Sedimentology and stratigraphic development of the upper Nyalau Formation (Early Miocene), Sarawak, Malaysia: A mixed wave- and tide-influenced coastal system

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ABSTRACT

This work presents the first detailed facies analysis of the upper Nyalau Formation exposed around Bintulu, Sarawak, Malaysia. The Lower Miocene Nyalau Formation exposures in NW Sarawak represent one of the closest sedimentological outcrop analogues to the age equivalent, hydrocarbon-bearing, offshore deposits of the Balingian Province. Nine types of facies associations are recognised in the Nyalau Formation, which form elements of larger-scale facies successions. Wave-dominated shoreface facies successions display coarsening upward trends from Offshore, into Lower Shoreface and Upper Shoreface Facies Associations. Fluvio-tidal channel facies successions consist of multi-storey stacks of Fluvial-Dominated, Tide-Influenced and Tide-Dominated Channel Facies Associations interbedded with minor Bay and Mangrove Facies Associations. Estuarine bay facies successions are composed of Tidal Bar and Bay Facies Associations with minor Mangrove Facies Associations. Tide-dominated delta facies successions coarsen upward from an Offshore into the Tidal Bar Facies Association. The Nyalau Formation is interpreted as a mixed wave- and tide-influenced coastal depositional system, with an offshore wave-dominated barrier shoreface being incised by laterally migrating tidal channels and offshore migrating tidal bars. Stratigraphic successions in the Nyalau Formation form repetitive high frequency, regressive-transgressive cycles bounded by flooding surfaces, consisting of a basal coarsening upward, wave-dominated shoreface facies succession (representing a prograding barrier shoreface and/or beach-strandplain) which is sharply overlain by fluvio-tidal channel, estuarine bay or tide-dominated delta facies successions (representing more inshore, tide-influenced coastal depositional environments). An erosion surface separates the underlying wave-dominated facies succession from overlying tidal facies successions in each regressive-transgressive cycle. These erosion surfaces are interpreted as unconformities formed when base level fall resulted in deep incision of barrier shorefaces. Inshore, fluvio-tidal successions above the unconformity display upward increase in marine influence and are interpreted as transgressive incised valley fills.

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1. Introduction

Three end-member models of siliciclastic, coastal depositional systems are represented by fluvial-, wave-, or tide-dominated shorelines (e.g. Galloway, 1975; Boyd et al., 1992; Dalrymple et al., 1992; Bhattacharya, 2010). The facies models comprising these end-member hydrodynamic regimes are well established, and have been useful in understanding and interpreting ancient coastal deposits. However, other important variables that are additional to the original process-based classification are sediment texture (Orton and Reading, 1993), changing rates of sediment supply and fluctuations in relative sea level (Zaitlin et al., 1994). This results in a wide array of clastic coastal depositional systems with variable morphologies, sand body types and facies relationships (Ainsworth et al., 2011).

Ancient clastic coastal sedimentary successions frequently do not easily fit into the ideal wave-, tide- and fluvial-dominated end-member coastal facies models. More commonly they display sedimentary characteristics that are transitional between the wave-, tide- and fluvial-dominated end-members (e.g. Lambiase et al., 2003; Fan et al., 2004; Rebata et al., 2006), which reflects a continuum of hydrodynamic, sediment supply and accommodation space interactions.

In this paper, we apply the above concepts to an evaluation of a thick (hundreds of metres) succession of Early Miocene coastal to coastal plain deposits from the Nyalau Formation in Sarawak,
Malaysia. The studied succession displays a wide range of facies and facies successions, with evidence for deposition by fluvial-, wave-, and tide-generated processes. The aims of the paper are as follows: (1) to document the facies characteristics and vertical facies successions; (2) to evaluate the relationship between fluvial-, wave- and tide-dominated deposits; and (3) to integrate these observations into a depositional model, including the broader sequence stratigraphic and palaeogeographic context of the studied succession.

2. Geological setting

The Nyalau Formation, and its hydrocarbon-bearing offshore equivalents (Cycles I and II), comprise a thick (hundreds to thousands of metres) succession of Early Miocene clastic coastal plain to coastal deposits in the Balingian Province of central Sarawak (Fig. 1) (Almond et al., 1990). The Nyalau Formation dominates the onshore geology of the southern part of the Balingian Province (Fig. 1A) (Mazlan and Abolins, 1999; Hutchison, 2005). The Balingian Province represents part of a peripheral foreland basin fill (the Sarawak Basin) related to the closure of the Rajang Sea and the Sarawak Orogeny, which occurred during the Late Eocene (Hutchison, 1996, 2005; Mazlan, 1999a,b,c). The foreland basin fill, including the Nyalau Formation, unconformably overlies strongly deformed deepwater deposits of the Pre-Oligocene Rajang Fold-Thrust Belt accretionary complex (Ismail, 2000) (Fig. 1A and B).

