The power of palaeocurrents: Reconstructing the palaeogeography and sediment flux patterns of the Miocene Sandakan Formation in eastern Sabah

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ABSTRACT

Up until now the use of palaeocurrents as a primary tool in establishing regional palaeogeography and sediment dispersal patterns in the ancient has been limited. An outcrop study on the Miocene Sandakan Formation in eastern Sabah identified five facies belts, subdivided on the basis of sedimentological and palaeontological data. More than 140 outcrop sections were measured over an area covering approximately 200 square kilometres. The facies were interpreted to have been deposited in settings ranging from ancient mangrove deposits through shoreface sediments and out into the open marine.

More than 200 palaeocurrent readings taken on these facies allowed a clear picture to be built up of the sediment dispersion patterns across the palaeo-Sandakan Basin, passing from northward directed flow through mangrove channels into a longshore drift dominated shallow marine, coastal shelf. This gave way northwards to a storm dominated belt of tempestite deposits cut by rip current channels. Flow through these channels, driven by frequent storms, was northward directed. Further to the north more quiescent, open marine, muddy conditions prevailed. A sediment budget can be estimated using the sand fraction of the various lithofacies identified during the study.

INTRODUCTION

Collision of a series of southward-moving microcontinents with the northern Borneo margin in the early Miocene led to Sabah undergoing compressive stress, uplifting the Eocene-Oligocene deposits of the Central Sabah Basin. Contemporaneous seafloor spreading in the Sulu Sea, to the east, rejuvenated the Basin, and formed a series of fault-controlled basins, trending NW-SE across eastern Sabah, in which relatively shallow marine to paralic sediments were deposited.

One of these basins is particularly well exposed on the Sandakan Peninsular in eastern Sabah (Figure 1), where the Sandakan Formation outcrops sporadically over an area of 200 km2. More than 140 sedimentological sections (Figure 2) have been logged through sediments interpreted to have been deposited in a paralic to marine setting. Five lithofacies associations have been defined based on their sedimentological and palaeontological character: mangrove; tidally dominated flats and occasional tidal channels; stacked, upper shoreface sandstone beds; rip current dominated, heterolithic, middle shoreface deposits; and lower shoreface to open marine mudstone beds with thin, ironstone cemented siltstone beds.

A series of more than 200 palaeocurrent measurements were taken from outcrops across the Sandakan Peninsula. Combined with several occurrences of the basal contact of the Sandakan formation with underlying basement volcanics, it was possible to reconstruct a detailed picture of the palaeogeography and sediment dispersal patterns across the basin.

GEOLOGICAL EVOLUTION OF EASTERN SABAH

Sabah is thought to be floored by crystalline basement and associated ophiolitic rocks (Clennell 1992). These may represent uplifted slices of the continental crust underlying Borneo (Leong 1974, Holt 1998). Overlying the basement is the Rajang Group representing a North-facing accretionary prism (Hamilton 1979, Bol and Hoorn 1980, Bénard et al. 1990, Hutchison 1996) comprising mainly turbidites of the Trusmadi and Crocker Formations, extending up into the Miocene (Hutchison 1996).

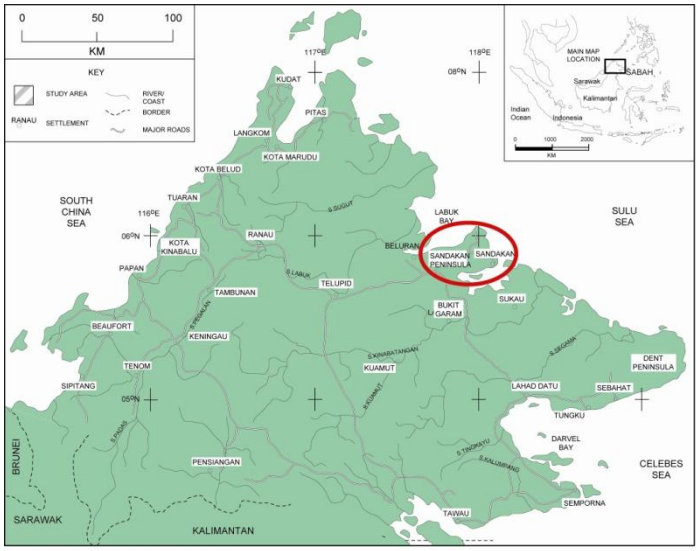


Figure 1. *Map of eastern Sabah, showing the location of the Sandakan Peninsula (circled).*

