

Palaeoenvironmental interpretation of Late Miocene outcrops (Miri and Seria formations) along Jalan Tutong in Brunei Darussalam

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Abstract: Eleven Neogene outcrops (seven of the Miri Formation and four of the Seria Formation) from Brunei Darussalam are described. Detailed stratigraphic columns are presented with special emphasis on the sedimentary sequences, providing insights into the depositional environments. The rocks are comprised mostly of sandstone, claystone and a mix of both lithologies, and are piled up in cycles of coarsening upward successions, which are here interpreted as parasequences. Most sections are characterized by abundant and diverse sedimentary structures, reworked fossiliferous deposits and organic fragments such as ambers and wood remains. Certain beds are rich in fossils: among the macrofossils, the most common are bivalves, gastropods and followed by fish remains (teeth and otholiths), crustaceans, corals and echinoderms, which are abundant at specific locations. Among the microfossils, the most common are foraminifera, which are mostly dominated by either rotaliids or textulariids; the most common genera are *Ammonia*, *Elphidium* and *Trochammina*. Porcelaneous and planktonic foraminifera are rare. Ostracods are also found. Ichnofossils are quite abundant in all sections but are represented mostly by *Ophiomorpha* and *Thalassinoides*. In view of the observations, the sections are interpreted as evidence of shallow-marine conditions, in which wave, fluvial and tidal actions strongly influenced the depositional environment. In a few cases, deposition of sediment seems to reflect the transition from wave-dominated to tide-dominated conditions. Our findings indicate that in such shallow marine deposits, the interpretation of sediment type and sedimentary structures alone cannot indicate one specific sedimentary environment, but such observations should include palaeontological evidence to generate more accurate palaeoenvironmental reconstructions. Lastly, our results are discussed in relation to the sedimentary evolution of the region.

Keywords: Brunei, Neogene, sedimentology, palaeoenvironment

Abstrak: Sebelas singkapan batuan dari zaman Neogene (tujuh dari Miri Formation and empat dari Seria Formation) di Negara Brunei Darussalam adalah dikaji. Kolum stratigrafik dari singkapan tersebut adalah dijelaskan dan penekanan terhadap urutan anapan untuk memberi pengukuhan kepada tafsiran palaeo-alam sekitar adalah dihuraikan. Singkapan batuan dikaji mengandungi lapisan batu pasir, batu lempung dan batu yang mengandungi campuran kedua-duanya sekali. Batuan juga tersusun dalam kitaran turutan mengasar ke atas ditafsirkan sebagai *parasequences*. Sebahagian besar batuan ini dicirikan dengan limpahan dan kepelbagaian jenis struktur sedimen, mendapan batuan yang mengandungi fosil terkerja semula dan serpihan organik seperti ambar dan sisa kayu. Sebahagian batuan adalah kaya dengan fosil: antaranya adalah makrofosil iaitu bivalves, gastropoda dan sisa-sisa ikan (gigi dan otholit), krustasea, kerang dan echinoderma dari tempat tertentu. Mikrofosil yang biasa dijumpai adalah foraminifera iaitu kebanyakannya rotaliid atau textulariid: *Ammonia*, *Elphidium* dan *Trochammina*. Foraminifera porcelane dan planktonik pula adalah jarang dijumpai. Ostracoda juga dijumpai. Kesan ichnofosil banyak dijumpai di kesemua bahagian batuan tetapi kebanyakannya adalah *Ophiomorpha* dan *Thalassinoides*. Kajian ini menunjukkan tafsiran pengendapan ialah suasana keadaan laut yang cetek, dimana terjejas oleh gelombang air, sungai dan air pasang surut semasa. Dalam beberapa kes, pengendapan sedimen menunjukkan peralihan dari keadaan lautan galombang ke suasana pasang surut. Penemuan kajian menunjukkan untuk endapan laut cetek, tafsiran daripada jenis sedimen dan struktur sedimen sahaja tidak mencukupi untuk memenuhi tafsiran persekitaran sedimen yang spesifik, namun pemerhatian termasuk bukti palaeontologi hendaklah dirangkumi untuk mendapatkan pembinaan semula tafsiran sekitar dengan lebih tepat. Terakhir, kajian ini juga membincangkan kaitan sedimen dengan evolusi sedimen di wilayah ini.

Kata kunci: Brunei, Neogene, sedimentologi, palaeo-alam sekitar

INTRODUCTION

The geology of the Sultanate of Brunei Darussalam has been intensively studied since the sixties, mostly in relation to its hydrocarbon and mineral resources (e.g., Liechti *et al.*, 1960; Wilford, 1961), but much earlier work was done mostly

by the British, German and Dutch geologists who mapped the region (Posewitz, 1892; Molengraaff, 1900; Schmidt, 1901; 1904). They reported on the mineral resources and recorded geological sections, which contained important structural and stratigraphic information, and their interpretations are

still valid today (Cullen, 2014). One of the major challenges faced by the geologists in this region was the lack of fresh rock exposures due to the thick vegetation. Some of the outcrops studied by the early explorers had already disappeared by the 1960s (Wannier *et al.*, 2011). During the last fifty years, the increase in hydrocarbon exploration and production in Brunei has resulted in more studies, on topics including lithostratigraphy (Liechti *et al.*, 1960; Wilford, 1961; Atkinson *et al.*, 1986; Sandal, 1999), biostratigraphy (Back *et al.*, 2005), structural geology (Back *et al.*, 2001; 2008; Morley *et al.*, 2003; Saller & Blake, 2003; Tingay *et al.*, 2005) and petroleum resources (Curiale *et al.*, 2000).

While seismic and well data have provided critical material for geological interpretation at a basin scale, stratigraphic and structural correlations based on outcrop observations still remain a major challenge (Lambiase *et al.*, 2003). The shallow water facies commonly observed in Brunei's outcrops are complex mixtures of deltaic deposits, which have been interpreted by previous workers as the result of riverine, wave and tidal processes. Three major deltaic systems have been recognized along the northern part of Borneo: the Meligan (active during the early Miocene), the Champion (middle Miocene to Pliocene) and the Baram deltas (still active today) (Tate, 1974; Lambiase *et al.*, 2002, 2003; Torres *et al.*, 2011, Rahman *et al.*, 2014; Kessler & Jong, 2015).

Sedimentary sequences produced by such active deltaic systems are often characterized by alternations of sandstone and claystone of several facies types forming parasequences that represent only a portion of a full eustatic cycle. In the region, the parasequences follow a coarsening upward trend from an offshore/prodeltaic claystone unit (e.g., Back *et al.*, 2001) at the base, to a sandstone unit toward the upper part of the sequence, indicating shoreface deposits (characterized by a reduction of the accommodation space). Such patterns are repeated vertically multiple times through a sedimentary sequence along the outcrops, and can have differing compositions due to environmental changes through time.

GEOLOGICAL AND STRATIGRAPHIC SETTINGS

The geology of Brunei is partly associated with the sedimentary record of Borneo Island (Wilford, 1961; Saller & Blake, 2003; Hutchison, 2005). From the Cretaceous to early Tertiary, the Eurasian plate collided with Sundaland to create an accretionary prism. This collision continued in the late Eocene to Miocene, and uplifted the accretionary wedge, resulting in the formation of a mountainous belt known as the Crocker Rajang Mountain belt (outcrops of which can be seen along the border of Sarawak to Kalimantan (Tan & Lamy, 1990). In the early Miocene, these uplifted sediments were eroded, resulting in a high sedimentary supply leading to the formation of huge deltaic systems, which extended into the South China Sea (Back *et al.*, 2005; Collins *et al.*, 2020). The most proximal part of such deltaic deposits in Brunei is represented mainly by the sedimentary succession of the Belait Formation (Lambiase *et al.*, 2003). More distal deposits,

which extend into marginal marine and possibly open shelf settings, are those belonging to the Miri and Seria formations, which outcrop in the western part of Brunei (Eckert, 1970a). The youngest formation is the Liang Formation, which has a fluvial to shoreface palaeoenvironment.

This study discusses eleven outcrops mostly located along Jalan Tutong (Tutong Road) that expose sedimentary deposits from the Miri and Seria formations (*sensu* Wilford, 1961). The study aims to record all sedimentary information collected in the field. and since most previous studies considered only the sedimentological evidence to constrain their palaeoenvironments, we have also included some results obtained from the microfossil assemblages (foraminifera).

Miri Formation

The Miri Formation was deposited during the middle to late Miocene. The sediments outcrop in Brunei in the Tutong District and along the westernmost part of the Brunei-Muara District (Wilford, 1961; Tate, 1974). They are characterized by shallow marine parasequences composed mostly of shoreface sandstones and offshore claystones (Sandal, 1996). The deposits are also relatively rich in fossils such as molluscs, foraminifera, fish remains, pollen and spores, and leaf imprints.

