the Campanario Formation. See Mangano & Buatois (2004) for more information on the zonation of the tidal-flat parasequence. B) Cross shore variation in wave and tidal activity on a sand-rich wave-tide-dominated coast. Adapted from (Anthony, 2000).

CONCLUSION

We discussed an ancient example of a tide-dominated coastal succession from the Tanjong Formation where it crops out in Imbak Canyon Study Centre, Sabah. Sabah's geological literature and previous research suggest little understanding of tide-influenced systems (tidal beaches). This study suggests that the Tanjong Formation Imbak Canyon is dominated by tide-influenced systems (possibly macrotidal), which are frequently linked to wide, shallow continental shelves where minor storms can rework sediment far from the shoreline. The rather prominent, tide-dominated type of sedimentation in the study area yields important derivations from the recognition of the traditionally tidally dominated coastal facies model. The facies association described according to measured sections and has been split into: (i) Intertidal; (ii) Subtidal; and (iii) Offshore. The absence of eolian deposits possibly explain the absence of supratidal or that it was not preserved in the sedimentary record. Identifying the presence of tidal effects within a wave-dominated system is a rarely-encountered phenomenon due to their limited preservation, but it holds the potential to prompt revisions in current shallow marine models.

ACKNOWLEDGEMENT

This research is funded by the Universiti Malaysia Sabah (UMS) through SPL Grant (Grant No. SLB 2245). Many thanks to Yayasan Sabah Group and Sabah Forestry Department for organizing the 2019 Imbak Canyon Expedition which made this research possible. Special thanks to the anonymous reviewers and the editor, for their constructive comments and recommendations in improving the revised manuscript.

AUTHOR CONTRIBUTIONS

KWC: Conceptualization, digitization and writing. ST & JA: Conceptualization, writing, methodology & data acquisition. BM, KB, RR & HS: Methodology & data acquisition.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest associated with this manuscript. All authors have reviewed and agreed with its contents, and there are no financial interests to report.

REFERENCE

Anthony, E.J., 2000. Marine and supply and Holocene coastal sedimentation in Northern France between the Somme estuary and Belgium. In: Pye, K. & Allen, J.R.L. (Eds.), Coastal and estuarine environments - Sedimentology, geomorphology and geoarchaeology. London Special Publications of the Geological Society of London, 175. 428 p.

Balaguru, A. & Nichols, G., 2004. Tertiary stratigraphy and basin evolution, southern Sabah (Malaysian Borneo). Journal of Asian Earth Sciences, 23, 537-554.

Che Aziz Ali & Kamal Roslan Mohamad, 2011. Jujukan batuan sedimen dan landskap di kawasan sekitar khemah Gunung Kuli, kawasan pemuliharaan kanion imbak. In: Latiff, A. & Sinun, W. (Eds.), Seminar on Imbak Canyon Scientific Expedition, 14-15 March 2011, 2011 Sabah. Academy of Sciences Malaysia, 125.

Clifton, H.E., 2006. A reexamination of clastic-shoreline facies models. Sepm. Special Publication, 84, 337.

Collenette, P., 1965. The geology and mineral resources of the Pensiangan and upper Kinabatangan area. Geological Survey Memoir 12. Geological Survey Department, Kuching. 150 p.

Dashtgard, S.E., MaceAchern, J.A., Frey, S.E. & Gingras, M.K., 2012. Tidal effects on the shoreface: Towards a conceptual framework. Sedimentary Geology, 279, 42-61.

Davies, J.L., 1980. Geographical variation in coastal development. Longman, New York. 212 p.

Desjardins, P.R., Buatois, L.A., Pratt, B.R. & Mángano, M.G., 2012. Sedimentological–ichnological model for tide-dominated shelf sandbodies: Lower Cambrian Gog Group of Western Canada. Sedimentology, 59, 1452-1477.

Fan, D., 2013. Classificatios, sedimentary features and facies associations of tidal flats. Journal of Palaeogeography, 2, 66-80.

Fitch, H., 1958. The geology and mineral resources of the Sandakan area North Borneo. Geological Survey Department British Territories in Borneo memoir 9. Government Printing Office, Kuching. 202 p.

Hayes, M.O., 1975. Morphology of sand accumulation in estuaries: An introduction to the symposium. In: Cronin, L.E. (Ed.), Estuarine Research, Volume II: Geology and Engineering. Academic Press.

Khairul Azlan Mustapha, Wan Hasiah Abdullah, Tongkul, F., Che Aziz Ali, Kamal Roslan Mohamed, Baba Musta, Asykury Abd Kadir & Wong, F.T., 2011a. The occurrence of volcanic rocks in the southern part of Imbak Canyon conservation area. In: Latiff, A. & Sinun, W. (Eds.), Seminar on Imbak Canyon Scientific Expedition, 14-15 March 2011, Sabah. Academy of Sciences Malaysia, Kuala Lumpur 125.

Khairul Azlan Mustapha, Wan Hasiah Abdullah, Tongkul, F., Che Aziz Ali, Kamal Roslan Mohamed, Baba Musta, Asykury Abd Kadir & Wong, F.T., 2011b. Organic petrological characteristics of the Kapilit Formation sedimentary sequence in the southern part of Imbak Canyon conservation area. In: Latiff, A. & Sinun, W. (Eds.), Seminar on Imbak Canyon Scientific Expedition, 14-15 March 2011, Sabah. Academy of Sciences Malaysia, Kuala Lumpur, 125.

Khor, W.C., 2013. Sedimentology, stratigraphy and depositional environment of Sandakan Formation, East Sabah, Borneo. MSc unpublished. Universiti Teknologi Petronas.