Deposition in the Central Sabah Basin , the onland extension of the SE Sulu Sea Basin (Hutchison 1992), produced the Labang and Kulapis Formations, both dominated by shelfal turbidites (Noad 1999), though the Labang shallows upwards into shallow marine deposits (Clennell 1996, Noad 1999). These sediments are then unconformably overlain by extensive mélange deposits, related to (SE Sulu Sea) basin initiation in an intra-arc setting (Clennell 1991) during the late early Miocene.

Following deposition of the mélange, gentle regional uplift and quiescent conditions led to the deposition of shallow marine clastic deposits of the Tanjong and Sandakan Formations in the Neogene Sabah Basin (Rangin 1990, Noad 1999). General eastward progradation fed sediment from the Bukit Garam area towards the Sandakan Peninsula, and then out into deeper waters of the Sulu Sea (Clennell 1992, Noad 1999). Later regional structural realignment segmented these Miocene shallow marine deposits into a series of outliers (Noad 1999), separated from the Sulu Sea by a large transform fault (Hinz et al. 1989, Clennell 1996). Associated compression, possibly related to the rotation of Borneo (Hall 1996), and uplift raised these deposits above sea level.

SEDIMENTOLOGY OF THE SANDAKAN FORMATION

The Sandakan Formation was first described in detail by Lee (Lee 1970), but his interpretations have been superseded by the findings described in this paper. The total thickness of the Sandakan Formation is estimated at around 300 metres (Noad 1999, in strong contrast to earlier authors), with clear examples of lateral transition between facies passing from south to north across the Sandakan Peninsula. Frequent normal faults cut across the Peninsula, complicating the geological picture. Five lithofacies associations (Figures 3 and 4) were identified during the outcrop study, and these are described below:

Lithofacies association A: Mangrove facies

Lithofacies A1 is made up of thick, highly carbonaceous. dark grey mudstone, with an abundant fauna. The mudstone often contains logs, up to at least 2.5 m in length, as well as common rooted, buttressed trees in life position (Plate 1). The mudstone also contains whole leaves, from a variety of species. Scattered amber clasts are present at most localities, and can reach 15 cm in diameter. They are well rounded, and have yielded an insect fauna that includes millipedes, spiders, ants, and parasitic wasps. A dominantly molluscan fauna includes *Corbicula* and *Hiatula*, as well as *Batillaria* and cerithiid gastropods, and the fossil wood is bored extensively by teredinids. Several outcrops have yielded specimens of the mangrove lobster *Thalassina sp.*, up to approximately 10 cm in length (Plate 2), as well as distinctive arthropod trackways.