Seria Formation

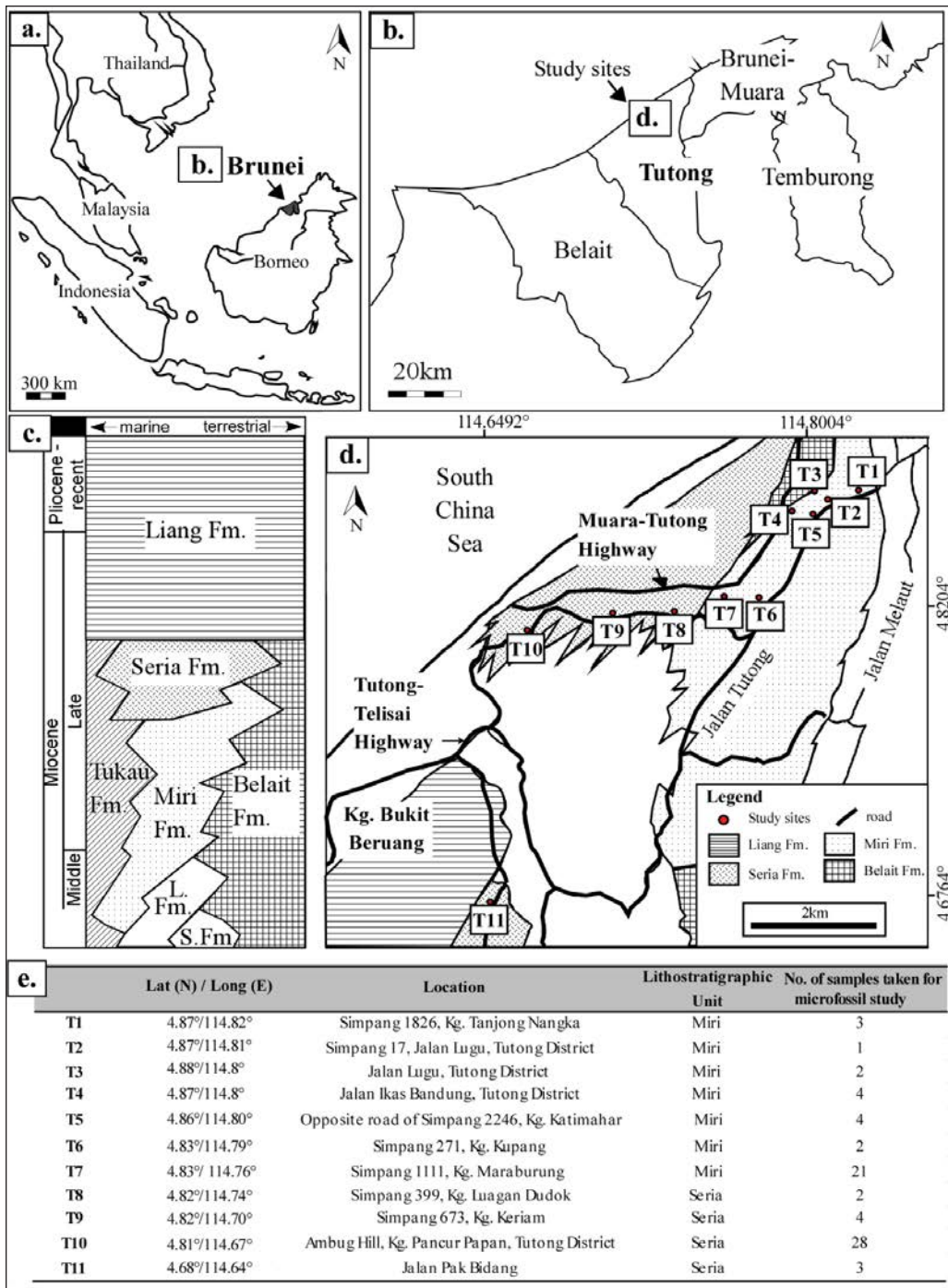
The Seria Formation was deposited during the late Miocene and the outcrops are found along the coastline of the Tutong District and in the north of the Belait District in Brunei. The lithological distribution and sedimentary patterns are similar to those of the Miri Formation, with some of the claystone having high fossil contents, especially at the base of the sequences (Sandal, 1996; Kocsis *et al.*, 2018; 2019; Harzhauser *et al.*, 2018; Roslim *et al.*, 2019). Similar sedimentary environments to the Seria Fm. have been described in the Nyalau Formation in Sarawak (north-northwest Borneo), which includes claystones eroded by sharp crusted beds of thin to moderate thick riverine deposits and sometimes has no claystones preserved in the sedimentary sections (Hassan *et al.*, 2013).

STUDY AREA AND FIELD OBSERVATIONS

Eleven outcrops of the Miri and Seria formations were studied (Figures 1a-e). Some materials on the two outcrops have been already published: the sedimentary sequences of T1 were discussed by Collins *et al.* (2018) and the stratigraphy and palaeontology of T10 were described by Kocsis *et al.* (2018) and Roslim *et al.* (2019), respectively.

Some sites have been investigated for their fossil content e.g., fish remains (Razak, 2017; Razak & Kocsis, 2018; Kocsis *et al.*, 2019) and ambers (Kocsis *et al.*, 2020). For additional references on these sites, refer to Table 1.

At each outcrop, all beds were measured, and the ichnofossils and sedimentary structures were carefully examined and documented.



For the purposes of micropalaeontological investigation, 66 clay samples were wet sieved through 125 and 63 µm mesh sizes and all shells/tests were picked. The microfossils were placed onto aluminium stubs and carbon-coated for examination under a Scanning Electron Microscope (SEM: JOEL JSM-7610F). The identification of the foraminifera was based on Parker (2009), Loeblich & Tappan (1994), and Billman *et al.* (1980). In addition, the mineral compositions of six red sandstone samples and associated nodules were analysed by X-ray diffraction (XRD) (Shimazu XRD 7000).

In most sections, it is possible to recognise coarsening upward sequences characterized by three main facies types, which are commonly known as offshore transition (FA1), lower shoreface (FA2) and upper shoreface (FA3). Similar facies types have been also used in other studies in the region (Back *et al.*, 2001; Hassan *et al.*, 2013, 2016; Collins *et al.*, 2017). Here, the variation from offshore into upper shoreface is visible along the profiles T1, T5, T6, T7, T9, T10 and T11.

In addition, three different facies types are recognised as representing a tidal dominated environment: tidal channel

Table 1: Different names that are used in this study and other palaeontological investigations (Razak, 2017) and ambers (Kocsis *et al.*, 2020).

This work	Location	Razak, 2017	Kocsis <i>et al.</i> , 2020	Roslim <i>et al.</i> , in press
T1	Simpang 1826, Kg. Tanjong Nangka	T1	JT1	S13
T2	Simpang 17, Jalan Lugu, Tutong District	-	-	-
T3	Jalan Lugu, Tutong District	-	-	S11, S12
T4	Jalan Ika Bandung, Tutong District	-	1B	S10
T5	Opposite road of Simpang 2246, Kg. Katimahar	T2	JT2	-
T6	Simpang 271, Kg. Kupang	-	-	-
T7	Simpang 1111, Kg. Maraburung	-	Mar	S8
T8	Simpang 399, Kg. Luagan Dudok	-	GH	S6
T9	Simpang 673, Kg. Keriam	T6	Ker	S5
T10	Ambug Hill, Kg. Pancur Papan, Tutong District	Ambug Hill	AH	Ambug Hill
T11	Jalan Pak Bidang	-	JPB1	S1

(FA4), tidal bar (FA5), and tidal flat (FA6). The tidal conditions were classified and recorded in the following sections or parts of the sections: T1, T2, T3, T4, T8, T10 and T11.

Description and interpretation of measured sections

T1

Description

The profile is 106.5 m thick (Figure 2a) and is characterized by an alternation of sandstone and claystone at different intervals. The first 15 m of section are mostly comprised of sandstones intercalated by dark-grey silt-claystone containing fossil leaves and mud clasts. The sandstone beds contain simple burrows of *Ophiomorpha* and *Thalassinoides*.

The central part of the section (until 62 m) comprises thick, dark-grey and fossiliferous claystone with some thin reddish to brown siderite cemented horizons containing reworked shells of bivalve and broken tubes of *Ditrupa* sp. (Figure 2b). The claystone yields abundant benthic foraminifera such as *Ammonia*, *Nonion*, *Elphidium*, *Criboelphidium*, *Bolivina* and *Ammobaculites*, a few miliolids and one planktonic specimen *Trilobatus* sp. (Figure 10). The claystone gradually changes to cross-bedded, bioturbated sandstones with abundant *Ophiomorpha* (Figure 2c), and a few bivalve moulds. In addition, common features that can be seen are gutter casts (Figure 2d), amber and plant remains.

The last portion of the section is also characterized by a thick claystone gradually changing into thick bioturbated sandstones. The claystone is interbedded with silt-claystone and concretion-rich beds full of fossils, such as molluscs, crabs, fish remains (e.g. otoliths), ostracods and foraminifera (*Ammonia* and *Elphidium*). Poorly preserved and reworked fossils were also found in small amounts at the base of graded coquina beds (Figure 9a, 9b). XRD analyses of the upper layer and matrix of the coquina bed yielded quartz

and siderite (Figure 9c), and the base, along with the fossils, shows quartz, calcite and siderite peaks (Figure 9d).

Interpretation

The entire section has been interpreted as representing four parasequences. The first two sequences differ greatly from the rest of the log and are interpreted as tidal influenced deposition. The rapid sand-clay alternation and the abundance of *Thalassinoides* and *Ophiomorpha* burrows are consistent with this hypothesis (Fiah & Lambiase, 2014). The two sequences are separated by a red crust that represents a period of non-deposition and possible immersion and re-drowning of the system, as has been discussed in connection with other outcrops in the region (Collins *et al.*, 2016; Kocsis *et al.*, 2018; Roslim *et al.*, 2019). The second sequence is interpreted as a tidal channel to tidal bar deposit based on the presence of heterolithic facies characterised by high-angle cross-stratification and flaser bedding.

The rest of the section shows distinctly wave dominated conditions, indicated by the repetitive offshore deposits passing to sandier sediments, capped by thick cross-laminated washed sandstones. This pattern may indicate a regression event or a forced regression, and the process is repeated twice at this locality. The different depositional conditions are further corroborated by the presence of microfossils that indicate open marine conditions, possibly an offshore to lower shoreface environment. The presence of the coquina beds is the result of very efficient proximal distributary systems that rapidly transported material to the offshore, creating fining upward graded horizons with shells at their bases and fine grain sizes towards the top.