The Nyalau Formation is estimated to be ca. 1000–2000 m thick in the Bintulu area and comprises alternating heterolithic beds, cross-bedded sandstones and coal-bearing mudstones (Liechti et al., 1960; Wolfenden, 1960). These strata are gently folded, with a general axis orientation of NE–SW (Fig. 1A and C), which forms a coast-parallel fold belt 120–160 km long (W–E) and 48–80 km wide (N–S), extending from the Tatau area in the southwest to

![Fig. 1. (A) Geological map of Bintulu and surrounding areas, Sarawak. Study area shown by box. Modified from Liechti et al. (1960) and Tate (2001). (B) Simplified stratigraphic framework for the onshore northwest coast of Sarawak. Modified from Mazlan (1999c) and Mohd Idrus and Redzuan (1999). (C) Map showing distribution of the Nyalau Formation around Bintulu, Sarawak, Malaysia, and location of studied outcrops. Geological structures derived from Liechti et al. (1960). (D) Early Miocene palaeogeography of the Sarawak Basin. White arrows mark main sediment transport pathways. Modified and compiled from Ismail and Swarbrick (1997), Mazlan (1999c) and Mansor et al. (1999).]
the Niah River in the northeast, and extending about 40 km inland (Liechti et al., 1960) (Fig. 1A).

Larger foraminifera from the Nyalau Formation give a biostratigraphic age range from stages Tcd–Tf1 of the Far East Letter Classification Scheme (originally from Van der Vlerk and Umgrove, 1927, with numerous revisions afterward, including Van der Vlerk, 1955 and Adams, 1985), which gives an age range from Early Oligocene (Rupelian) to the Early Miocene (Burdigalian) (Liechti et al., 1960). More recent biostratigraphic work indicates an Early Miocene age (Aquitanian – Burdigalian), with possible extension into the earliest Middle Miocene (Langhian) (Morley, 1998).

The gross depositional environment ranges from lower coastal plain to shallow marine (Liechti et al., 1960; Hutchison, 2005) (Fig. 1B). Micropalaeontological studies indicate significant brackish water influence (Liechti et al., 1960), which supports a paralic environment interpretation. Palynological studies show a warm, seasonally dry environment for Southeast Asia during the Oligocene – Early Miocene (Morley, 1998).

The Nyalau Formation conformably overlies Oligocene age shallow marine deposits of the Buan Formation, and Eocene shallow marine deposits of the Tatau Formation in the southwest and south (Fig. 1B). In the main study area around Bintulu (Fig. 1C), the Nyalau Formation is unconformably overlain by Pleistocene-Holocene coastal deposits and alluvium. The Late Miocene-Pliocene Liang Formation is sporadically exposed around Bintulu and also unconformably overlies the Nyalau Formation.

The Nyalau Formation passes northwards, and offshore, into the laterally equivalent Cycles I and II, and all these sandstone-bearing stratigraphic units interfinger and gradually pinch out northeastward into mudstone-dominated, neritic-deepwater marine deposits of the Setup Shale (Fig. 1D). Cycles I and II of the offshore Balingian Province are composed of coal-bearing, interbedded sandstone and mudstone that were deposited in various coastal plain, coastal and deltaic depositional environments (Almond et al., 1990; Hageman, 1987; Mazlan, 1999c). The younger Cycle II resembles the upper part of the Nyalau Formation in displaying an interaction between fluvial and coastal depositional systems (Almond et al., 1990) and a broadly retrogradational stratigraphic succession (Fig. 1B). In places, Cycles I and II also display stronger fluvial influence (Almond et al., 1990; Mazlan and Abolins, 1999). The inferred regional shoreline orientation would have formed a large-scale embayed coast during the Early Miocene (Hageman, 1987; Ismail and Swarbrick, 1997; Mazlan, 1999c). In the offshore Balingian Province, Cycle II forms substantial hydrocarbon-bearing reservoirs, with several large oil and gas accumulations in coastal and coastal plain sandstones located within structural traps (Almond et al., 1990; Mazlan and Abolins, 1999).

3. Study area

There are many extensive, and relatively new, outcrops of the Nyalau Formation in and around Bintulu, mainly along the Bintulu–Tatau road in the south and the Bintulu–Miri coastal road in the north (Fig. 1C). The best exposed and most complete sections (10 in total) were selected for detailed sedimentological study. Precise correlation of the studied sections is not possible, due to the complex deformation, vegetation and lateral facies variations, but their approximate stratigraphic positions were inferred from published geological maps (Liechti et al., 1960). The majority of outcrops represent the upper part of the Nyalau Formation, with one section probably representing the lower part (Sebauh Stop 2 section, Outcrop Locality H). Palynological analysis of 5 mudstone samples from two of the studied sections (Sungai Mas Camp Entrance, Outcrop Locality A and Meteorological Department Outcrop, Outcrop Locality C) indicate an Early Miocene age for the upper part of the Nyalau Formation, based on the regular occurrence of Floraschvetzia trilobata.

