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The Mangking Sandstone Formation of Kuala Tahan to Kampung Bantal: Sedimentology and Depositional Environment

(Pembentukan Batu Pasir Mangking Kuala Tahan ke Kampung Bantal: Sedimentologi dan Persekitaran Pemendapan)

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ABSTRACT

The Mangking Sandstone of Tembeling Group in the Kuala Tahan region records part of the infill of the continental extensional basin formed at the end of the Triassic. Described facies of this formation include sandy matrix conglomerate (that shows evidence of pseudoplastic debris flow and traction-dominated deposition), sandstones with trough, tabular and horizontal stratification, laminated and massive mudstone. Groups of associated facies are arranged into six distinct architectural elements (channel, sandy bedform, crevasse splay, laminated sand sheet, downstream and lateral accretion and floodplain fines), which are constant with a fluvial origin for the succession. The types of architectural elements present and their relationship to each other demonstrate that the Mangking Sandstone preserves a record of a meandering river system.

Keywords: Depositional environment; facies analysis; fluvial; Mangking Sandstone; Tembeling Group

ABSTRAK

Formasi Batu Pasir Mangking yang merupakan Kumpulan Tembeling di rantau Kuala Tahan merekodkan sebahagian daripada lembangan perluasan kebenuaan yang dibentuk pada akhir Trias. Fasies yang ditakrifkan dalam pembentukan ini termasuk konglomerat matriks berpasir (yang menunjukkan bukti aliran puing pseudo-plastik dan pemendapan secara golekan), batu pasir bersilang palung, bersilang mendatar serta batu lumpur berlaminasi dan masif. Enam sekutuan fasies disusun menjadi enam unsur arkitektur yang menyokong tafsiran fluvial (alur, perlapisan berpasir, perlapisan helaian pasir, megar krevas, tokokan hilir dan mendatar serta dataran banjir). Jenis arkitektur dan hubungan sesamanya menunjukkan Batu Pasir Mangking ini dienapkan dalam sistem sungai berliku.

Kata kunci: Analisis fasies; Batu Pasir Mangking; fluvial; Kumpulan Tembeling; persekitaran enapan

Introduction

Fluvial deposits represent the preserved record of one of the major continentals/ nonmarine environments. The nature of the fluvial assemblage - its lithofacies composition, vertical stratigraphic record and architecture reflects the processes and geomorphology of rivers. In fluvial sedimentology studies, huge and well-preserved outcrops are needed to identify the architectural elements. However, large-sized outcrops are rare and hard to encounter. This study identifies fluvial environment and architectural elements with emphasis on bounding surfaces at small to moderately sized outcrops exposed along Kuala Tahan to Kampung Bantal.

The Jurassic – Cretaceous rocks in Peninsular Malaysia are distributed extensively in Central Belt. These rocks, namely, Ma'okil Formation, Panti Formation, Tembeling Group, Paloh Formation and Payung Formation, were deposited in a continental environment (Khor et al. 2017). These rocks are understudied due to poor accessibility and lack of exposure. Recent urbanisation in this area allowed detailed sedimentological studies on new roadcut outcrops. The vicinity of Kuala Tahan area comprises the Triassic Semantan Formation and the Lower Jurassic to mid-Cretaceous Tembeling Group. The boundary between Semantan Formation and Tembeling Group, as mapped by Jabatan Mineral dan Geosains Malaysia (JMG), runs in a north-south orientation westward of the Kuala Tahan village. The geology of this area consists of Semantan Formation and other two Jurassic-Cretaceous formations, namely Mangking Sandstone and Termus Shale (Kamal Roslan 1996). However, only Mangking Sandstone are cropped. This paper focuses on unravelling the depositional environment through sedimentological characteristics and facies architecture of Mangking Formation (Tembeling Group) cropped along Kuala Tahan to Kampung Bantal Road (Figure 1).

LITERATURE REVIEW

In general, the geology of the Malay Peninsula can be divided into three longitudinal belts, namely the Eastern Belt, Central Belt, and Western Belt. Most of the Jurassic-Cretaceous rocks in Malay Peninsula are located in the Eastern and Central Belts. Only the Saiong Formation, formerly known as the Saiong Beds, represents a Jurassic-Cretaceous unit in the Western Belt. The sediment deposition in Malay Peninsula during the Jurassic to Early Cretaceous was heavily influenced by the Earth's surface created by continental uplift resulting from igneous activity in the Late Triassic. In the Central Belt, several elongated basins formed during the Triassic were filled with sediments eroded from newly emerged mountains in the surrounding alluvial, fluvial, floodplain, and lake environments.

Tembeling Group was reported to contain three different formations chiefly, old to young, i) Kerum Formation ii) Mangking Sandstone, iii) Lanis Conglomerate, and iv) Termus Shale (Khoo 1977; Tjia 1996) (Figure 2). However, Kerum Formation was

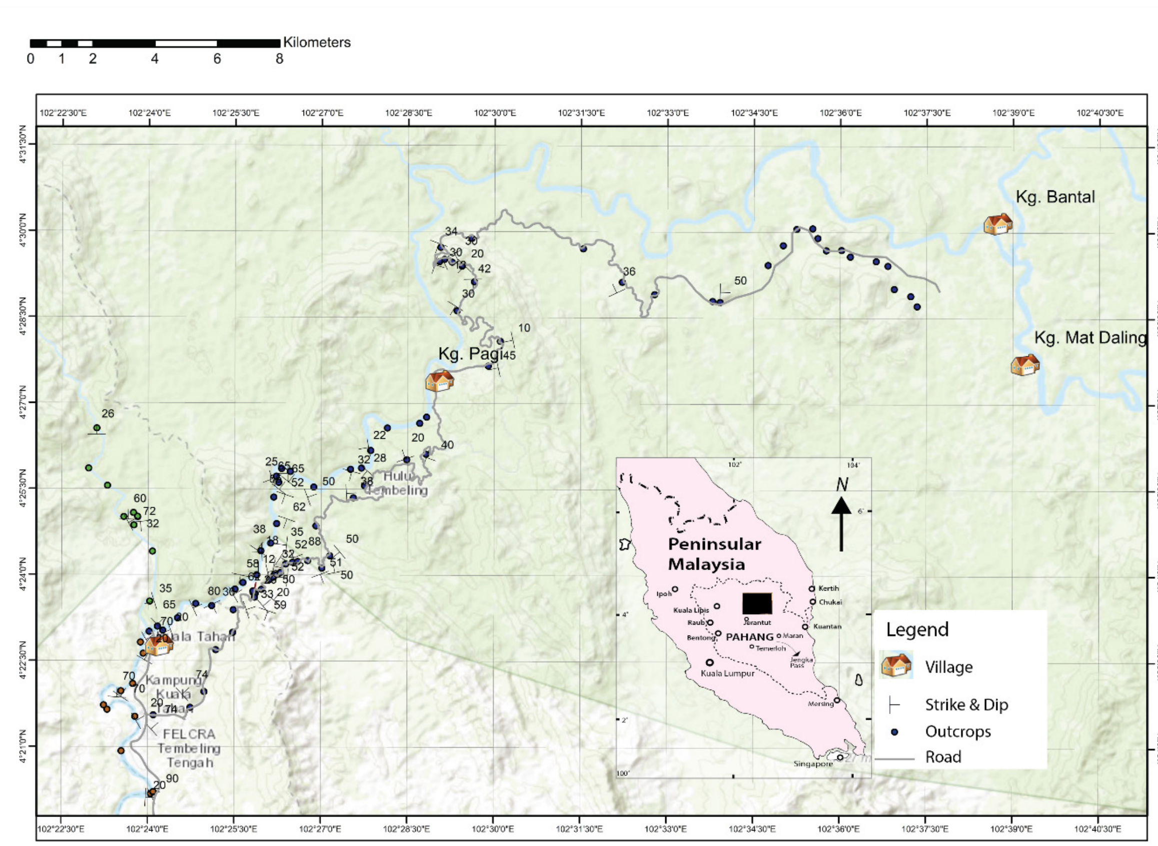


FIGURE 1. Topographic map showing the region surrounding the Sungai Tembeling across Kuala Tahan

removed from the Tembeling Group and correlated to the middle to upper Triassic Semantan Formation for the presence of volcanic clastic elements. In Maran district, Mohamad Pauzi (2013) introduced Serentang Formation as the oldest member of the Tembeling Group with reference to Serentang Tuff. The age of the Mangking Formation is well-dated, ranging from late Jurassic – early Cretaceous (Zainey, Marahizal & Uyob 2007).