T2

Description

This section is 30.3 m thick (Figure 3a) and is composed mainly of bioturbated to weakly-laminated heterolithic

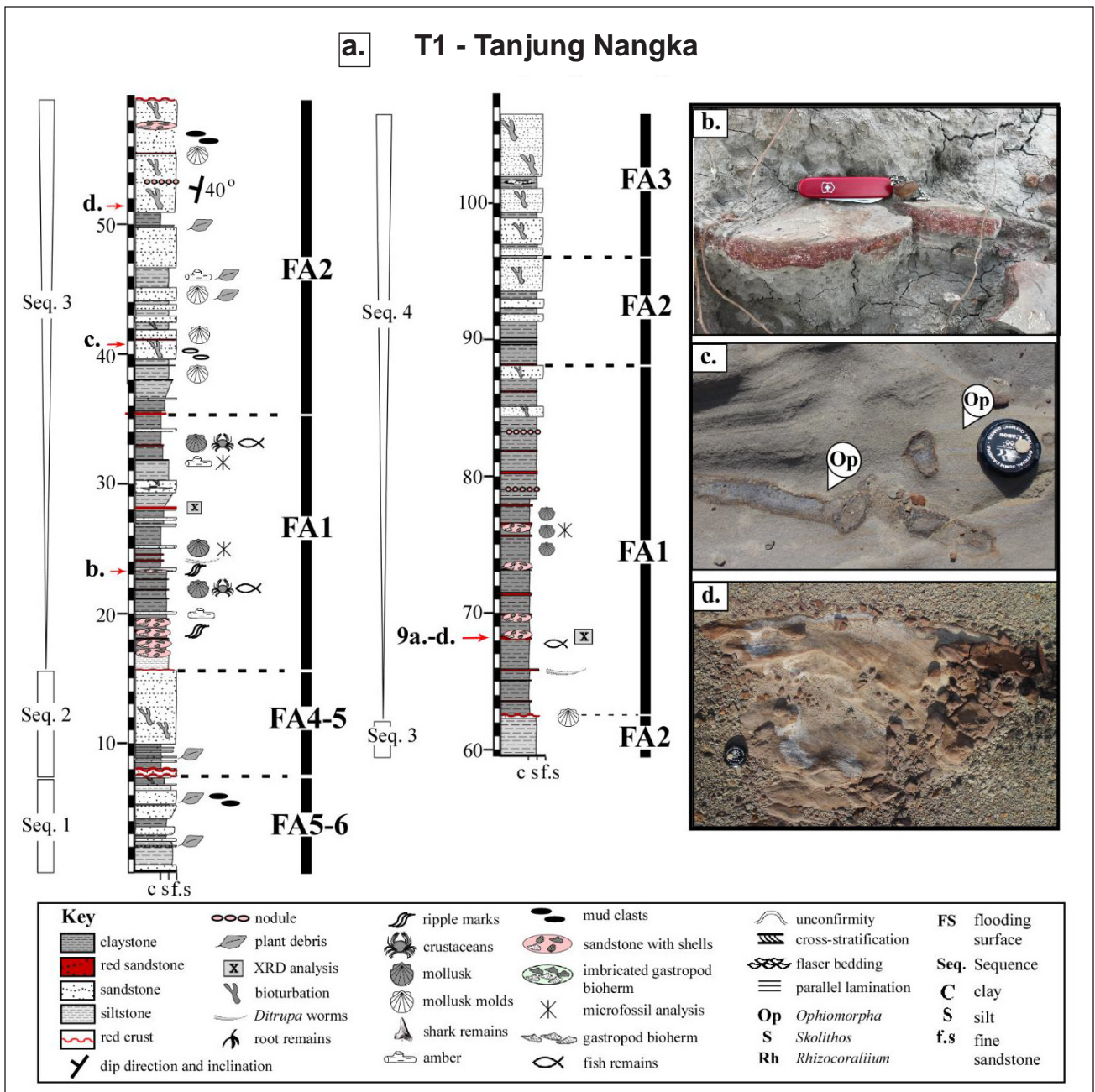


Figure 2: Sedimentary profile of T1 in Tanjung Nangka located in Jalan Tutong, Brunei: (a) Sedimentary profile of T1- Tanjung Nangka, (b) Fossiliferous siderite horizons containing reworked calcareous *Ditrupa* sp. (Serpulidae) worm tubes, (c) Bioturbated sandstones with *Ophiomorpha* assemblages ichnofacies, (d) Gutter cast erosion feature at 51.2 m. Camera lens cap is 5.5 cm in diameter.

clay/siltstone (Figure 3b) and thick wavy-laminated sandstones (Figure 3c) with ripple marks. The most common bioturbation structure found in the sandstone beds is the “box-type” burrow system produced by *Ophiomorpha* (Figure 3d). Poorly preserved flaser bedding (Figure 3e) in the alternating heterolithics can be seen, but it tends to diminish laterally throughout the bed (at 23 m). We recorded no evidence of calcareous macro- and microfossils.

The lower part of the profile is characterized by relatively thick sandstones with moderate bioturbation and

high-angle stratifications. The upper part of this sequence is characterized by a rapid alternation of sand and clay in thin beds (Figure 3f) and small-scale lenses. Mud drapes over fine sandstones are common to abundant and are widely distributed throughout the upper part of the section.

Interpretation

The lower part of the section, with cross-stratified sandstones, is interpreted as an upper shoreface environment, where wave action on the sandy seafloor can hamper biogenic

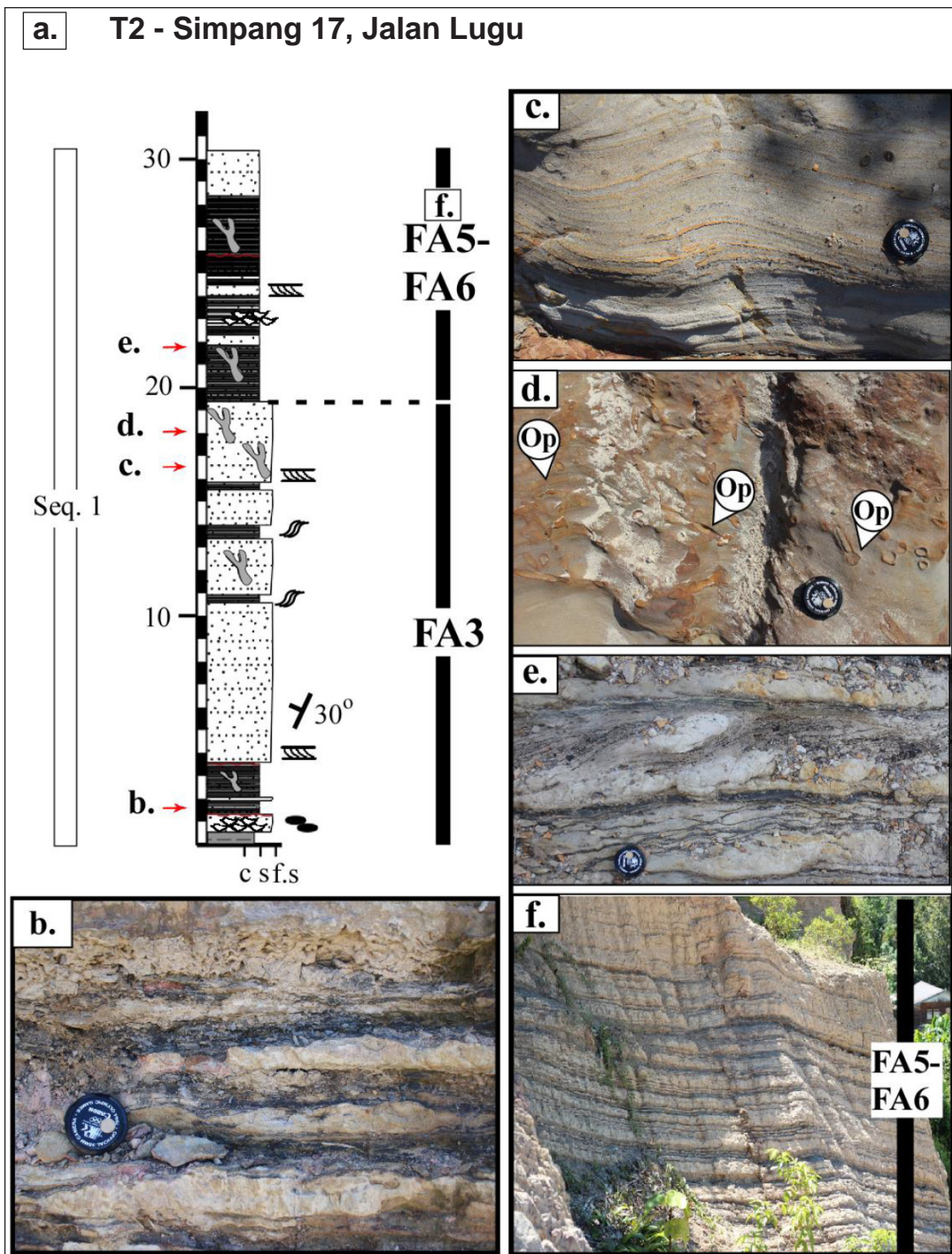


Figure 3: Sedimentary profiles of T2, an exposure from Simpang 17, Jalan Lugu and T3, an outcrop in Jalan Lugu, Brunei: (a) Sedimentary profile of T2 - Simpang 17, Jalan Lugu, (b) Weakly-laminated heterolithics in clay/siltstone at 1.8 m, (c) Thick wavy-laminated sandstones at 16.5 m, (d) Typical "box-type" burrow systems produced by *Ophiomorpha* found in sandstone beds throughout the profile. (e) Poorly preserved flaser bedding in heterolithic clay/siltstone intervals, (f) Extension of tidal deposits shown by continuous oscillation thin beds of coarsening upward alternations.

activity. The upper part of the section is characterized by an oscillation of sandy to clayey beds, common in tidal settings. We interpret the upper deposit as a mixed tidal flat deposit developed above an upper shoreface environment. As

mentioned above, a deposit of this type is possible in shelf edge system tracts and requires the creation of an extended low-lying region sheltered from wave action, so that it can be affected only by tidal influence (Saller & Blake, 2003).