Most of the studied sections were created by civil engineering projects over the past 6 years which resulted in clean outcrops with minimal vegetation. The sections are up to 72 m in stratigraphic thickness and provide the first opportunity for a detailed facies analysis of the upper part of the Nyalau Formation.

4. Sedimentary facies characteristics

4.1. Facies associations

The sedimentary rocks of the Nyalau Formation have been assigned to nine facies associations, which are summarised in Fig. 2 (see also the sedimentary logs in Figs. 3 and 4). Detailed descriptions of individual facies associations are given in the supplementary document and supplementary figures. The Offshore Facies Association (FA 1) is characterised by bioturbated mudstone and interbedded mm- to cm-thick siltstone and sandstone layers displaying normal grading, micro-hummocky cross-stratification and symmetrical ripples, representing suspension and storm deposition below fair-weather wave base.

The Lower Shoreface Facies Association (FA 2) is characterised by successions of interbedded cm- to dm-thick, bioturbated mudstone and hummocky cross-stratified sandstone (HCS) displaying a sand:mud ratio of 0.75 or less. FA 2 represents storm and wave deposition above fairweather wave base.

The Upper Shoreface Facies Association (FA 3) displays a similar facies composition with FA 2, but also comprises cross-bedded sandstone and has a higher sand content (sand:mud ratio > 0.75).

The Tidal Bar Facies Association (FA 4) forms coarsening upward heterolitomorphic packages displaying abundant tide-generated structures (mud drapes, heterolithic and rhythmic bedding) and inclined stratification. FA 4 is interpreted as representing prograding, elongate tidal bar deposits.

The Fluvial-Dominated Channel Facies Association (FA 5) commonly forms dm- to m-thick, sandstone and/or conglomeratic scour fills at the base of multi-storey channel stacks. Sandstone beds commonly display cross-bedding, parallel lamination and climbing ripple cross-lamination. Bioturbation is absent. FA 5 is interpreted as representing fluvial channel fill deposits.

The Tide-Influenced Channel Facies Association (FA 6) forms up to 5 m thick, erosive based, fining upward packages. FA 6 generally comprises cross-bedded sandstone, laminated sandstone and heterolithic bedding occasionally displaying tide-generated structures (mud drapes, lenticular, wavy, flaser bedding). Bioturbation ranges from absent to sparse. The scarcity of tidal features and the mainly non-bioturbated character of FA 6 indicates a freshwater, fluvial channel but with significant tidal influence.

The Tide-Dominated Channel Facies Association (FA 7) also forms several m-thick, erosive based, fining upward successions of cross-bedded sandstone and heterolithic bedding. However, FA 7 displays abundant tide-generated structures, including cross-beds with abundant mud drapes displaying thick-thin alternations (neap-spring cycles) and thick successions of heterolithic and rhythmic bedding. Concave upward channel profiles are common, with infilling heteroliths commonly forming inclined stratification (IHS). Bioturbation is generally sparse to moderate and comprises a low diversity, impoverished marine ichnofauna. The combination of tidal features and impoverished marine ichnofauna is used to interpret a brackish water, tide-dominated channel fill.