The type locality for Mangking Formation is located at Mangking River and was described by Khoo (1983). It is characterised by interbeds of argillaceous rocks and quartzose sandstone. The sandstone shows fining-upwards trend with tabular and trough cross-bedding. Plant fossil, *Gleichenoides gagauensis*, was reported and this formation dates from Jurassic to Late Cretaceous (Khoo 1977). The thickness is 600 to 800 m (Harbury et al. 1990).

Termus Shale was first introduced by Khoo (1983), with Termus River as the type locality. This formation is the youngest in the Tembeling Group and consists of red ferruginous mudstone and siltstone, with minor red shale, sandstone and breccia. The thickness is suggested to be 300 to 500 m (Harbury et al. 1990).

Materials and Methods

The sedimentology of this area was analysed from 11 sedimentary sections which contains 32 logged outcrops along Tembeling River and Kuala Tahan to Kampung Bantal road. Facies, bounding surfaces and architectural elements were identified. Modified lithofacies and architectural elements were constructed based on Miall (1996) (Figures 3 & 4). Architectural elements and their bounding surfaces including their lateral variability were fabricated from photomosaic and outcrop profiles. The principles governing stratigraphy and the methodologies employed when correlation between geological sections and outcrops are outlined as follows: 1) the dip of strata in each section is consolidated into an average, 2) both the left and right limbs of folds are considered stratigraphically equivalent and can be effectively correlated, and 3) it is recognized that within a syncline, the central part is typically the most recently formed, whereas within an anticline, the central portion is generally the oldest.