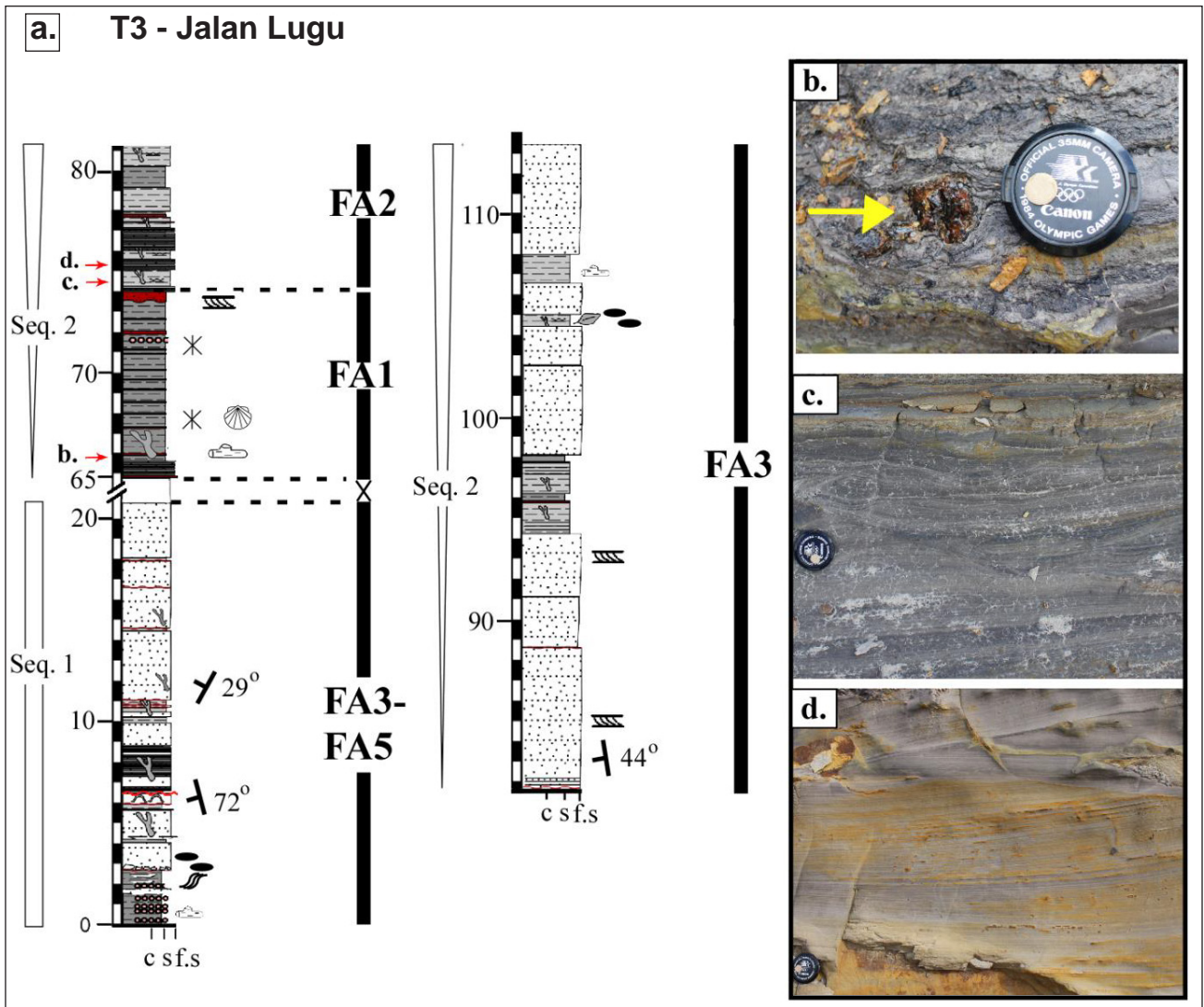


Figure 4: (a) Sedimentary log of T3- Jalan Lugu. (b) Amber intrusion in laminated silty-shale intercalates, (c) Thin, weakly-laminated laminae in silty-shaly mudstone at 74.6 m and, (d) Horizontal to moderately inclined parallel laminated feature in sandstone at 75 m. Camera lens cap is 5.5 cm in diameter.

T3

Description

The section is 113.5 m thick (Figure 4a) with an approximately 43 m gap in the lower part due to vegetation coverage. The lowest portion of the outcrop contains bioturbated, parallel-laminated to wavy-laminated sandstone, with laminated silty-shale intercalations and five concretion-rich intervals. Occasionally, mudclasts and amber fragments (Figure 4b) were identified.

The upper part of the section consists of a succession of offshore clayey deposits to silty-shaly mudstones that are dark to dull grey, and show thin, weakly-laminated beds (Figure 4c). The brown to red fine-grained sandstone bed at 75.2 m is characterized by the presence of horizontal to moderately inclined parallel laminated sets (Figure 4d). This bed passes gradually into sandier sections toward the top of

the profile. Bioturbation consists of only simple *Ophiomorpha* burrows, and the micropalaeontological investigation yielded only agglutinated foraminifera, *Trochammina* sp.

Interpretation

The first part of the section is interpreted as an upper shoreface unit with some beds indicating tidal bar deposits. The latter are marked by an abundance of alternating beds that are full of laminated silty-shale interactions, mud clasts, amber and organic remains. Multiple burrows are present throughout this parasequence. The second unit is interpreted as a complete parasequence with offshore deposits passing into lower to upper shoreface deposits. This interpretation is further supported by the abundance of agglutinated foraminifera of the genus *Trochammina* sp., a common taxon in some sandy, shoreface settings.

T4

Description

The section is 87 m thick (Figure 5a) and begins with thick fossiliferous claystone (Figure 5b) followed by alternating laminated and cemented claystone / siltstone beds. The fossils retrieved include bivalves, gastropods, otoliths, crustaceans, ostracods, foraminifera (*Ammonia* sp., *Elphidium* sp., *Palaeonummulites* sp. and *Ammobaculites* sp.), and disintegrated coal and amber fragments. The upper part of the section is characterized by a frequent alternation of sandstone to sand-claystone beds with rare bioturbation (*Rhizocorallium*) (Figure 5c). The sandstones are characterised by cross stratifications and ripple marks (Figure 5d, 5e).

Interpretation

The lowest part of the profile is characterized by thick claystone deposits and abundant fossil remains, both suggesting an open marine environment, likely in a prodeltaic setting (sensu Renema, 2018; Goeting *et al.*, 2018; Zaini *et al.*, 2020). From 20 m to the end of the profile, the constant alternation of sandstone and claystone

in tidal deposits is interpreted as evidence of a tidal setting with a potential accumulation of tidal bars scoured by tidal channels. Toward the uppermost portion of the sequence, the rippled sandstone beds could be interpreted as thick sand bars in a macrotidal setting.

T5

Description

The section is 60.2 m thick and is generally well exposed (Figure 5f). The first unit of the section (until 19 m) consists of an alternation of two different sediment types: sandy to silty bioturbated sandstone and silty to shaley claystone. The claystone is generally grey and alternates with poorly laminated sandstone beds; when exposed it reveals a flaky appearance. Microfossil findings reveal abundant benthic foraminifera, including different species of the rotaliid genus *Ammonia*, and other genera such as *Nonion*, *Elphidium*, *Bolivina* and *Ammobaculites*. Only one specimen of a poorly preserved planktonic foraminifera species, *Trilobatus* sp. was recovered.

Halfway up the section, thick sandstone beds outcrop with some *Ophiomorpha* burrows and intense cross-stratification. The section continues with thick claystone