The Bay/Subtidal Flat Facies Association (FA 8) forms 1–15 m thick successions of mud-dominated, heterolithic bedding. This is mainly in the form of laterally continuous, horizontally layered,
<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Characteristics</th>
<th>Bioturbation</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA 1 Offshore (OS)</td>
<td>Silty bioturbated mudstone with thin graded siltstone, micro-hummocky cross-stratified and bioturbated sandstone interbeds</td>
<td>Moderate to intense, Diverse trace fossil assemblage</td>
<td>Fairweather suspension deposits and thin storm deposits laid down below fairweather wavebase in a wave-dominated environment</td>
</tr>
<tr>
<td>FA 2 Lower Shoreface (LSF)</td>
<td>Non-amalgamated and minor amalgamated beds of fine-grained sandstone with thin mudstone interbeds. Hummocky cross-stratification in sandstones commonly capped by wave rippled layers</td>
<td>Moderate</td>
<td>Fairweather suspension deposits and thicker, more proximal storm deposits laid down above fairweather wavebase in a wave-dominated environment</td>
</tr>
<tr>
<td>FA 3 Upper Shoreface (USF)</td>
<td>Amalgamated beds of fine to medium grained sandstone with minor mudstone interbeds. Hummocky cross-stratification, planar lamination and cross-beding in sandstones</td>
<td>Moderate</td>
<td>Fairweather oscillatory flow deposits, proximal storm deposits, and longshore current deposits laid down in shallower waters above fairweather wave base in a wave-dominated environment</td>
</tr>
<tr>
<td>FA 4 Tidal Bar (TBR)</td>
<td>Fine grained sandstone beds with mud drapes and interbeds. Coarsening upward successions from lenticular into wavy and finer bedding. Inclined heterolithic stratification</td>
<td>Sparse to moderate (Impoverished ichnofauna or monospecific assemblages)</td>
<td>Prograding barform composed of heterolithic bedding deposited by cyclical tidal currents and intervening slackwater periods.</td>
</tr>
<tr>
<td>FA 5 Fluvial-Dominated Channel (FDC)</td>
<td>Fine to medium grained sandstones, minor interbedded mudstone. Scoured base sometimes with basal conglomerate. Trough cross bedding, parallel lamination, climbing ripple and wavy beds in the sandstone. Unimodal paleo currents</td>
<td>Absent</td>
<td>Fluvial-dominated channel fill bodies, freshwater rivers</td>
</tr>
<tr>
<td>FA 6 Tide-influenced Channel (TIC)</td>
<td>Fining upward package from medium grained sandstone to fine grained heteroliths. Scoured base with basal coal or mud clast conglomerate. Channel-shaped geometries. Cross-beding with mud / carbonaceous debris drapes.</td>
<td>Generally absent (Rare, local intervals of bioturbation)</td>
<td>Fluvial-dominated channel fill bodies, but significantly tidal currents. Dominantly freshwater, but with periodic brackish marine incursions</td>
</tr>
<tr>
<td>FA 7 Tide-Dominated Channel (TDC)</td>
<td>Fining upward package from medium grained sandstone to heteroliths, sometimes completely mud-filled. Scoured base with basal mud clast conglomerate. Channel-shaped geometries. Cross-beding with rhythmic mud drapes. Inclined heterolithic stratification</td>
<td>Sparse to moderate (Impoverished ichnofauna)</td>
<td>Tidal-dominated channel fill bodies</td>
</tr>
<tr>
<td>FA 8 Bay/Subtidal Flat (B/F)</td>
<td>Very fine to fine grained sandstone with mudstone interlaying. Muddy heteroliths, lenticular bedding and structureless mudstone</td>
<td>Sparse to moderate (Impoverished ichnofauna)</td>
<td>Brackish water, tide-dominated estuarine/ intertidal/distributary embayment fills or subtidal flats</td>
</tr>
<tr>
<td>FA 9 Mangrove (M)</td>
<td>Carbonaceous mudstone and thin coal. Abundant carbonaceous debris, rooted</td>
<td>Absent to intense</td>
<td>Tidal-dominated, mangrove vegetated tidal flats</td>
</tr>
</tbody>
</table>

Fig. 2. Table summarising the characteristics of the facies associations present in the Nyalau Formation, Sarawak.

lenticular bedding and associated mm- to cm-thick sand-mud interlayering. Bioturbation is generally sparse to absent, with local intervals of strong bioturbation. The combination of muddy heterolithic deposition and generally sparse bioturbations indicates...
a restricted, low energy, tide-dominated environment, inshore embayment or subtidal flat environment.

The Mangrove Facies Association (FA 9) comprises 2–15 m thick successions of carbonaceous rooted mudstone, and associated thin coal (0.1–1 m thick). The coals are interpreted as marine-influenced, mangrove-derived coals, based on the high abundance of carbargillite microfossil types and high liptinite content of predominantly suberinitic constituents of probable *Rhizophora* sp. (Wan Hasiah, 2003; Wan Hasiah and Abolins, 2006). FA 9 is interpreted as representing intertidal mangrove vegetated mudflats.
4.2. Large scale facies successions

The stacking patterns of successive facies associations in the Nyalau Formation form larger-scale, cyclical packages (facies suc-
cessions). The facies successions range in thickness between sev-
eral metres to 45 m (Figs. 3 and 4). Four facies successions are
identified: (1) wave-dominated shoreface facies successions; (2)
fluvio-tidal channel facies successions; (3) estuarine bay facies suc-
cessions; and (4) tide-dominated delta facies successions.

4.2.1. Wave-dominated shoreface facies successions

The wave-dominated shoreface facies succession is mainly
composed of offshore and shoreface facies associations (FA 1–3),
and ranges in thickness between 3 and 26 m (e.g. Supplementary
Fig. 4). The succession usually overlies an estuarine bay or
fluvio-tidal channel facies succession. An ideal wave-dominated
shoreface facies succession displays a thin (2–4 m thick) lower part
composed of a fining upward Lower Shoreface Facies Association or
a basal, coarse grained sandstone lag deposit (e.g. Meteorology
Office, interval 28–30 m on sedimentary log, Fig. 3C). In some
cases, the lower sandstone is not present.