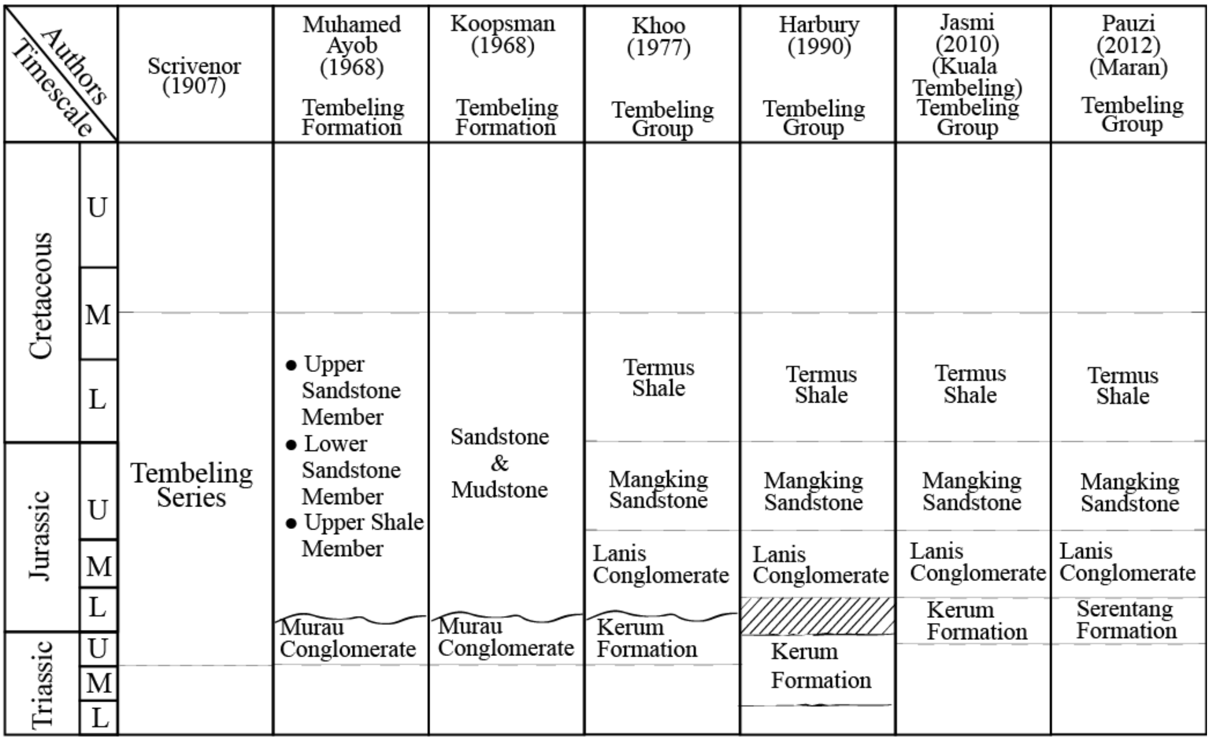


FIGURE 2. Stratigraphic terminology of Tembeling Group

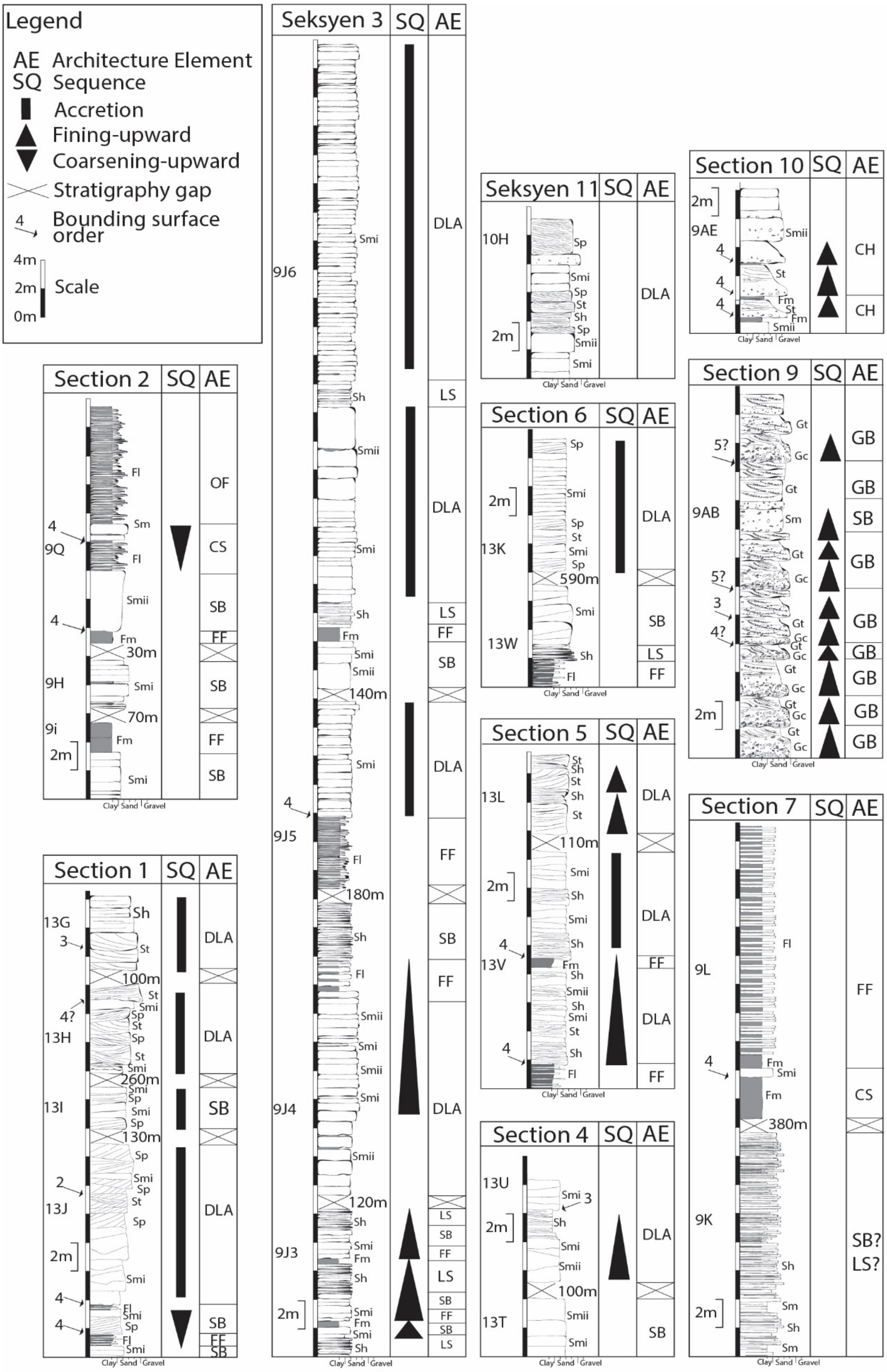


FIGURE 3. Sedimentary log sections of the Kuala Tahan region

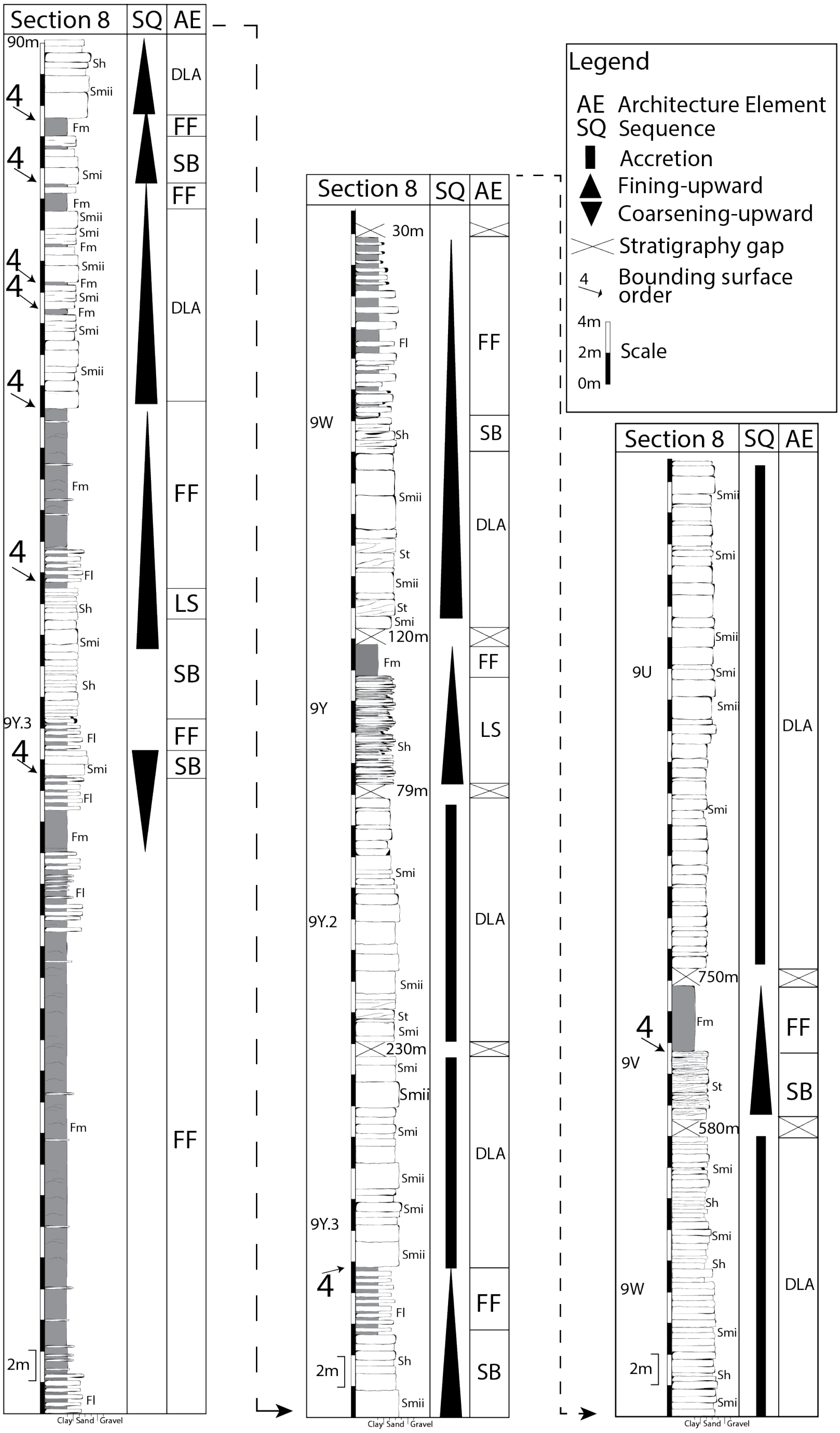


FIGURE 4. (Continued) Lithostratigraphic columnar sections of the Kuala Tahan region

RESULTS AND DISCUSSION

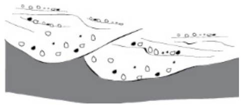
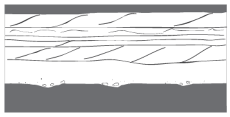
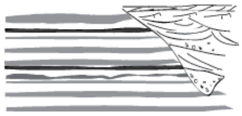
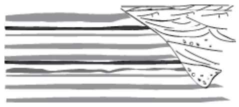
FACIES DESCRIPTION OF KUALA TAHAN

Facies description of this area was carried out using a modified version of Miall's (1996) lithofacies classification scheme. The identification of facies was according to their physical, observable characteristics, which are grain size, sorting, framework, sedimentary structures, external geometry, and nature of contacts (Table 1). Eight listed facies are clast-supported conglomerate facies (Gc), trough cross-stratified conglomerate facies (Gt), trough cross-stratified sandstone facies (St), massive sandstone facies (Sm), tabular cross-stratified sandstone facies (Sp), parallel laminated sandstone (Sh), interbedded sandstone and mudstone stripes (Fl), and mudstone facies (M). The facies are repetitive between individual outcrops and are sorted into six architectural elements (Table 2) (Figure 4 & 5).