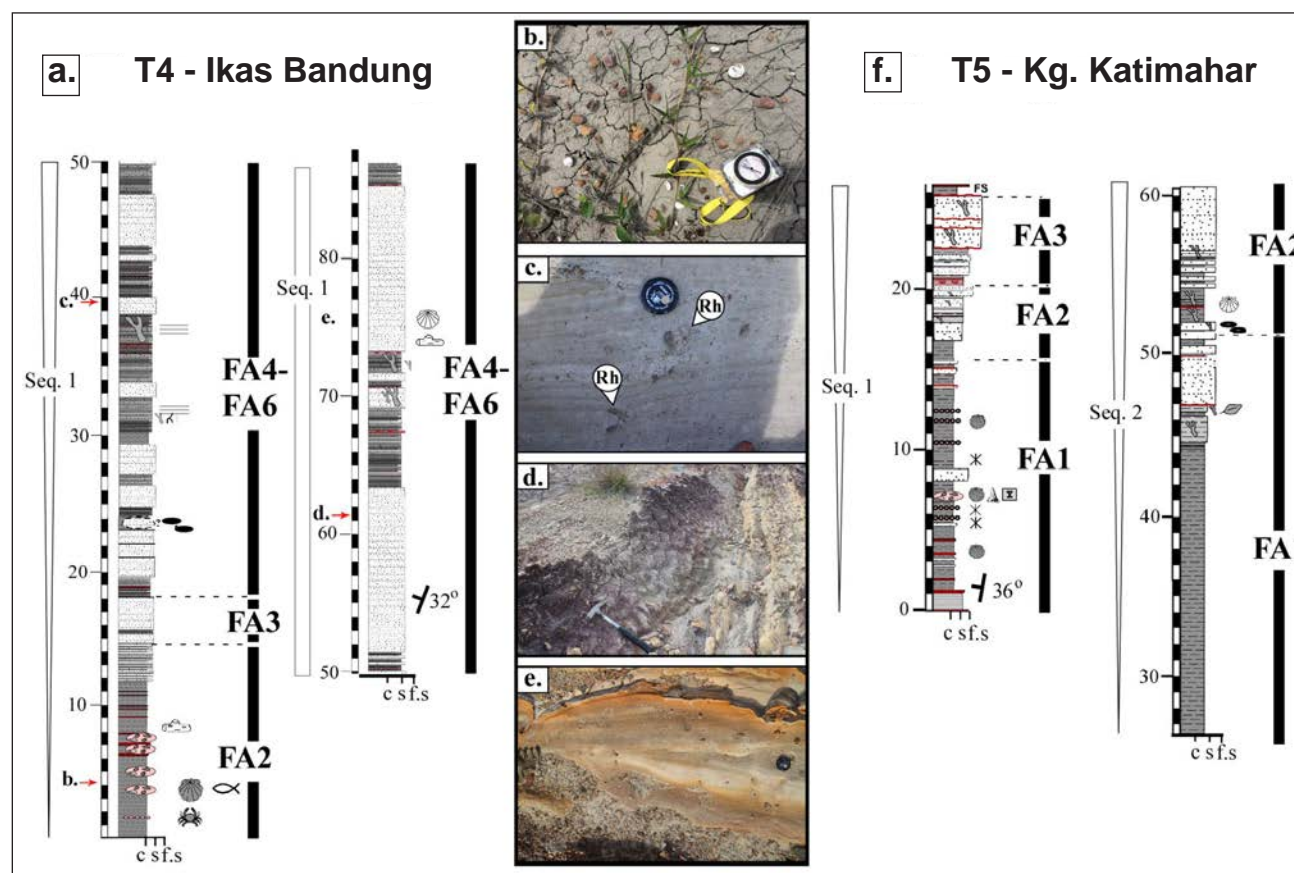


Figure 5: Sedimentary profiles of T4 from Ikas Bandung and T7 from Kg. (Kampung) Katimahar, Brunei: (a) Sedimentary profile of T4 - Ikas Bandung, (b) Fossiliferous claystones common at the beginning of the profile. Here shown is at 4.2 m, (c) Rare *Rhizocorallium* burrow from the *Cruziana* Ichnofacies at 39 m of the profile, (d) Common ripple mark features on thick sandstones at the top, (e) Poorly visible low-angle stratifications commonly alternating in between thick sandstone beds, (f) Sedimentary profile of T5 - Kg. Katimahar. Camera lens cap is 5.5 cm in diameter. Hammer is 30 cm.

and silty-claystone intervals containing very abundant fossil remains, which often appear as coquina accumulations. The macrofauna of such accumulations often contain bivalves and gastropods, but crustacean and fish remains also occur. This assemblage is very similar to those fossil-types previously mentioned in T1 and T4. The uppermost part of the section is characterized by sandstone beds, which are yellow to brown in colour and contain parallel to high-angle laminations with several reactivation surfaces. Very small bioturbation (mostly *Thalassinoides* assemblages) can be spotted among the laminations. Large ichnofossils are limited to complex *Ophiomorpha*, which are common throughout the sandstones in other sections as well.

Interpretation

All the retrieved fossils, the thick clay deposits with thin sandstone beds and the lack of bioturbation indicate open marine conditions. Coquina accumulations point to gravity flows from a more proximal region, as indicated by

the abundant and well-preserved fossils. The lower half of the section is interpreted as a wave dominated parasequence with deposits from offshore conditions that pass to a lower and then an upper shoreface environment. The upper unit of the section is interpreted as a second parasequence composed only of offshore to incipient lower shoreface facies.

Among all the profiles presented here, this is possibly one of the most distal ones, displaying two parasequences, with rather thick claystone accumulations in the offshore setting and relatively thin sandstones in the lower to upper shoreface sections.

T6

Description

The section is 52.5 m thick and is composed mostly of clay and silt, with a few sandstone beds toward the top (last 10 m) (Figure 6a).

The claystone is grey and alternates with weakly-laminated siltstone beds and sharp-based strongly

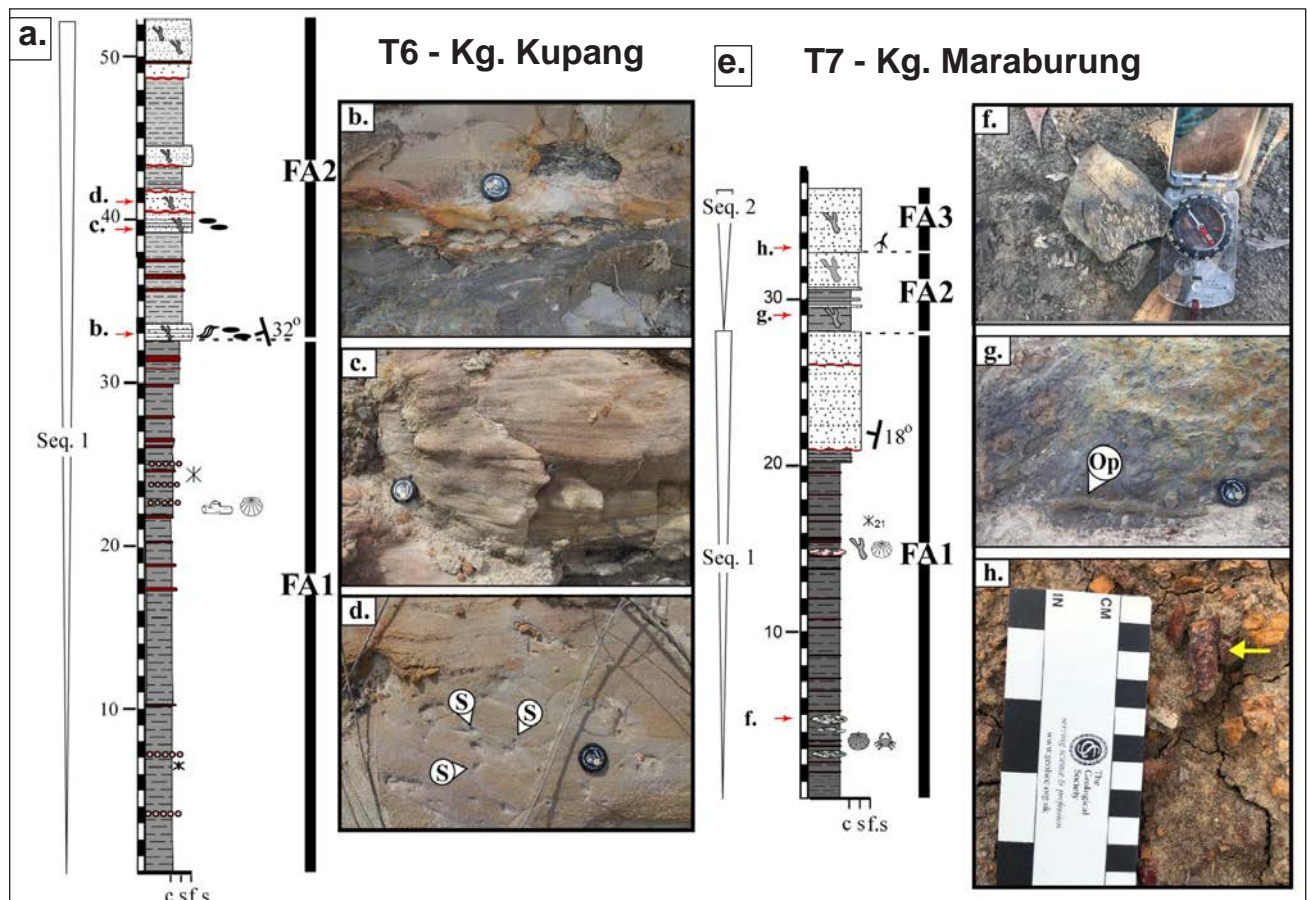


Figure 6: Sedimentary profile of T6, which is an exposure from Kg. (Kampung) Kupang and T7; outcrop from Kg. Maraburung in Brunei: (a) Sedimentary profile of T6 - Kg. Kupang, (b) Laminated sandstone observed at 32.8 m, showing sharp, leached and erosional base contacts, (c) Fine sandstone with parallel laminated features, (d) Rare traces of *Skolithos* assemblages identified in laminated sandstones both at 33.8 -34.5 m and 39.2 - 40 m, (e) Sedimentary profile of T7 - Kg. Maraburung, (f) Coquina bed with abundant small gastropod shells and moulds observed at 4.6 m in the profile, (g) Distinct trace of macro-burrow, most identified are derived from *Ophiomorpha* assemblages seen at 39 m, (h) Red and oxidized sporadic root cast observed in between the contact within the sandstone at 33. Root is about 2 cm long. Camera lens cap is 5.5 cm in diameter.

laminated sandstone beds with thickness ranges from 10 cm to 1 m.

The sandstone beds are darker brown to reddish and tend to possess sharp, erosional base contacts (shown by leached intervals). Near such contacts, coal remains, pebble scours (Figure 6b) and traction carpets are often visible, which then normally grade into a fine-grained sandstone with parallel laminations (Figure 6c). Bioturbation by *Ophiomorpha* and rare *Skolithos* are generally identified within the fine sandstone beds (Figure 6d). The faunal content retrieved from the clay is very scarce compared to other fossil sites (e.g., T5), and is dominated by agglutinated foraminifera (e.g., *Ammobaculites*). No other foraminifera types are present.

Interpretation

The entire profile has been interpreted as a parasequence that starts from a proximal offshore setting and tops within a lower shoreface environment. The pebble trace through the section is an indicator of prodeltaic settings and the proximity of a delta.

The pebble scours and the traction carpet deposits are interpreted as dense and coarse gravity flows deposited into the offshore transitions, as the result of high-energy events. The ichnofossils are rare and also indicate a high-energy depositional environment, as is expected in a prodeltaic (delta front) area. The relatively high-energy environment creates less than optimal conditions for certain foraminifera that normally thrive in an offshore setting e.g., calcareous benthic foraminifera; these types have not been found here. *Ammobaculites* is a genus that can occur in paralic to marine settings and traditionally resides on sandy seafloors. The lack of other taxa might be explained by a low preservation potential and / or sampling bias.

T7

Description

The section is 36.5 m thick (Figure 6e) and is composed mainly of fossiliferous, weakly laminated claystone and strongly laminated sandstone beds, especially toward the top of the exposure. At 4.5 m, we have identified one cemented fossil-rich bed (coquina) with a high abundance of small gastropod shells and moulds (Figure 6f). Other coquina beds reveal similar findings to those referred to in the other profiles.

Some of the retrieved macro- and micro-forms are small gastropods, small bivalves, ostracods, shelly fragments, bryozoans, crustaceans, and foraminifera. The latter are listed in the order of highest abundance: *Ammonia* (different morpho-types) and *Elphidium* followed by *Nonion*, *Bolivina*, *Cibicides* and the agglutinated genera *Ammobaculites* and *Trochammina* (Figure 10).