The thin sandstone is then overlain by the main body of the
succession, which coarsens upward from the Offshore Facies
Association (FA 1) into a Lower Shoreface Facies Association
(Supplementary Fig. 4). Some examples of this succession also
comprise an Upper Shoreface Facies Association (FA 3), but this
usually occurs when the succession is overlain by a successive
wave-dominated shoreface facies succession. However, in most
cases, the upper shoreface (FA 3), and sometimes even the Lower
Shoreface (FA 2), is completely eroded by an overlying fluvio-tidal
channel or estuarine bay facies succession (leaving only a muddy
FA 1 interval).

The wave-dominated shoreface facies succession is interpreted
as representing the deposits of a prograding wave-dominated
shoreface, based on the dominance of wave-generated facies and
offshore-shoreface facies associations displaying a coarsening up-
ward trend. The thin basal sandstone at the base of the facies rep-
resents a transgressive sand/lag deposit formed by wave
ravinement and associated with a flooding surface (e.g. Swift
et al., 1991; Murakoshi and Masuda, 1992). The transgressive nature
of the lower part is indicated by its position overlying more proximal
inshore facies of the estuarine bay or fluvio-tidal channel facies
succession. The main body of the wave-dominated shoreface
facies succession, which coarsens upward, represents a prograding
wave-dominated shoreline.

4.2.2. Fluvio-tidal channel facies successions

This facies succession can reach up to about 30 m thick, and is
usually represented by a multi-storey succession of channel facies
associations (FA 5–7) (e.g. Supplementary Fig. 5).

The base of the fluvio-tidal channel facies succession is sharp,
and represents an erosive, composite basal channel scour. The ba-
sal surface usually overlies wave-dominated shoreface or estuarine
bay facies successions (Supplementary Fig. 5A and B). Tide-domi-
nated and tide-influenced channel deposits (FA 6 and 7) are the
main facies associations in these successions. The Fluvial-Domi-
nated Channel Facies Association (FA 5) is only present at Sebauh
Stop 2 (Fig. 4H), Bay/Subtidal Flat (FA 8) and Mangrove Facies Asso-
ciations (FA 9) form a minor element of this facies succession,
intercalated between channel facies associations, although they
can represent the basal facies association in the succession (e.g. Se-
biew Junction Outcrop 1; Supplementary Fig. 5C and D). In some
cases, the fluvio-tidal channel facies succession is not significa-
tly thick but is composed only of single-storey channel fill deposits
(Supplementary Fig. 2E) or even thin mangrove mudstone and
mud-filled channel deposits (FA 7 and FA 9) (1 m thick) with a thin
basal coarse grained lag (Supplementary Fig. 6A).

The fluvio-tidal channel facies successions are interpreted as
laterally extensive, fluvially-supplied, tide-influenced river chan-
nel-belt complexes, based on the presence of a continuum of flu-
vial-dominated, tide-influenced and tide-dominated channel fill
deposits, bay and subtidal flat deposits, mangrove deposits and
the fining upward trend of individual channel fill deposits. Variations
in the facies composition of the fluvio-tidal channel facies
successions reflect longitudinal variations in river and tide energy
along the channel belt. More proximal (landward) locations pre-
serve a succession dominated by fluvial-dominated channel depos-
its (FA 5), while more distal (seaward) locations preserve a suc-
cession dominated by tide-influenced or tide-dominated chan-
nel deposits. Fluvio-tidal channel facies successions comprising
single-storey channel fills, bay/subtidal flats and mangroves repre-
sent areas away from the channel belt axis.

4.2.3. Estuarine-bay facies successions

Estuarine bay facies successions form an overall fining upward
trend ranging in thickness between 3 and 45 m (e.g. Supplemen-
tary Fig. 6B). The facies succession commonly sharply overlies
deposits of the fluvio-tidal channel facies succession, but may also
directly overlie a wave-dominated shoreface facies succession
(Supplementary Fig. 7A). The estuarine bay facies succession is typ-
ically overlain by a wave-dominated shoreface facies succession
(Supplementary Fig. 6B).

The basal part of the estuarine bay facies succession usually
comprises a Tidal Bar Facies Association (FA 4). The Tidal Bar Facies
Association is then overlain by one or more Bay/Subtidal Flat Facies
Associations (FA 8). In some examples, the Tidal Bar Facies Associ-
ation is absent, and the estuarine bay facies succession is repres-
teved only by the Bay/Subtidal Flat Facies Association (FA 8)
(e.g. Meteorology Department Outcrop, 14–28 m interval on sedi-
mentary log, Fig. 3C).