TABLE 1. Summary of the characteristic features of the lithofacies types

	Facies	Description	Interpretation
Gravelly Facies	Clast-Supported Conglomerate Facies (Gc)	Clast- supported, no imbrication, subangular to subrounded, cobble to coarse pebble sized, erosion surface, gently undulating, lenticular geometries	Pseudoplastic debris flow or longitudinal bars, sheet flood to channel deposits
	Trough Cross-Stratified Conglomerate Facies (Gt)	Matrix- supported, clasts accumulate along trough cross-bedding cosets, extraformational clasts of mudstone	Channelized lag and bedform deposits
Sandy Facies	Cross-Stratification Sandstone Facies (St)	Cross-bedding, fine – coarse grained	3D dunes
	Massive Sandstone Facies (Sm) Subfacies: Smi & Smii	Smi: Thin, structureless, fine to medium grained sandstone. Smii: Thick, crude, structureless, medium to coarse	Rapid deposition from highly concentrated sediment flow
	Planar Cross-stratified Sandstone Facies (Sp)	Planar stratified, fine to medium grained	2D dunes
	Parallel Laminated Sandstone Facies (Sh)	Parallel lamination	Laminar flow. Lower flow regime
Muddy Facies	Mudstone with Thin Sandstone Stripes Facies (Fl)	Both mudstone- and sandstone- dominated. Sandstones are stripes shaped	Alternating flow energy. Waning flow deposits
	Mudstone Facies (Fm)	Laminated and massive	Suspension deposits, overbank or abandoned channel

TABLE 2. Architectural elements in Mangking Sandstone and Termus Shale of Kuala Tahan region

Architecture Element	Code	Facies Assoc.	Geometry & Relations	Order Bounding Surfaces	Scheme
Crevasse Splay	CS	St Sm Sm Sh Fl	Extensive, overlaying floodplain fines (FF)	4th order truncation	
Minor Channel	CH	Gt Gc	Channels fills with asymmetric fill	2nd order scouring	
Downstream and Lateral Accretion (Mesoform)	DLA	St Smi Smii Sh Sp	Multiple sheet-like sandstone beds	4th order bounding surfaces with lower internal surface	
Sandy Bedform	SB	St Smi Smii Sp Sh	Sheets, Minor bars, cross-stratification	1st, 2nd & 3rd order, ripple, cross & horizontal lamination, undulating surface	
Laminated Sand Sheet	LS	Sh	Sheet-like, ribbon with minor and thin silt and mudstone	1st order lamination & 2nd order thin beds	
Floodplain Fines	FF	Fm Fl	Mudstone with thin interbedded of sheet-like units	1st order lamination & 2nd order thin beds	

Clast- supported conglomerate, Gc

This facies is disarray, lenticular, wedge-like and clast-supported conglomerate. It comprises 80% angular mudstone and 20% subangular sandstone clasts. The clasts show no imbrication and are in random orientation. The base of these conglomerates is erosive and undulating with relief approximately 30 cm thick. Top boundaries are common diffused, and the conglomerate beds are overlain by trough stratified conglomerate (facies Gt), pebbly and massive sandstone (facies Ss). Each bed ranges from 70 cm – 150 cm in thickness. Conglomerate bodies are stacked with underlaying and scoured thin lenticular mudstone.

Interpretation: This facies is interpreted as pseudoplastic debris flow (Schultz 1984). Being grain-supported and lenticular geometries suggest grain flow in a confined condition (i.e., channels). This facies represents deposits of gravel sheets or low-relief longitudinal bars that are emplaced by high velocity flood flows (Hein & Walker 1977; Todd 1989).

Trough-cross-bedded Conglomerate, Gt

The gravels are distinctly stratified and up to 5 cm in diameter. This facies is also poorly sorted with medium to coarse sand matrix. The clasts form lenses, typically 10 cm – 30 cm and commonly cut into each other both laterally and vertically. The clasts comprise mostly of angular and broken dark grey and white mudstone. It commonly exhibits fining upwards or in some cases, overlain by thin to moderately thick trough cross-bedded sandstones.

Interpretation: This facies reflects minor channel fills. The angular mudstone clasts represent rip-up clasts. The thin overlaying trough cross-stratified sandstone signify dune deposits which usually is represented by fining upwards sequence. Isolate sets of trough cross-stratified conglomerate have been commonly interpreted to record scour-fill features (Khadkikar 1999; Siegenthaler & Huggenberger 1993).

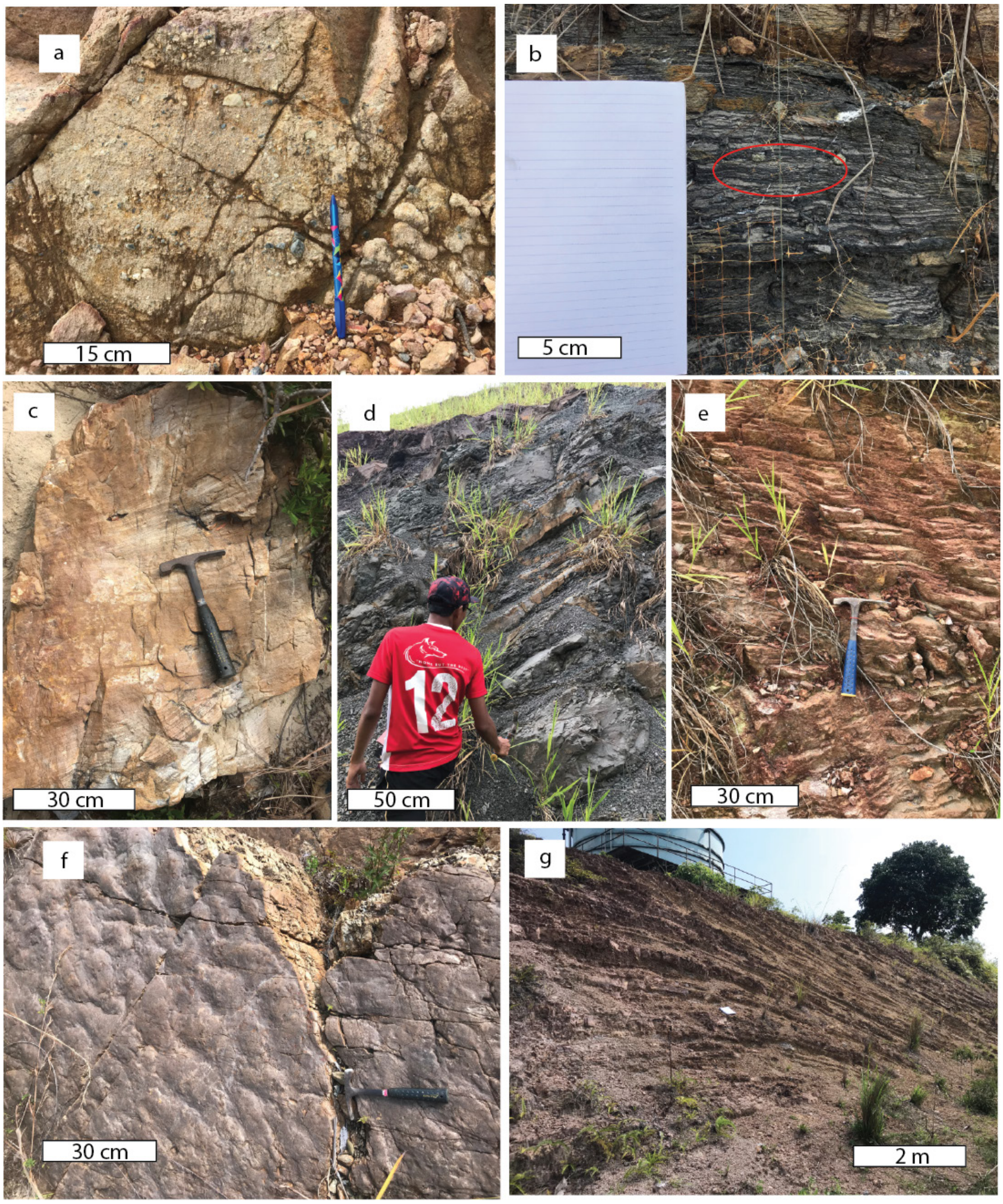


FIGURE 6. Sedimentary facies distinguished in outcrops along Tembeling River, Kuala Tahan. a) dark mudstone (Fm), b) cross-bedded sandstone (Sc), c) Planar cross-bedded sandstone (Sp), d) mudstone facies (Fm), e) horizontally laminated reddish sandstone