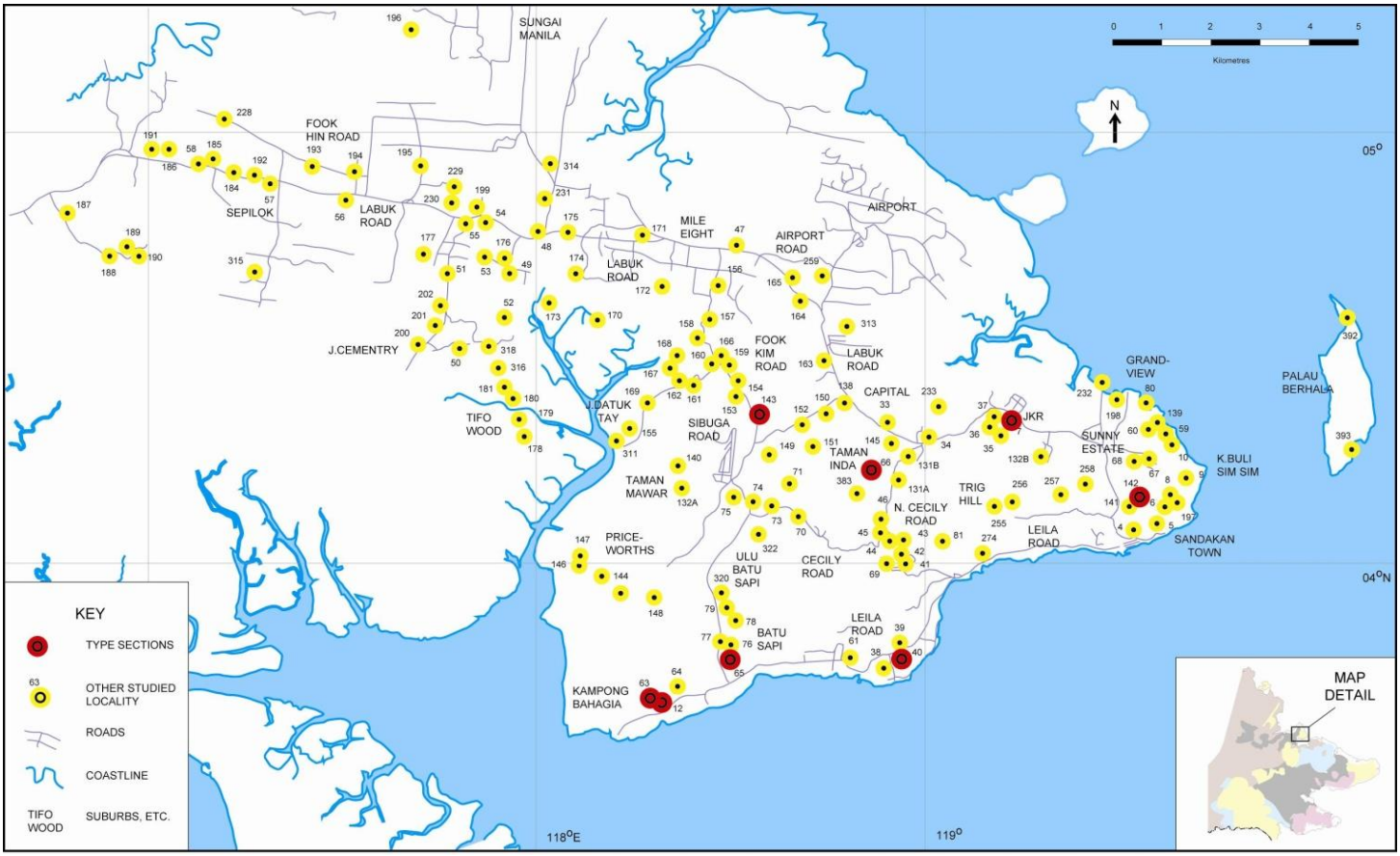


Figure 2. *Map of the Sandakan Peninsula, showing the locations of all sections logged in the area by the author.*