The upper portion of the section (Seq. 2) consists of laminated to micro-bioturbated siltstone to macro-bioturbated sandstone intervals. Micro-bioturbation is poorly preserved, whereas macro-burrows have been identified as

Ophiomorpha (Figure 6g).

Additionally, sporadic root casts that are red in colour due to oxidation can generally be identified at the erosive contact within the sandstone (Figure 6h).

Interpretation

The thick clay and the diverse foraminifera assemblages point to open marine conditions with only minor indications of nearby deltaic activity. The coquina beds and laminated limestones still indicate a delta front depositional environment.

Considering the entire section, we interpret this as a partial parasequence composed of an offshore section (the fossiliferous portion) and a small portion of a lower shoreface to upper shoreface unit. It is plausible that, within the thick sandstones at 25 m, an erosional surface occurs indicating the incipient beginning of a new parasequence, which recorded only the lower shoreface environment and a small part of the upper shoreface.

T8

Description

The section is 29.5 m thick (Figure 7a) and contains a combination of often cross-stratified fine to medium-grained sandstone for the first 10 m, which is capped by a few flaky intercalated claystone intervals (Figure 7b) with flaser bedding.

Upwards, the sandstones are yellowish brown to orange-red and are relatively barren of ichnofossils, except for one specimen of *Ophiomorpha*, which appears as a long vertical burrow of (Figure 7c), and very rare fragments of bivalves. The sandstones also display low-angle trough crossbedding, and convex foreset laminae with spoon-shaped bottom surfaces (Figure 7d).

Interpretation

The occurrence of multiple sandy sequences with cross-stratifications indicates an upper shoreface setting with high energy and a high sedimentation rate. This passes gradually into a tidal influenced environment, with extended mixed sand and mud beds with some flaser bedding. The relatively high abundance of clay in the tidal sequence may indicate a muddy tidal flat setting with the appearance of sandy tide bars only at sporadic intervals. Body fossils (bivalves) and small amounts of bioturbation are visible only toward the top of the section, indicating restricted or stressed conditions in the lower portion of the section.

T9

Description

The section is 16 m thick and comprises two clay units, one at the base and one at the top; the middle part of the section is characterized by a 3 m thick sandier unit (Figure 7e).

The lower clay beds are very similar to the claystones in other profiles: rather fossiliferous and composed of an alternation of fine laminated siltstones. The claystone is

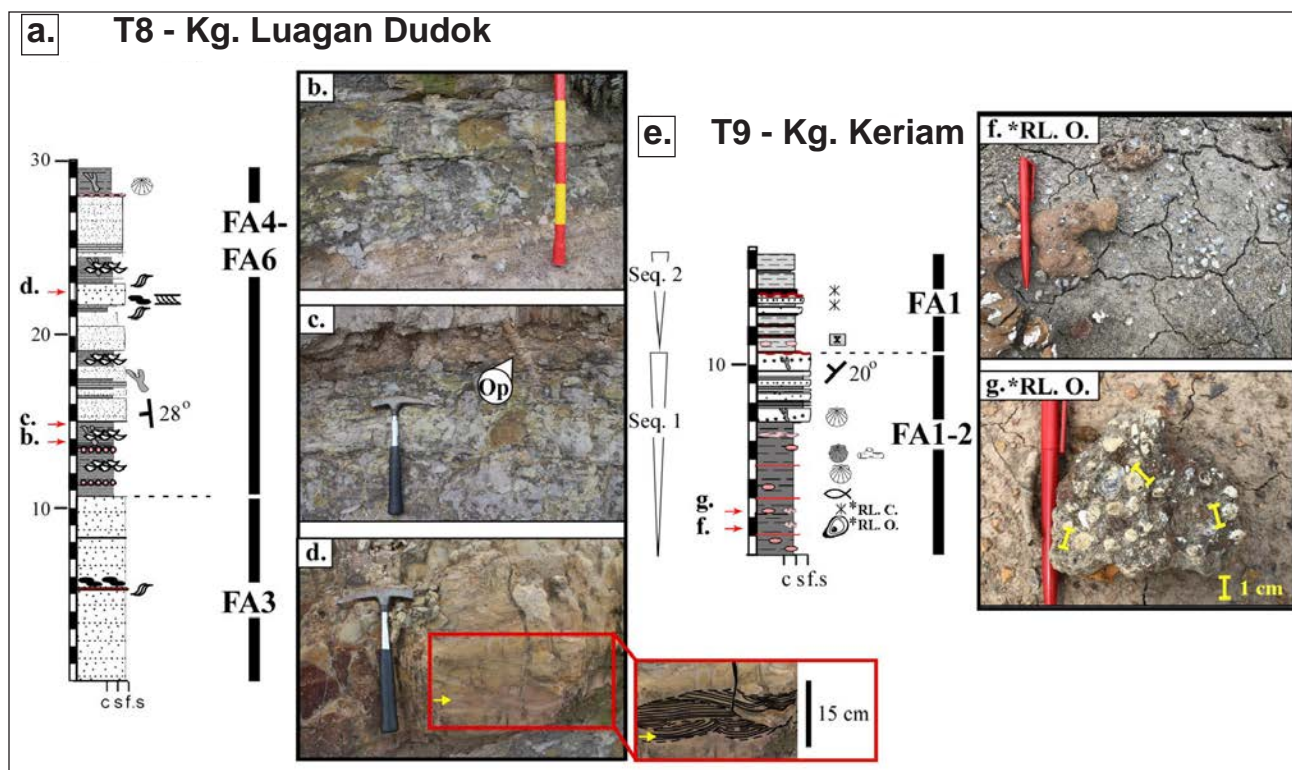


Figure 7: Sedimentary profile of T8, an outcrop from Kg. Luagan Dudok and T9: from Kg. Keriam, Brunei: (a) Sedimentary profile of T8 - Kg. Luagan Dudok, (b) Flaky claystone intervals observed at 13.8 m, (c) Very deep rare burrow imprint found and been identified to have been produced by *Ophiomorpha* assemblages, (d) Sandstones with low-angle trough crossbedding, convex foreset laminae with spoon-shaped bottom surfaces observed at 22.5 m, (e) Sedimentary profile of T9 - Kg. Keriam, (f) Coquina bed at 1.5 m rich in oysters and, (g) Coquina bed at 2.2 m yielding abundant solitary stony coral of *Heterocyathus* sp. Hammer is 30 cm and pen is 14 cm.

dark to dull grey, and at times it appears thicker instead of alternating with silty beds. Mud-rich intervals with several fossil-rich red concretion beds occur throughout this section; at 1.5 m there is a level exceptionally rich in oysters (Figure 7f), and another at 2.2 m yields abundant solitary stony corals, identified as *Heterocyathus* sp. (Figure 7g).

Foraminifera found in this part of the profile include *Ammonia* sp., *Nonion commune*, *Elphidium craticulatum*, *Asterorotalia* sp., and *Ammobaculites agglutinans* (Figure 10). No planktonic foraminifera have been recovered.

The middle portion of the section contains occasional nodules and some bioturbated, low-angle laminated sandstone beds. These are separated from the rest of the section by an erosional contact at 10.5 m. Here, the section is dominated by silty clay deposits, nodules and thin laminated sandstone beds. No fossil remains were recovered from this uppermost part. One of the red nodular horizons was tested for mineralogical composition with XRD, which revealed the presence of siderite (Figure 9e, 9f).

Interpretation

The section is interpreted as two incomplete parasequences separated by a sequence boundary,

identified as an erosional surface at 10.5 m. The lower sequence was deposited under incipient shallow offshore to lower shoreface conditions, identified by the thick clay accumulation with abundant coquina beds and the diversified fossil assemblage. This assemblage and the thickness of the clay are typical of prodeltaic environments, as has been observed by Ho (1971). In addition, the red beds whose occurrence was noted above can be regarded as event beds caused by low-energy gravitational flow from shallower areas (Atkinson *et al.*, 1986), in a similar manner to other prodeltaic deposits (e.g., T1, Sequence 2 of T3, T4, T5, T6, T7, T9, T10 and T11). The second sequence appears to start from a proximal lower shoreface environment. However, the lack of fossils in the silty clay beds at the top might indicate that there were preservation issues in the depositional environment.

T10

The sedimentary section (Figures 8a, 8b) reported here has already been presented and discussed by Kocsis *et al.* (2018). The section has been divided into four parasequences. For a detailed description the reader can refer to Roslim *et al.* (2019) and Kocsis *et al.* (2019, 2020), which contain extensive data on the fossil content of the section. The