FIGURE 5. Characteristic examples of lithofacies encountered in the Mangking Sandstone of Kuala Tahan area, a) Conglomerate lenses - trough infill with pebbly lag deposits (facies Gt), b) Pyrite nodules in laminated silt and mud (facies Fm), c) Trough cross-stratified sandstone with low relief erosional base, d) Thinly interbedded sandstone and mudstone (facies Fl), e) horizontal stratified sandstone (facies Sh), f) Ripple surface at the top of structureless sandstone (facies Sm), and g) Thickly stacked of facies Sh

Cross-stratified sandstone, Sc

Sandstone beds in this facies show cross-bedding structures such as low-angle, parallel, trough, and planar cross-stratification. Grain size of the sandstone varies from fine to medium and rarely coarse. Pebbles are not rare in this lithofacies. The top surface of the beds is commonly irregular and rippled. While the bottom contacts are irregular to erosional. The sandstone bodies are wedge-like and commonly arranged into stacks that extend laterally for several tens of meters.

Interpretation: The variety of cross-stratification identified in this facies is interpreted to form by the migration of straight- or sinuous crested dune in a fluctuating water-level condition (Cant & Walker, 1976; Capuzzo & Wetzel 2004; Jackson II 1976a).

Massive Sandstone, Ss

The massive and structureless sandstone facies can be divided into 2 subfacies, Ssi and Ssii.

a) Thinly-bedded massive sandstone subfacies, Ssi

Structureless sandstone lithofacies consist of structureless, medium to fine sandstone with thickness ranges from 1 m to 30 cm. Pebbles are not rare in this lithofacies. The bottom contact of the sandstone beds often exhibits irregular and erosional contact. Occasionally there are load cast structure. This lithofacies often associate with cross-bedded sandstone lithofacies (Sc).

Interpretation: Deposition of this lithofacies took place from visco-plastic debris flows of a longitudinal bar or channel-lag deposits (Costa 1988; Schultz 1984; Shultz & Hubbard 2005). Alternatively, the lamination feature may be picked out by weathering resulting in structureless sandstone.

b) Thickly-bedded massive sandstone subfacies, Ssii

This subfacies consists of 1 m to 5 m thick, structureless, wedge-shaped and coarse to medium grained sandstones. Sandstone and mudstone clasts are common at the base of the beds. This subfacies is commonly observed at road cut outcrops.

Interpretation: This preservation of sedimentary structures in this subfacies is suggest to be weak and share similar dimension to trough cross-bedded facies, St, and planar sandstone facies, St, of Miall (1996) by Goro et al. (2015). Alternatively, longitudinal bars are also known to display massive to crude bedding and they are inferred to form in lower regime condition.

Parallel laminated sandstone, Sp

This facies exhibits thinly bedded sandstones (5 cm - 15 cm). The sandstone beds occur in bulk up to meters in thickness. The lamination is commonly faint to not identifiable at road cut outcrops. Coarse grains including pebbles are rare in this facies. The sandstone beds in this facies stacks up to 4 m in thickness. Top and bottom contacts are mostly sharp. Outcrops by the river feature clearer parallel lamination.

Interpretation: This facies is interpreted to form at the velocity around 1 m/s and water depths of 0.25 to 0.5 m and shallower (Miall 1996). This bed configuration is likewise characterized by low sedimentation and transportation rate.

Thinly bedded sandstone and siltstone, Sh

This facies consists of 3 different types of lithology, mainly, sandstone and siltstone. Mudstones are subordinate and feature as flat and thin beds (commonly less than 5 cm in thickness). Sandstone and siltstone beds are generally thicker and range from 3 cm - 10 cm. The sandstone beds are commonly very fine to fine and rarely medium in grain size. Thicker units of the facies show plane horizontal and low-angle cross-lamination. The mudstone beds are commonly grey in colour and exhibits parallel lamination. Thin sandstone beds bounded by sharp upper surfaces. Ripple height and length vary irregularly on each bedding surface as well as from bed to bed. Unidentifiable plant fragments are observed at outcrop 9A.

Interpretation: The coal fragments indicate continental origin (Fielding & Webb 2008). The flat feature reflects deposition in upper flow regime plane bed condition. This thinly bedded sandstone facies is interpreted to develop as overbank deposits or alternatively in shallow water on the upper parts of point bars (Kraus & Wells 1999; Plint 1983).

Interbedded sandstone and mudstone lithofacies, Fl

Sandstone is brown to brownish grey and the mudstone is commonly dark grey in colour. The sandstone beds in this facies are averagely 25 cm in thick while the mudstone beds appear to be thinner (~10 cm). Horizontal cross-bedding is commonly seen at the sandstone. The grain size of the sandstone ranges from fine to medium and occasionally coarse. Thickness of this facies ranges from 3 m – 6 m and often feature alongside with mudstone and structureless sandstone lithofacies. Unidentifiable plant fragments are rare in this facies.

Interpretation: Alternating extensive thin sandstone bed with mudstone reflect proximal overbank sedimentation (Capuzzo & Wetzel 2004; Smith & Perez-Arlucea 1994). Thicker channel-shaped sandstone bodies suggest crevasse channel.

Mudstone facies, Fm

The mudstone in this facies is massive to laminated. Occasionally it contains pyrite nodules. The thickness of this facies ranges from 1.5 m to 5 cm meter. It often occurs along with massive sandstone and thinly bedded sandstone facies. Forty cm thick and 2.5 m wide siltstone lenses are observed in this lithofacies at outcrop 9AE. Coal fragmented lamination is recorded and not rare.

Interpretation: The presence of pyrite nodules suggests a reducing condition during deposition. Low energy – suspension. Most deposition occurred in this facies is by suspension with limited bedload transport. This facies is interpreted to represent the deposits of waning stage flood deposition (Hjellbakk 1997). Alternatively, this facies could likewise represent shallow lake condition of a floodplain deposits.

ANALYSIS OF THE SEDIMENTARY ARCHITECTURAL ELEMENTS

Six architectural elements were recognised: channels (CH), sandy bedforms (SB), downstream and lateral accretion (DLA), crevasse splay (CS), laminated sand sheet (LS) and floodplain fines (FF) (Table 2) (Figures 7 & 8). These elements were defined by their facies association, geometries, and bounding surfaces (Miall 1996). Various architectural elements recognised have a hierarchical arrangement whereby some smaller elements are nested and stacked within larger elements. For example, one common type of nested element that is discussed below is sandy bedform element (SB) occurs within lateral accretion element (LA) and crevasse splay element (CS).