The estuarine bay facies succession is interpreted as tide-domi-
nated estuarine sub-environments based on the dominance of ti-
dal facies associations. Most of the tidal bars at the base of the
estuarine bay facies successions probably represent prograding,
tide-influenced bay-head deltas (e.g. Fenies and Tastet, 1998).
However, some of the landward migrating tidal bars (e.g. Sungai
Mas Entrance) may represent flood-tidal delta deposits. The over-
lying Bay/Subtidal Flat Facies Association (FA 8) probably repre-
sents central basin estuarine muds, lagoonal muds or embayment
muds which drape the bay-head delta as the shoreline transgressed.

4.2.4. Tide-dominated delta facies successions

Only four examples of the tide-dominated delta facies success-
se are present in the study area, all forming part of a single out-
crop (Sebauh Stop 1) (Fig. 4G, Supplementary Fig. 7B). This facies
succession forms coarsening upward trends ranging in thickness
between 5 and 9 m. The succession ideally coarsens upward from
the Offshore Facies Association (FA 1), into the Tidal Bar Facies
Association (FA 4). The Tidal Bar Facies Association in this facies
succession differs from those in the estuarine bay facies succession
in having a higher mud content (thicker and more abundant mud
drapes), a thicker lower muddy part composed of lenticular bed-
ding and displaying a low abundance and low diversity trace fossil
assemblage (estuarine bay facies succession tidal bars display a
more diverse assemblage). The tidal bars in the tide-dominated
delta facies succession also gradually overlie the Offshore Facies
Association (FA 1) and form thick stacks of successive delta suc-
cessions, rather than sharply overlying a wave-dominated shoreface
facies succession, as in the estuarine bay facies succession.
The facies succession is interpreted as representing prograding lobes of tide-dominated deltas, based on the thick coarsening upward trend grading from an Offshore Facies Association (FA 1) directly into tidal bar deposits (FA 4), the relatively low degree of bioturbation and the abundance of tidal indicators. The thick lenticular bedded lower part of the Tidal Bar Facies Association is interpreted as representing prodelta deposits. The overlying sandy part of the tidal bar probably represents delta front, distributary mouth bar and/or in-channel bar deposits. The impoverished marine ichnofauna associated with the tidal bars of the tide-dominated delta facies succession is characteristic of a deltaic environment experiencing high sediment supply and salinity stresses (MacEachern et al., 2005). The restriction of this facies succession to a single outcrop indicates the presence of a subordinate, locally restricted tide-dominated delta system along a mixed wave- and tide-influenced coastline.

5. Depositional model

The marginal marine nature of the sedimentary facies and ichnology of the Nyalau Formation is indicative of a nearshore, coastal plain environment, at the boundary between the landward limit of marine processes, and the seaward limit of alluvial and shoreline processes. Palynological analysis of mudstone from Sungai Mas Entrance Outcrop and Meteorology Office Outcrop (Samples S1, S2 and S6 from Sungai Mas Entrance outcrop and S13 from Meteorology Office outcrop; refer to Fig. 3 for sample location) indicate a mangrove to back mangrove palynomorph assemblage, with only a low percentage of freshwater palynomorphs. This is consistent with a brackish water, lower coastal plain environment.

The facies associations and large scale facies successions indicate significant interaction of river, wave and tide processes within an interconnected, contemporaneous coastal to coastal plain depositional system. The high proportion of both wave and tidal facies associations (FA 1, FA 2, FA 3, FA 4, FA 7, FA 8, and FA 9) compared to the less common fluvial deposits (FA 5 and FA 6) indicates a location in the region of mixed energy, wave-, tide- and fluvial-influenced shorelines in the ternary process-based classification for coastal systems (Dalrymple et al., 1992; Reading and Collinson, 1996; Ainsworth et al., 2011) (Fig. 5A). This includes depositional environments such as wave-dominated barred lagoons, tide-dominated mixed wave- and tide-influenced estuaries and tide-dominated to tide-influenced deltas.

The vertical organisation of the Nyalau Formation comprises repeating cycles of prograding wave-dominated shoreface successions that are erosively overlain by more tidally-influenced successions (either fluvio-tidal channels and/or estuarine bay facies successions). The erosional surfaces separating the wave-dominated shoreface facies successions from overlying fluvio-tidal channel or estuarine bay facies successions are either in the form of a sharp and flat erosional surface (at the outcrop scale) or a sharp, uneven, concave-upward, coalesced channel scour. The relief of the erosion is small in outcrop (0.5–3 m relief), but the absence of the upper shoreface in most of the coarsening upward, wave-dominated shoreface facies successions suggests the erosion of at least 6 m of deposits. Successive depositional cycles are bounded by flooding surfaces which are associated with thin transgressive lag deposits.

The strong vertical facies partitioning between wave-dominated and tide-influenced deposits is interpreted as reflecting lateral facies partitioning between an inshore (tide-influenced) environment and a shoreline (wave-dominated) environment (Fig. 5B). This facies partitioning also supports a mixed energy coastal depositional model. The coarsening upward, wave-dominated shoreface facies successions are interpreted as representing barrier shoreface environments. A coastal barrier/shoreface system provides a good mechanism for the partition of offshore and inshore processes.