Khor, W.C., Chow, W.S. & Abdul Hadi, A.R., 2015. Stratigraphic succession and depositional framework of the Sandakan Formation, Sabah. Sains Malaysiana, 44, 931-939.

Lee, D. T.C., 1970. Sandakan Peninsula, Eastern Sabah, Eastern Malaysia. Geological Survey East Malaysia Report No. 6. Govt. Print. Off., Kuching. 75 p.

Leong, K.M., 1999. Geological setting of Sabah. In: Leong, K.M. (Ed.), Petroleum geology and resources of Malaysia. PETRONAS, Kuala Lumpur. 665 p.

Li, M., 2012. Sediments, morphology and sedimentary processes on continental shelves. Special Publication 44 of the International Association of Sedimentologists. Wiley-Blackwell, UK. 432 p.

Longhitano, S.G., Mellere, D., Steel, R.J. & Ainsworth, R.B., 2012. Tidal depositional systems in the rock record: A review and new insights. Sedimentary Geology, 279, 2-22.

Mangano, M.G. & Buatois, L.A., 2004. Reconstructing Early Phanerozoic intertidal ecosystems: Ichnology of the Cambrian Campanario Formation in northwest Argentina. Fossils and Strata, 51, 17-38.

Nordfjord, S., Goff, J.A., Austin, J.A. & Duncan, L.S., 2009. Shallow stratigraphy and complex transgressive ravinement on the New Jersey middle and outer continental shelf. Marine Geology, 266, 232-243.

Palmer, S. E., Burn, M.J. & Holmes, J., 2020. A multiproxy analysis of extreme wave deposits in a tropical coastal lagoon in Jamaica, West Indies. Natural Hazards, 104, 2531-2560.

Pemberton, G., MacEachern, J., Dashtgard, S., Bann, K., Gingras, M. & Zonneveld, J.-P., 2012. Shorefaces. Developments in Sedimentology, 64, 563-603.

Rangin, C. 1989. The Sulu Sea, a back arc basin setting within a Neogene collision zone. Tectonophysics, 119-141.

Satyana, A., Nugroho, D. & Surantoko, I., 1999. Tectonic controls on the hydrocarbon habitats of the Barito, Kutei, and Tarakan basins, eastern Kalimantan, Indonesia: Major dissimilarities in adjoining basins. Journal of Asia Earth Sciences, 17, 99-122.

Sebok, S.S., Csato, I. & Nemes, I., 2020. Sedimentology and depositional system of a transitional shallow marine - coastal complex, Lower Visean deposits in the central Volga-Ural petroleum province, Orenburg. Central European Geology, 64, 113-132.

Staufer, P. H. & Lee, D.T. C., 1972. Sedimentology of the Sandakan Formation, East Sabah. Geological Survey of Malaysia 1, 10 - 17.

Steel, E., Simms, A.R., Steel, R. & Olariu, C., 2018. Hyperpycnal delivery of sand to the continental shelf: Insights from the Jurassic Lajas Formation, Neuquén Basin, Argentina. Sedimentology, 65, 2149-2170.

Tjia, H.D., Ibrahim, K., Lim, P.S. & Surat, T., 1990. Maliau Basin, Sabah: Geology and tectonic setting. Bulletin of the Geological Society of Malaysia, 27, 261-292.

Tongkul, F. 1991. Tectonic evolution of Sabah, Malaysia. In: Nichols, G. J. & Hall, R. (Eds.), Proceedings of the Orogenesis in Action Conference London 1990. Journal of Southeast Asia Earth Sciences, 6(3-4), 395-405.

Tongkul, F., 1993. Tectonic control on the development of the Neogene basins in Sabah, East Malaysia. Bulletin of the Geological Society of Malaysia, 33, 95-103.

Tongkul, F., 2010. Geological evolution of the Maliau Basin. In: Komoo, I., Othman, M., Said, I. & Latiff, A. (Eds.), Maliau Basin. Academy of Sciences Malaysia, Kuala Lumpur.

Tongkul, F., Mohammed, K.R., Ali, C.A., Musta, B. & Javino, F., 2010. Geology of the Eucalyptus Camp. In: Komoo, I., Othman, M., Said, I. & Latiff, A. (Eds.), Maliau Basin. Academy of Sciences Malaysia, Kuala Lumpur.

Tongkul, F., Musta, B., Wong, F.P., Ali, C.A., Mohamed, K.R., Mustapha, K.A. & Kadir, A.A., 2011. The Geology of the southern part of the Imbak Canyon Conservation Area. In: Latif, A. & Sinun (Eds.), Imbak Canyon Conservation Area, Sabah: Geology, Biodiversity and Socio-economic Environment. Proceedings of the Seminar on Imbak Canyon Scientific Expedition, 2011. Academy of Sciences Malaysia, Kuala Lumpur, pp 5-26.

Tucker, M.E., 2011. Sedimentary rocks in the field : A practical guide. Wiley-Blackwell, Chichester. 304 p.

Vakarelov, B.K., Ainsworth, R.B. & MacEachern, J.A., 2012. Recognition of wave-dominated, tide-influenced shoreline systems in the rock record: Variations from a microtidal shoreline model. Sedimentary Geology, 279, 23-41.

Witts, D., Hall, R., Nichols, G. & Morley, R., 2012. A new depositional and provenance model for the Tanjung Formation, Barito Basin, SE Kalimantan, Indonesia. Journal of Asian Earth Sciences, 56, 77-104.

Wright, C.I. & Mason, T.R., 1990. Sedimentary environment and facies of St Lucia estuary mouth, Zululand, South Africa. Journal of African Earth Sciences (and the Middle East), 11, 411-420.

Manuscript received 6 September 2023;
Received in revised form 21 November 2023;
Accepted 13 December 2023
Available online 30 May 2024