Sandy Bedform, SB

Sandy bedform (SB) is the most common element recognised and identified within all stratigraphic sections of Kuala Tahan. This element comprises stacked lens-tabular-, lenticular-shaped with grain size ranging from fine- to coarse-grained, cross- and horizontally stratified sandstone bodies (Smi, Smii, St, Sp and Sh). The recorded thickness ranges from 2 m to tens of meters (Rush & Jones 1987; Singh & Kumar 1974). It is also observed to be laterally persistent for over 30 m (limited by the exposure of the outcrops). Sandy bedform element is commonly overlain by fine-grained floodplain sediments (Fl and Fm). The base of this element is composed of sandstone rich with mud clasts that is a product of reworking of the underlaying floodplain fines element (FF). First-, second- and third-order bounding surfaces are contained in sandy bedform element (SB). This element is the key diagnostic characteristic in other higher hierarchical elements such as DLA element and CS element.

Interpretation: The different types of sandy facies in this element signify various fluvial settings and assemblages. This element represents the deposition of migratory dune-scale bedforms in either mid-channel bars as well as on the flanks of point bars (Allen 1983, 1963; Cant & Walker 1978; Capuzzo & Wetzel 2004; Jackson II 1976a, 1976b; Korus et al. 2018; Miall 1996, 1985; Rodrigues et al. 2015). The lens- and wedge-shaped geometry of the sand bodies represent the presence of crested dunes. Rip-up mud clasts at the bottom of this element reflect the erosion of the overbank area during lateral channel migration and the redeposition to form a channel lag (Nichols 2009).

Floodplain Fines, FF

Floodplain fines element is observed up to 16 m in thickness. The beds are mainly mudstone (Fm), mudstone, siltstone and sandstone interbedded (Fl). The mudstone-dominated units in this element are dark grey to purplish-red in colour, poorly laminated as well as massive. Thin sheet-like units in this element can be traced laterally for more than 60 m and are reported to reach up to several kilometres (Willis & Behrensmeyer 1995). Commonly, these facies is truncated by channel elements (CH element) and associated with the top part of crevasse splay deposits (CS element). Pyrite nodules and carbonaceous plant fossil fragments are common.

Interpretation: The extensive sheet-like geometry of the fine grain deposit indicates deposition over a wide area and distal to the main channel (Brierley 2006; Kraus & Wells 1999; Miall 2014). The purplish-red mudstone colour suggests a semi-arid, oxidising environment (McCarthy & Plint 1998; Reed 1991). The presence of thin fine sands indicates a low energy traction current. Thus, suggesting a continual slow settling of fine-grained via suspension at swamps or ponds with seasonal flood and drying out. Miall (1996) suggested that this element may be interbedded with paleosols.

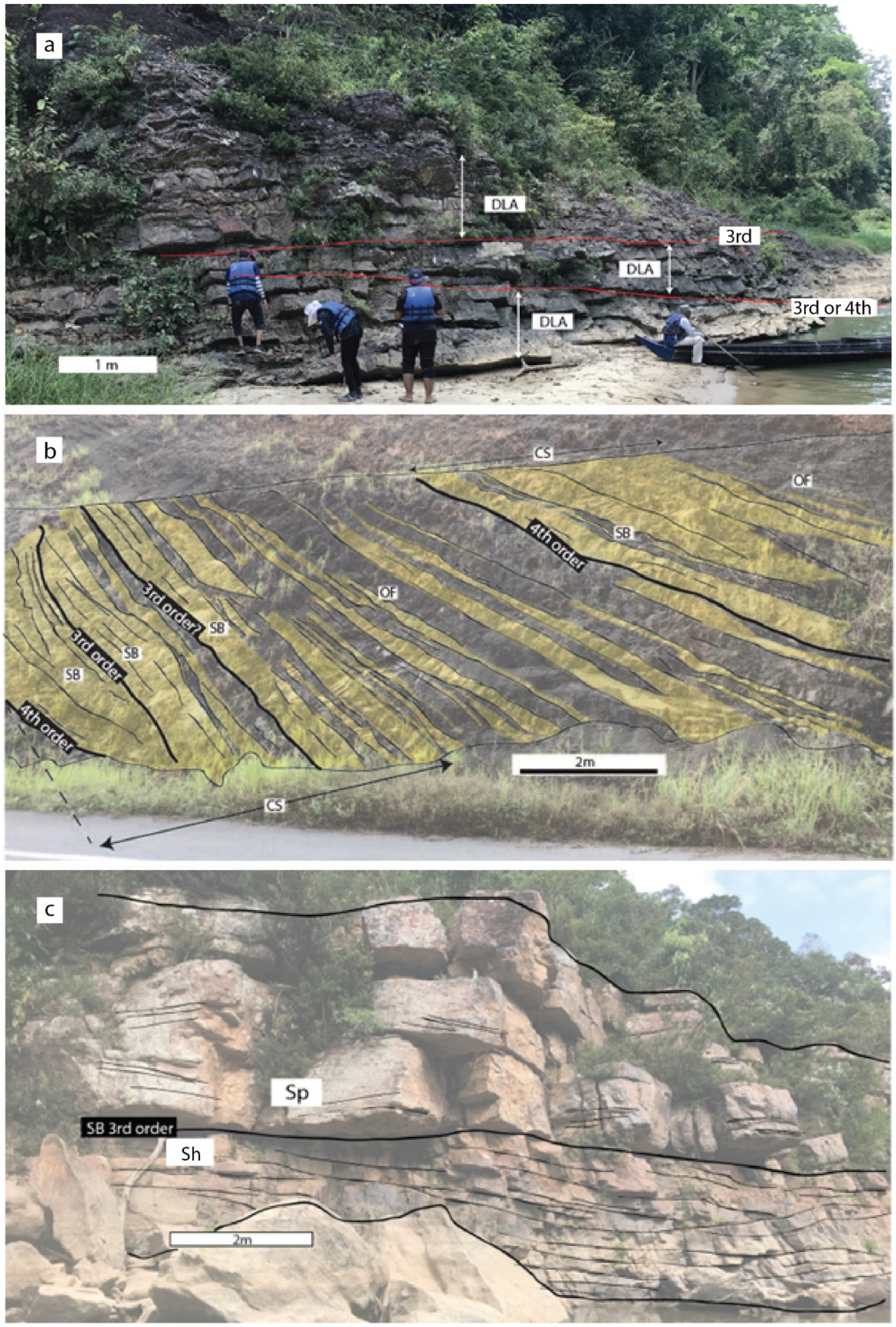


FIGURE 7. Outcrop photos with elements. a) Outcrop 13O that exhibits DLA elements, b) boundaries are fourth-order bounding surfaces for CS elements with nested lower hierarchical SB element, and c) third-order gently dipping bounding surface between facies Sc and Sp. SB – Sandy bedform element