The fluvo-tidal channel facies successions erosively overlying wave-dominated shoreface facies successions in the depositional cycles are interpreted as the fills of fluviolubly-supplied channels which generally flowed perpendicular to the shoreline and cut into the barrier shoreface. The variety of channel-fill types displayed in the fluvo-tidal channel facies successions, ranging from fluvial-dominated, tide-influenced and tide-dominated channel facies associations (FA 5–7), is interpreted as forming a shore perpendicularly reflecting the gradual seaward increase in tidal energy, and the gradual seaward decrease in fluvial influence (Dalrymple and Choi, 2007). Mud-filled variants of the Tide-Dominated Channel Facies Association could equally represent either blind-ended, mud-filled, tide-dominated channels not connected to a fluvial source, or the abandoned seaward reaches of distributary channels. In either case, these channels would cross-cut, and lie adjacent to extensive tidal flats and mangroves of muddy embayments/lagoons in a lower coastal to delta plain setting (Fig. 5C).

The finer grain, estuarine bay facies succession probably represents the fill of low energy, tide-dominated back-barrier environments. Tidal Bar Facies Associations (FA 4) could represent tide-dominated bay-head deltas, or bars in the mouths of tidal distributary channels or ebb and/or flood tidal deltas associated with tidal inlets cutting into the barrier shoreline. There is no independent evidence to distinguish between these options.

The Bay/Subtidal Flat Facies Association (FA 8) represents suspension and lower energy traction deposits (estuarine mud) filling a backbarrier embayment/lagoon and forming the subtidal extension of fringing tidal flats and mangroves.

The above association implies that the tidal range during Nyalau Formation times was meso-tidal (2–4 m). In macrotidal systems (>4 m tidal range) the coastal barrier-shoreface system is usually suppressed (cf. the north German barrier to Elbe-Weser-Jade estuary system). Conversely, there is no evidence of a wave-dominated, microtidal barrier island-lagoon system. In addition, the high volume of fluvial sediment input supports substantial riverine processes and argues against a purely wave-dominated shoreline.

The thick stacks of tide-dominated delta facies successions are restricted only to a single outcrop, which may represent a relatively restricted tide-dominated delta.

The specific interpretation of the depositional cycles depends on the nature of the sharp stratigraphic surfaces separating the wave-dominated shoreface successions from the fluvio-tidal channel and estuarine bay successions.

Two contrasting, end-member depositional models can be considered for the Nyalau Formation. These models need to explain the wave-, tide- and river-generated facies, the partitioning between offshore wave-dominated and inshore tide-influenced successions, and the significant fluvial input. The two end member models are: (1) transgressive, mesotidal, mixed energy wave- and tide-influenced estuary; and (2) regressive, mesotidal, mixed energy wave- and tide-influenced delta.

Progradational wave-dominated shoreface successions can represent a regressive barrier shoreface system (Bernard et al., 1962; Fitzgerald et al., 1992). The interpretation of an estuarine depositional system depends on whether the inshore tidal facies successions represent the product of continued shoreline regression or transgression. Estuaries are drowned river mouths and therefore, overall transgressive in nature, according to the widely accepted definition of Dalrymple et al. (1992). However, it is difficult to determine whether most of the thick fluvio-tidal channel facies successions in the Nyalau Formation display transgressive or...
regressive vertical facies patterns, since many examples comprise thick stacks of a single type of channel facies association. But two examples appear to support a transgressive succession (two thick fluvio-tidal channels at Sungai Mas Entrance, Outcrop Local-ity A, Fig. 3A). The lower succession (between approx. 5 and 18 m log interval) comprises several mud-filled, coal capped tide-dominated channel deposits. Thin (up to 15 cm thick) coaly sandstone lenses with scoured bases at the base of the succession probably represent relict fluvial deposits. These are sharply overlain by transgressive mud-filled tide-dominated channel deposits. The upper fluvio-tidal channel succession (between approx. 28 m log interval until the top of the log) has a thin, erosive basal conglomerate bed with pebbles of assorted composition (sandstone, mudstone and coal fragment clasts), which is then overlain by successive sand-filled, tide-dominated channel deposits. The succession is also interpreted as transgressive, with the basal conglomerate interpreted as fluvial deposits. The sharp vertical facies change thus represent initial progradation of a barrier system, followed by base level fall and erosion, which is then followed by transgression with significant tidal ravinement. A thick
estuarine bay facies succession sharply overlies a wave-dominated shoreface facies succession at Airport Road Stop 1 (Locality D, Fig. 3D). The succession fines upward from a thin tidal bar deposit into thick muddy bay deposits. This succession closely resembles the ideal succession expected in a mixed energy estuary (Dalrymple et al., 1992), with the facies transition reflecting transgression from a tidally reworked bay-head delta into central basin deposits. Similar tidal bay-head deltas are present in the present-day, mixed energy Gironde Estuary (Fenies and Tastet, 1998), where they form elongate, shore perpendicular, tide reworked morphologies. The thick fluvioidal channel and/or estuarine bay succession reflects high rate of transgression coupled with high rate of fluvial supply. This is also consistent with an estuarine model, with the tidal deposits representing the fill of an incised valley.