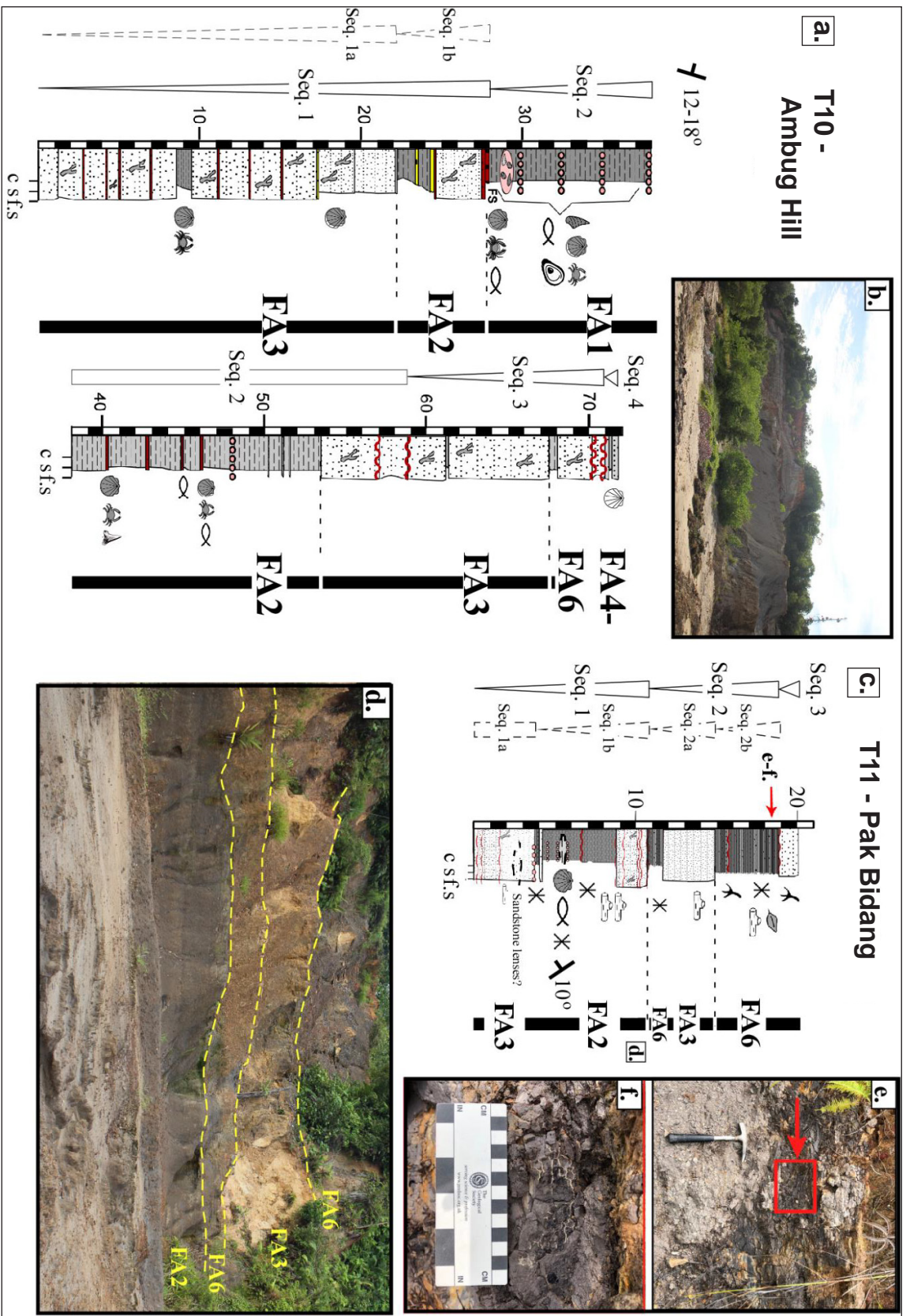


Figure 8: Sedimentary profiles of T10 from Ambug Hill and T11 from Pak Bidang in Brunnei. (a) Sedimentary profile of T10 - Ambug Hill, which was already been presented and discussed by Kocsis *et al.*, (2018). The profile has been divided into four sequence. For a detailed description, reader can also refer to Roslim *et al.* (2019), which has extended data also regarding the fossil content of part of the section. (b) Outcrop picture of Ambug Hill. (c) Sedimentary profile of T11 - Pak Bidang representing the last sequences of the Seria Formation. (d) Outcrop picture of Pak Bidang outcrop. (e) Poorly preserved plant imprint features identified at 18.4 m. (f) Close-up view of plant remain in heterolithic clay/siltstone deposit at 18.4 m of the profile. Hammer is 30 cm.

diversity of fossils retrieved here is unprecedented in all the sections. Unfortunately, the locality has been intensively worked to extract clay for building purposes. The outcrop was visible until 2017 but has now drastically changed due to construction work. The thick claystone in Seq. 2 has been removed and the uppermost sandstone bed (Seq. 3-4) is no longer reachable.

T11

Description

This is the only outcrop that is not located along Jalan Tutong. It is situated west of the other sites along the Jalan Pak Bidang, at the base of the Lumut Hills. It is likely the latest sequence of the Seria Formation. The section is 20 m thick (Figures 8c, 8d) and consists predominantly of an alternation of thin sandstone and claystone deposits. At the base, silt and fine, bioturbated sandstone occur with mollusc and amber fragments. This is followed by the thickest claystone in the profile (between 3.3 m to 7 m). The claystone is rich in fossils such as bivalves, fish remains, gastropods, ostracods and foraminifera. The microfauna shows low diversity, with *Ammonia* sp. dominant (Figure 10). At 10.8 m, an erosional surface with some reworked marine fossils occurs. Above this, a series of thin alternating sandstones and claystones occurs with interbedded thick laminated sandstones at ~12 – 14 m. The lamination in the sandstone is poorly preserved, possibly due to intense bioturbation, and in some beds plant imprints are identified (Figures 8e, 8f). At the top of the profile a very leached sandstone bed was observed.

Interpretation

The first parasequence represents a proximal marine environment with both thick beds of sandstones, and thick sequences of claystones present. This interpretation is supported by the microfossil assemblage dominated by the taxon *Ammonia* spp. and the low diversity of foraminifera, indicating restricted marine conditions in a proximal region, perhaps in a protected lower shoreface setting occasionally interrupted by intertidal inputs. Moreover, the occurrence of thick, structureless clay units and the presence of bony fish, shark and foraminifera remains, together with ambers and organic-rich deposits, indicate a mixed marine and tidal environment. Simmons *et al.* (1999) interpret such combined assemblages as characteristic of lower shoreface conditions. The erosional surface at 10.8 m marks the beginning of a new parasequence. Here, the alternation of thin sandstone and claystone beds, and abundant plant remains, indicate more proximal conditions with a stronger tidal influence.

DISCUSSION

Depositional setting

All the deposits investigated show evidence of a shallow water setting. This is confirmed by several studies in the region that point to complex deltaic systems, in which the

deposits are influenced by the combined action of river, waves and tides (e.g., Lambiase *et al.*, 2003; Hassan *et al.*, 2013; Collins *et al.*, 2018; Collins *et al.*, 2020).

The dynamics of deltas have also been investigated recently (Collins *et al.*, 2017; 2020), with the goal of understanding the way they accumulate such large amounts of sediments within relatively short periods of time. One major advance in the understanding of such thick deposits has been made by Liu *et al.* (2016), who conclude that the so-called “source-to-sink” effect will be the key to solving this issue. This effect occurs whenever a very efficient delta can transport and distribute sediments directly onto the continental shelf and then onto the abyssal plain, bypassing all the intermediate zones. Thus, the sediment passes directly from its source (the delta) into its final sink. This bypass system may be enhanced by intense weathering, increased tectonic uplift and unconsolidated lithologies (Liu *et al.*, 2016).

The major difference observed in the depositional environment here is that the strongest force acting on the sediments is either waves or tides.

Wave dominated environments (FA1 – FA2 – FA3)

Wave-dominated deposits are very common in our study areas. In shallow offshore settings (i.e., FA1), the seafloor is constantly affected by the bypass or deposition of fine sediments that happens during prograding stages; laminated stratifications, cross bedding and sharp-based sandstones are common and increase in abundance toward the beginning of the FA2 facies. Some of the FA2 in outcrops investigated here, are characterized by normally graded beds resulting from gravity flows. This is especially visible along the T1 and T5 outcrops, where some of the beds display a fining upward gradation, whereas in others the upper portions of the bed contain coquina concretions of molluscs fragments formed by proximal to distal periodic gravity flows, which deposit shallower sediments containing highly diverse fauna (Atkinson *et al.*, 1986). Such deposits indicate an increased instability of the delta due to whether incipient progradation or a sudden reduction of the accommodation space on the delta front. If progradation continues, the entire system develops into a coarsening and shallowing upward gradation influenced more strongly by wave action on the seafloor. This is visible in the increased occurrence of sedimentary structures e.g., ripple marks or cross-stratifications, preserved in the sandstone beds (Figures 2-10).

A further difference is seen in the abundance and diversity of ichnofossils. Fiah & Lambiase (2014) have already described those differences, and the data reported here confirms their conclusions: a higher diversity and lower abundance of ichnofossils occurs in deeper environments.

Tide-dominated environments

Tidal flats are stratigraphically controlled by active deltas at the end of the highstand. When the delta front has

migrated extensively over the shelf, the most proximal region becomes extremely flat and protected from wave action. As a result, all particles are moved and sorted only by deltaic activity and tidal currents, thus creating an alternation of coarse and finer sediments (Saller & Blake, 2003).

Tide-dominated deposits are characterized by an extremely large amount of cross bedding, and a more or less constant repetition of very thin beds with alternations of sand and clay lithotypes. The only observations that can help in discriminating different tidal facies and determining their distribution over environmental gradients (i.e., distance from the riverine input) are the diversity and abundance of sedimentary structures and ichnofossil assemblages. Both have been largely used over the years for this very purpose, with excellent results (e.g., Fiah & Lambiase, 2014; Melnyk & Gingras, 2019). In this study, the fine alternation of sandy to clayey deposits testifies to the presence of three different facies: tidal channels (FA4), tidal flats (which can be muddy or sandy) (FA5) and tidal bars (FA6). The differences among these three facies types are mostly the types of sedimentary structures and the amount of clay and sand in the beds. Tidal channels are commonly characterized by channel shaped geometries, cross bedding and heterolithic inclined stratification, which may include a scoured base and a fining upward gradation. Tidal bars have coarsening upward gradations and may show flaser beddings and possible inclined stratifications. Tidal flats can generate both sandy and muddy beds and in some studies are differentiated into mud flats and sand flats. However, all have a large variety of sedimentary structures, such as mud drapes, ripple marks and gutter casts; rarely are they structureless mudstones.

In this study, the tidal-influenced deposits exposed in the outcrops from T1, T2, T3, T4, T8, T10 and T11 indicate that the sections have been developed partly during a period of reduced accommodation space.