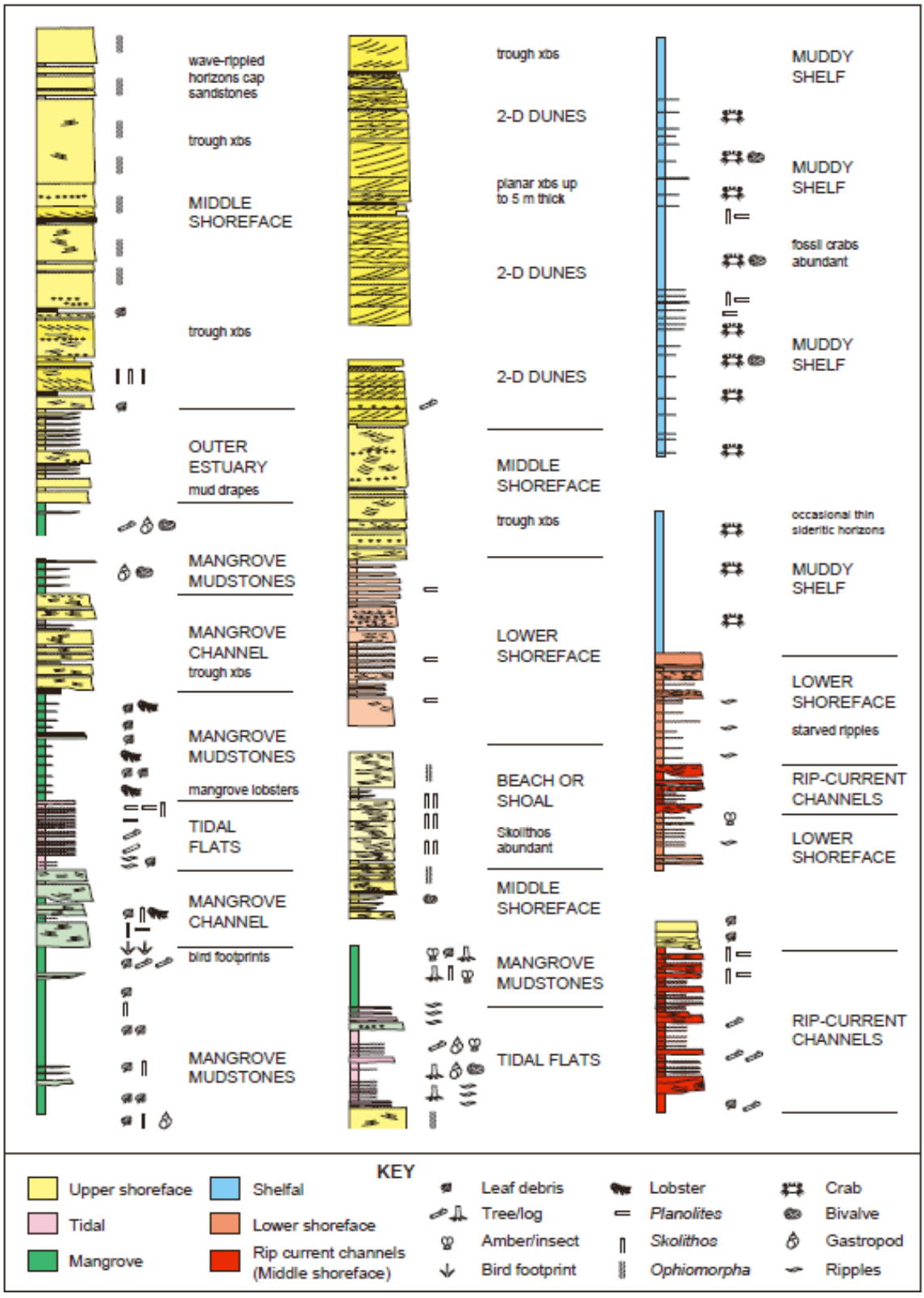


Figure 3.

Summary section of the lithofacies identified in the Sandakan Formation, ranging from proximal mangrove deposits to distal mudstone beds.

Lithofacies A2 is represented by steep sided, fine grained, sandstone filled, channel deposits. Typically between 1 and 5 metres in width, they have a width:thickness ratio of 2 to 5. The sandstone shows few sedimentary structures beyond some trough cross-beds, partly due to a homogeneous grain size. However the top and basal channel surfaces may exhibit fossil bird, lobster and deer tracks. Lithofacies A3 comprises sheet-like sandstone beds up to a metre in thickness and at least 50 metres in width. They occasionally exhibit low angle planar cross-beds and wave rippled tops.

Interpreted depositional setting:
The juxtaposition of fully marine molluscs, a brackish water fauna, abundant mangrove lobsters (which are restricted to a mangal environment), rooted trees and amber yielding a rain forest insect fauna strongly suggests that this lithofacies was deposited in a coastal mangrove swamp environment. Many of the modern mangrove trees at Kuala Selangor, in the Klang Estuary, Peninsula Malaysia, are buttressed in a way similar to the Sandakan flora from Lithofacies A1.