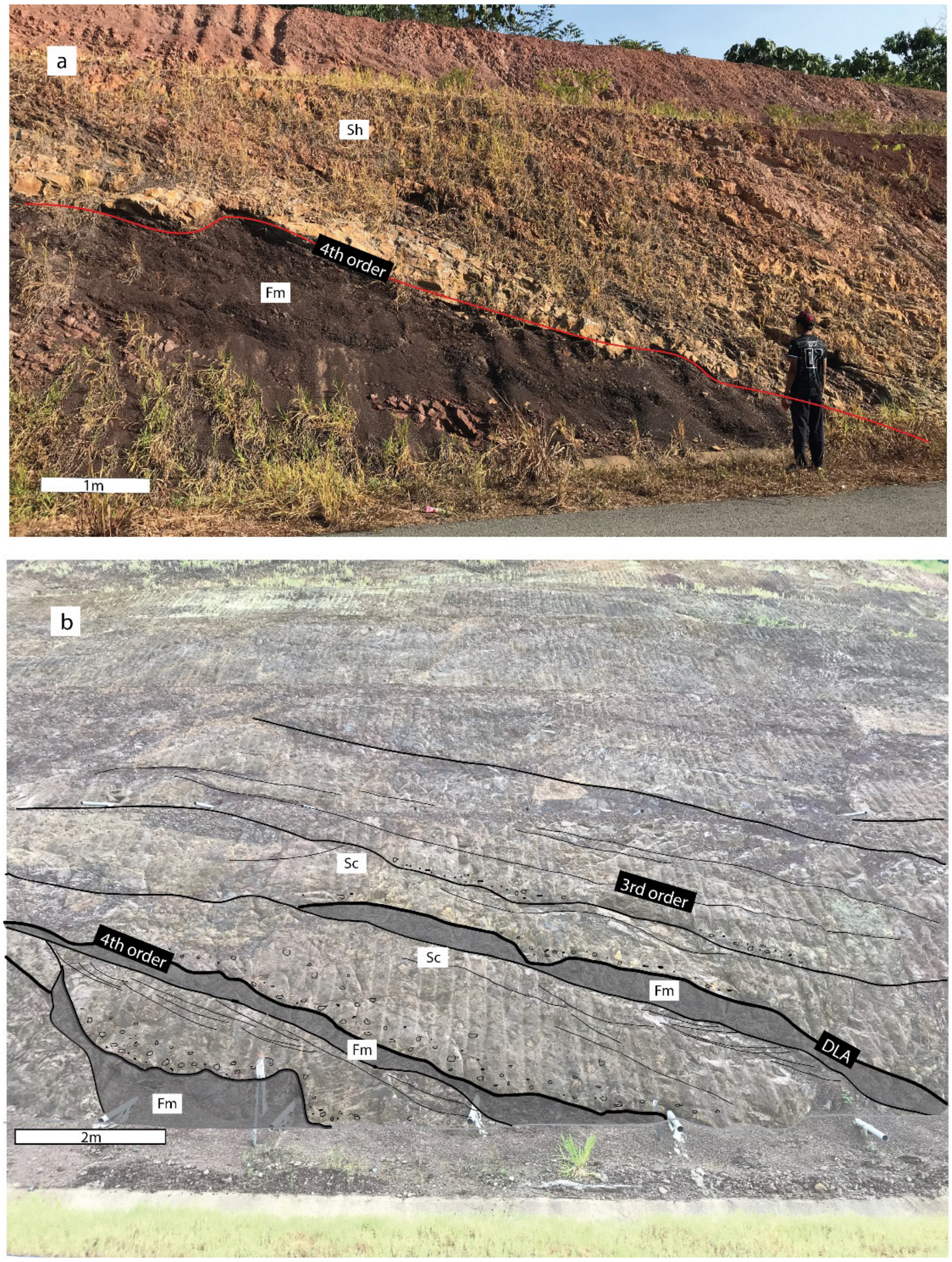


FIGURE 8. Outcrop photos with architecture elements. a) base of a channelized sand bed, and b) multi-storey and fining-upward minor channels. The erosional bases overlaying lenticular mudstones indicate fourth-order bounding surfaces. Third-order bounding surfaces indicate accretion and are usually gently dippin

Crevasse Splay, CS

The crevasse splay, CS element is characterised by sharp to slightly wavy based sandstone lobes (facies Smi, Smii, St and Sh) which are commonly sandwiched by mudstone, siltstone and thinly bedded interbeds (facies Fm and Fl). Fining upward trend can be observed at the top, while pebbles and mud clasts are common at the base. This element is observed to extent over 70 m. Internally this element is massive to faintly cross-lamination and low angled to horizontal bedding.

Interpretation: This element is recorded to extend laterally for more than 400 m and reported up to 10 km long and 5 km wide (Bown & Kraus 1981). The surrounding mudstone, siltstone and interbedded laminated fine-grained sand and mudstone (facies Fl and Fm) represent overbank sedimentation or avulsion belt (Smith 1989) (Smith & Perez-Arlucea 1994). This element is introduced into the floodplain fines (element of FF) by crevasse channels and is deposited because of bank failure. The bounding surfaces of splay deposits are classified as fourth-order surfaces (Miall 1985). The widespread occurrence of crevasse splay elements throughout the Mangking Sandstone suggests that seasonal flooding and vertical aggradation of the floodplain were common and frequent (Roberts 2007).

Channel Fill, CH

This element is characterised by multi-storey channel-fill deposits nested by lower hierarchical rank elements such as gravel bar (GB) elements. Commonly, this channel-fill deposit is stacked into multi-storey which are superimposed on each other. Lenticular mudstones are commonly observed between the channel-fill and are measured up to 0.5 m thick and 5 m wide. Individual channel-fill bodies are 1.5 - 3 m thick and comprise mainly matrix supported and trough cross-bedded conglomerates (facies Gc, Gt and Sg) with subordinate cross-bedded and massive sandstone (St, Smi and Smii), all of which are arranged into fining-upward packages. Facies Gc and Gt in this element are usually impersistent, transition vertically and laterally into sandstone beds with sharp, erosional bases and the geometry of elongated lobes. These conglomerates contain mudstone clasts that are the product of the reworking of components of the underlying element FF. Internally, the conglomerates at the base of this element have weak to no orientation and exhibit both fining-upward trends into stratified gravelly beds (facies Gt).

Interpretation: The low-amplitude bars formed sheet-like bodies during larger flood events (Miall 1985). The fining-upward trend with low relief upper surface, rip-up mud clasts and erosional lower boundary are common in this element which indicates channel lag (Allen 1983). The wedge-like geometry and thinly developed conglomerate with flat or undulating erosional boundaries are categorised as a fourth-order bounding surface (Bridge & Diemer 1983; Miall 1988, 1996, 2014; Simon 1990). The individual conglomerate bed represents gravel bar element (GB) and they occur as the lags at the base of the channel. Multi-storey channel-fill is interpreted to represent the vertically stacked fills of channels.

Downstream and Lateral Accretion, DLA

Downstream and Lateral Accretion element contains stacked lens-shaped sandy facies (Smi, Smii, St and Sp) with subordinate Sh facies. Gravelly facies are rare though pebbles are common at the base of the sandstone beds. Internally, clear changes in sedimentary structures could be observed in sandstone beds with gently dipping third-order basal bounding surfaces. Reactivation is common on these surfaces. This element ranges from 5 m to 20 m in thickness.

Interpretation: DA and LA elements are common in braided sheet sandstones. Accretion units in a fluvial environment are likely to represent a succession of mid-channel transverse (DA element) and point bars (LA element) within the central parts of a sinuous channel (Halfar, Riegel & Walther 1998; Smith & Perez-Arlucea 1994). However, detailed paleocurrent information is needed to distinguish these two elements at small-scaled and two-dimensional outcrops. The variety of sandy facies and internal structures indicate the development of vigorous bedform and bar progradation as well as chute (Willis 1993). The gently dipping surfaces indicate accretion direction and reactivation surfaces (third-order) are interpreted in terms of fluctuating water depth (Miall 1993, 1988; Roberts 2007). Stacked thickness could reach up to 30m (Gibling & Rust 2006).

Laminated Sand Sheet element, LS

This element contains fine, ribbon and thinly bedded facies (facies Sh and Sp) with subordinate facies St, Sp and Sm. It is commonly observed up to 3 m in thickness. Individual sandstone bed ranges from 3 cm to 8 cm in thickness and extends laterally for more than 100 meters. Stacked sequences of these facies are observed up to 16 m but are commonly 2 m – 3 m in thickness.