Micropalaeontology

The microfauna retrieved from several samples studied in this work is relatively rich in both textulariid and rotaliid foraminifera. This indicates deltaic influence in mixotrophic to eutrophic conditions. This is particularly important for outcrops in a wave-dominated environment, where calcareous fossils indicate holomarine conditions. The most common genus is *Ammonia*, which prefers an inner to middle neritic zone and is well adapted to eutrophic conditions and to the stress of a prodeltaic setting (Novak & Renema, 2018). In Malaysia, similar rotaliids (e.g. *Ammonia aomoriensis*, *A. beccarii*, *A. tepida* and *A. papillosa*) have been reported from muddy deltas no deeper than 60 m (Ho, 1971; Lambert, 2003; Faiz *et al.*, 2016). The lack of planktonic foraminifera for all investigated samples rules out deeper waters, even in offshore transition environments, and points to depths shallower than 60 m.

Outcrops barren in foraminifera (e.g., T2, T3, T6, T8) can either represent stressed depositional environments with high sedimentation rates and wave winnowing (Atkinson *et al.*, 1986; Collins *et al.*, 2017), or suggest that diagenesis and dissolution have destroyed them, as has been proposed in previous studies of the region (Wilford, 1961; Sandal, 1996).

CONCLUSION

In this work, we have combined sedimentological evidence and micropalaeontological findings to determine the palaeo depositional settings of the sequences. We conclude that it is crucial to consider the micropalaeontological evidence together with the sedimentological data when the palaeoenvironment oscillates from shallow marine to tidal. The interpretation of sedimentary structures alone can be misleading, if all the evidence is not considered.

From our data, we conclude that the palaeo environments were highly variable, as the type deposits can change from open marine, and thus affected by wave action, to more proximal, and therefore sheltered from wave action but exposed to tidal movements. All the outcrops presented here, from T1 to T11 can be stacked vertically in a virtual sequence, as they represent tiny portions of the entire sedimentary succession that extends from the Brunei-Muara district into the Tutong district (for a total thickness of around 15 km). Previous studies of the Miri and Seria formations (Tate, 1974) tend to make distinctions based on the intensity of marine conditions in the sequences: sandier deposits dominate in the Miri Formation, whereas muddier and siltier deposits dominate in the Seria Formation. Based on our findings, we cannot confirm this difference. Further lithostratigraphic studies need to be done to define both formations in detail. However, neither sedimentological differences nor palaeontological ones seem to be discriminatory so far, at least at the scale of a single outcrop.

What is a novel aspect of this study is that the micropalaeontological investigation of the claystone beds can yield information essential for improved palaeoenvironmental interpretations. It is hoped that further studies will include micropalaeontological investigation, so as to constrain the biostratigraphic boundaries of the deposits under study.

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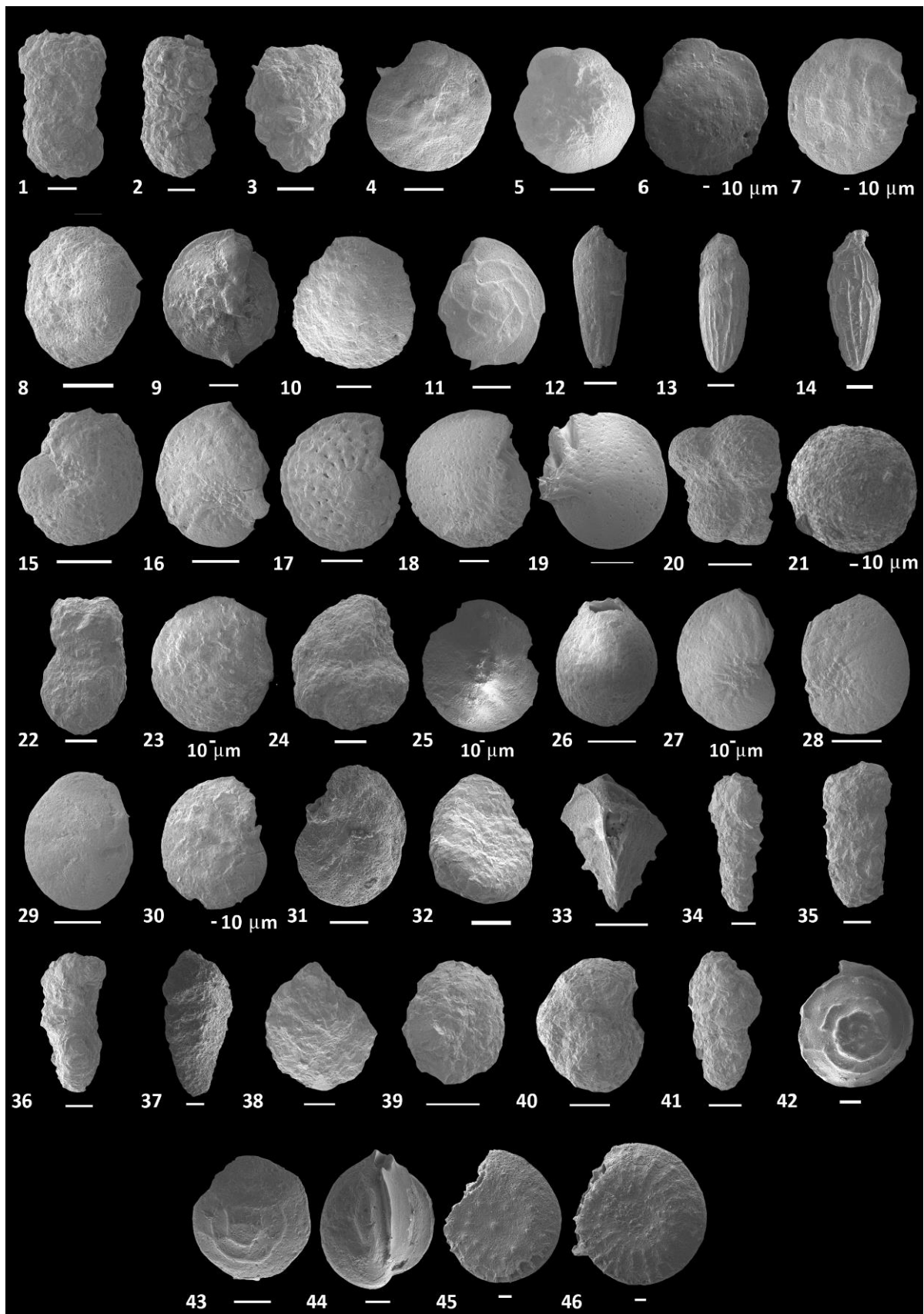


Figure 10: Documentation of foraminifera with SEM imaging and their occurrences listed in brackets. 1. *Ammobaculites agglutinans* (d'Orbigny, 1846) (T1, T3, T4, T5, T6, T7, T9, T10, T11), 2. *Ammobaculites* sp. 1 (T1, T3, T4, T5, T7, T9, T10, T11), 3. *Ammobaculites*

sp. 2 (T1, T5, T7, T9, T10, T11), 4. *Ammonia beccarii* (Linnaeus, 1758) (T1, T4, T5, T7, T9, T10, T11), 5. *Ammonia* spp. (T1, T4, T5, T7, T9, T10, T11), 6. *Ammonia takanabensis* (Ishizaki, 1948) (T1, T5), 7. *Ammonia umbonata* (Le Roy, 1944) (T1, T5, T7, T9), 8. *Asterorotalia concinna* (Millett, 1904) (T1, T5), 9. *Asterorotalia dentata* (Parker & Jones, 1865) (T1, T5), 10. *Asterorotalia* sp. (T1, T5), 11. *Asterorotalia yabei* (Ishizaki, 1943) (T1, T5, T7, T9), 12. *Bolivina* cf. *B. fastigia* Cushman, 1936 (T5, T7), 13. *Bolivina rukasi* Hussey, 1950 (T4, T5, T10), 14. *Bolivina striatula* Cushman, 1922 (T5, T10), 15. *Elphidiella* sp. 1 (T5, T7, T9), 16. *Elphidiella* sp. 2 (T5, T10), 17. *Elphidium advenum* (Cushman, 1922) (T1, T5, T10), 18. *Elphidium craticulatum* (Fichtel & Moll, 1798) (T1, T4, T5, T10), 19. *Criboelphidium excavatum* (Terquem, 1875) (T1, T5, T10), 20. *Trilobigerina* sp. (T5, T10), 21. *Gyroidinoides venezuelana* Renz, 1948 (T5, T10), 22. *Haplophragmoides* sp. (T1, T5, T10), 23. *Hanzawaia boueana* (d'Orbigny, 1846) (T1, T5), 24. *Heterolepa* sp. (T1), 25. *Karriella microgranulosa* Graham, de Klasz & Rerat, 1965 (T1), 26. *Lagena* sp. (T1, T5, T10), 27. *Nonion commune* (d'Orbigny, 1846) (T5, T7, T10, T11), 28. *Nonion incisum* (Cushman, 1926) (T1, T5, T10), 29. *Nonionellina labradorica* (Dawson, 1860) (T1, T5, T7), 30. *Nonionellina* sp. (T1, T5, T10), 31. *Pseudorotalia indopacifica* (Thalman, 1935) (T5), 32. *Polystomamina* sp. (T1, T5), 33. *Reussella spinulosa* (Reuss, 1850) (T1, T4, T5, T7, T10), 34. *Reophax* sp (T1, T4, T5, T7, T9, T10), 35. *Textularia* sp. 1 (T1, T4, T5, T9, T10), 36. *Textularia* sp. 2 (T5, T9), 37. *Textularia* sp. 3 (T2, T5), 38. *Trochammina* sp. 1 (T1, T3, T4, T5, T6, T7, T9, T10, T11), 39. *Trochammina* sp. 2 (T5, T7), 40. *Trochammina inflata* (Montagu, 1808) (T5, T7, T11), 41. *Valvulina flexilis* Cushman & Renz, 1941 (T1, T4, T5, T7), 42. *Ammonia* sp. 1 (T4, T5), 43. *Ammonia* cf. *A. umbonata* (Le Roy, 1944) (T2, T4), 44. *Quinqueloculina* sp. (T4, T5, T10), 45. *Palaeonummulites* sp. (T1, T4, T5, T10), 46. *Operculina ammonoids* (Gronovius, 1781) (T1, T4, T10).

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