The abrupt facies change across erosional surfaces that separate Offshore or Lower Shoreface Facies Association (FA 1 or FA 2) from a Tidal Bar, Bay or Channel Facies Association (FA 4–8) could be interpreted as progradational sequences. In such a scenario, the erosional surfaces are interpreted as fluvial to tidal-erosion surfaces associated with coastal progradation, where offshore migrating tidal bars and laterally migrating fluvioidal channels cut into a wave-dominated shoreface (Oomkens, 1974; Swift et al., 1991; Meyer et al., 1998). Areas seaward of the distributary channel mouths were not deeply eroded by tidal currents and preserve a normal wave-dominated shoreline displaying a typical progradational shoreface pattern, as seen in the modern Niger Delta (e.g. Oomkens, 1974). However, the thick multi-storey fluvioidal channel successions are less consistent with a distributary channel interpretation compared with a drowned incised valley. Distributary channel deposits are more commonly single storeyed, due to low rates of accommodation space creation during progradation (Bhattacharya, 2010). In contrast, thick, aggradational multi-storey, tide-influenced channel stacks are more consistent with a transgressive, incised valley fill system, which was still receiving significant fluvial input (an estuary). The interpretation of the thin basal lag deposits as relict fluvial deposits and overlain by increasingly tide-influenced channel deposits, including fining upward estuarine bay successions, is more suggestive of a transgressive, rather than regressive succession.

The lower coastal plain setting of the Nyalau Formation contains fluvial channels that were responding to fluctuations in the rate of accommodation creation, with variable rates of sediment flux and, in their lower reaches, influenced by a mixed-energy shoreline. During the Early Miocene it can be concluded that there were repeated, high frequency periods of coastal progradation and retrogradation, superimposed on longer term periods of retrogradation (Supplementary Fig. 8). Although we discuss two end-member models, there was clearly frequent fluctuation between the two: rivers passing basinwards into tide-influenced distributaries when there was an excess in sediment flux, and periods of coastal retreat retreating resulting from river avulsion, reduced sediment supply or when the rate of sea-level rise exceeded sediment supply. In a shoreline supplied by multiple rivers it is likely that there was extensive along-strike variability in coastal morphology, including linear, lobate and embayed shapes, plus simultaneous coastal progradation and retreat (e.g. as seen in the modern Brunei Bay; Abdul Razak, 2001).

The regional palaeogeographic setting shows the study area to have occupied a broad, embayed setting (Fig. 6). The offshore Balingian Province shows greater fluvial dominance, including deltaic shorelines (Almond et al., 1990), coarser grained sediment within the fluvial channels (Mazlan and Abolins, 1999), mixed fluvial-tidal coastal systems and a paucity of wave-dominated successions (Meor, 2011). Uplifted horst blocks of the West Balingian Line and the Penian High in the northwest margin of the Sarawak Basin was the source of sediments for the offshore deltas. In contrast, the
onshore outcrops seem to represent a part of the Nyalau coastline where fluvial processes were relatively suppressed and where tide and wave processes were relatively enhanced. Hence, the onshore study area may have comprised lower gradient rivers that were draining a lower relief hinterland. The evidence points to multiple rivers, rather than a single river that was capable of building a point-sourced, deltaic shoreline. Wave energy may have been relatively greater towards the north-east, where a more linear shoreline is evident (e.g. Hageman, 1987).

6. Conclusions

A detailed sedimentological study of the Early Miocene, upper Nyalau Formation indicates the presence of a variety of wave-, tide- and fluvial-influenced coastal deposits. The strata form tens of metres thick depositional cycles comprising a coarsening upward, wave-dominated shoreface succession in the lower part, which is sharply overlain by fluvo-tidal channel and/or estuarine bay successions. The strong vertical facies partitioning between wave- and tide-influenced facies is interpreted as representing a coastal/barrier shoreface system, with the wave-dominated shoreface succession representing a prograding barrier, while the fluvo-tidal channel and estuarine bay successions represent inshore, transgressive estuarine deposits. Each of these depositional cycles represent phases or shoreline regression followed by transgression which are bounded by flooding surfaces. The sharp erosive surfaces separating shoreface and estuarine facies in individual regressive-transgressive cycles are interpreted as unconformities.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2012.12.018.

References