Interpretation: This element is suggested to result from intermittent flood and contemporaneously deposited with channel filling under upper flow-regime plane bed conditions (Miall 1996; Slingerland & Smith 2004). These beds represent the margins of individual flood sheets of levee deposits and are interpreted as vertical accretion deposits, which represent channel levees developed between channel and floodplain areas (Bridge & Lunt 2006). The very fine-grained sandstone units are interpreted as levee breach deposits that supplied crevasse splay lobes on the unconfined floodplain (Lucas & Krainer 2013). Alternatively, these thinly bedded ribbon-like sandstones, which are attributed to upper flow regime plane bed conditions may also develop in shallow water on the upper parts of point bars (Plint 1983).

DEPOSITIONAL MODEL

The environmental interpretation of the Mangking Formation is based on the lithofacies, architectural elements and bounding surfaces in ten measured sedimentary sections. Four different orders of bounding surface are recognised from lithological and sedimentary features of Kuala Tahan. First- and second-order bounding surfaces are defined by Miall (1996, 2014) to represent simple laminae, cross-stratification and coset boundaries. The lamination in Fl and Fm facies, cross-stratified boundaries in St and Sp facies, and bed contact boundaries in Sh facies are examples of first- and second-order surfaces. The third-order represents boundaries of dunes that are contained in a migrating dune or stacked sand bar in accretion units. The third-order surfaces commonly have gentle dipping around 15°, which reflects the gentle angle of the bar front (Roberts 2007). Based on Miall (1996), the third-order surfaces in a macroform form as the product of individual flooding cycles. The fourth-order are recognised from the truncated surfaces in between sandy CS and DLA elements with the underlying FF element. Besides, the presence of erosional surfaces with thin lenticular mudstone in within DLA element is likewise interpreted as fourth-order (Halfar, Riegel & Walther 1998). The fifth-order surface is defined by the erosional surfaces channel-fill with the underlying overbank deposits (FF element) while the sixth-order surfaces are even larger in scale which is represented by the contact between two different environments (e.g., fluvial and shallow marine settings) (Hjellbakk 1997). However, both fifth- and sixth-order are not observed (Figure 9).

The range of facies and their assemblage into fining-upward sequences characterised by distinct architecture elements support the hypothesis that Mangking Sandstone deposits in a fluvial environment

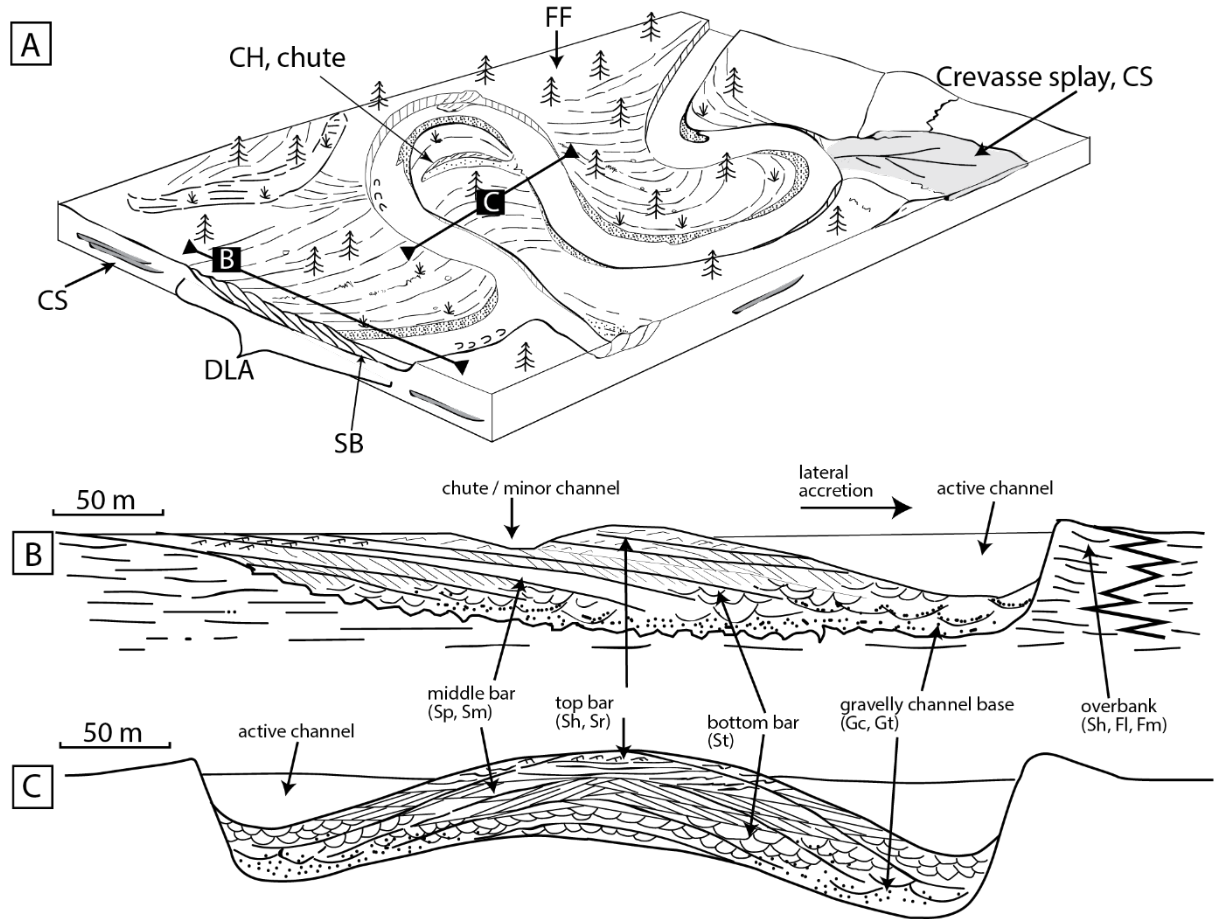


FIGURE 9. Summary of depositional model for the Mangking Sandstone of Kuala Tahan region. A) Skematic drawing of meandering river, B) Cross-section along B transect, and C) Cross-section along C transect. Architecture elements: CH – channel, SB – sandy bedform, CS – crevasse splay, DLA – downstream lateral accretion, FF – floodplain fines (Sh), & d) interbedded sandstone and mudstone (Fl)

and possibly meandering fluvial environment (Jackson II 1978). Besides, the relatively high ratio of floodplain, overbank and crevasse splay deposits compared to channel deposits suggest either rapid aggradation which leads to avulsion or broad floodplain across which the channel meandered (Heller & Paola 1996). Mangking Sandstone Formation in this area shows fining-upward sequences with lateral migrated point bar deposits (facies Sm and St), shallowing (facies Sh) and eventually overlain by floodplain deposits (facies Fl and Fm) as shown in many high-sinuosity fluvial successions (Collinson 1978; Visher 1972). The coarsening-upward of crevasse deposits are represented by sandy facies (St, Sm, Sp and Sh) overlaying floodplain deposits.

CONCLUSIONS

The Mangking Sandstone and Termus Shale formation in Kuala Tahan region is fluvial in origin and was deposited by sinuosity, accreting, meandering fluvial system. The succession is characterised by eight distinct lithofacies types (Gc, Gt St, Sm, Sp, Sh, Fl and Fm). The lithofacies can be seen to arrange in fining-upward sequences, which reflect channel deposits into avulsion. Sandbar accretion and crevasse splay deposits are likewise present. Six distinctive architectural elements, each with their distinctive geometry and arrangement of facies, are recognised (CH, SB, LV, CS, DLA and FF). These architectural elements are interpreted with the first four orders of bounding surfaces.

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