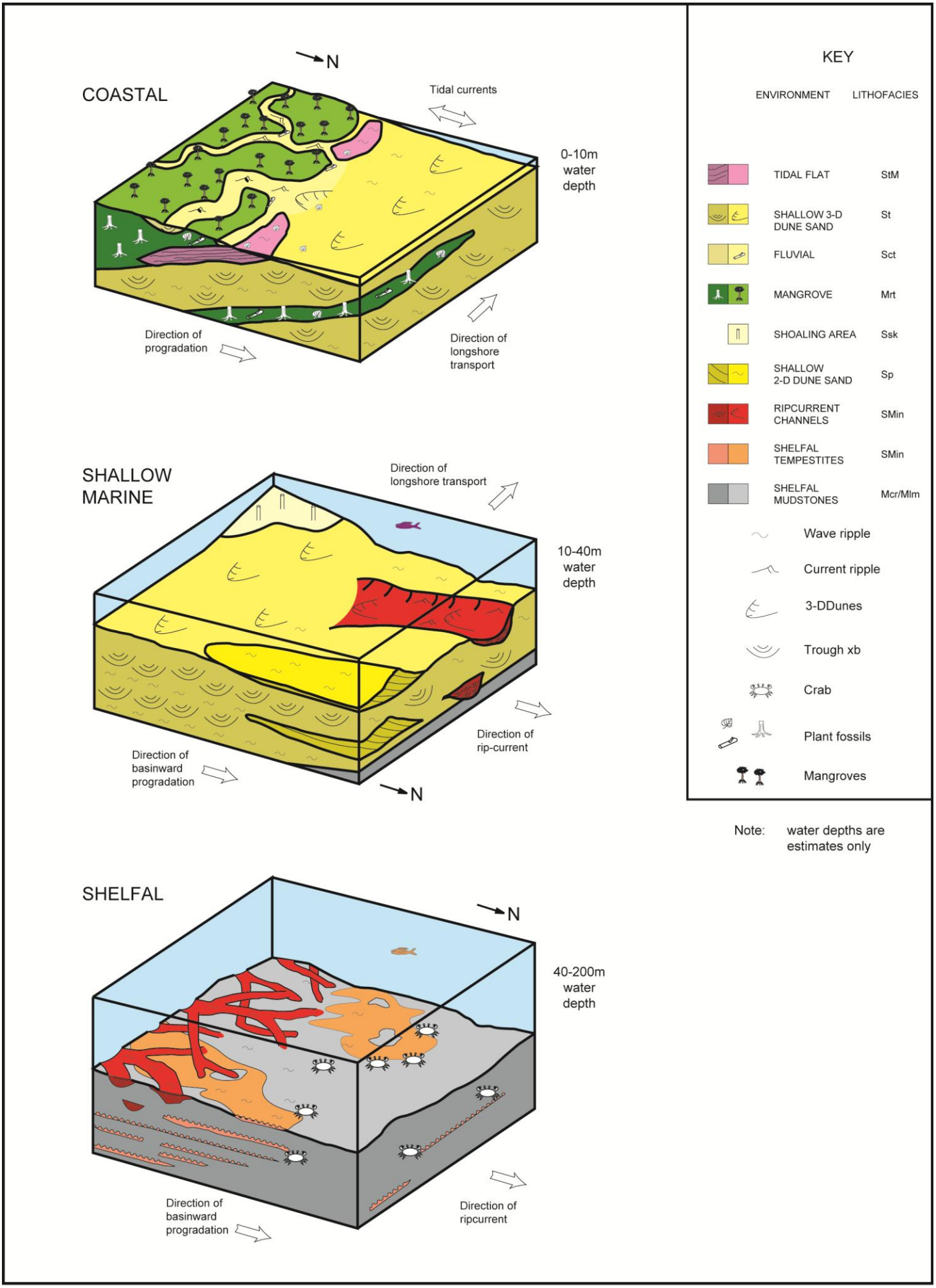


Figure 4. *Reconstructions of the major lithofacies associations identified in the Sandakan Formation.*

The presence of gastropods such as cerithiids is also indicative of a mangrove setting (Plaziat 1995). The sandbodies of Lithofacies A2 are interpreted as mangrove channels, steep sided due to being confined by rooting, similar to channels observed in the mangroves of the Florida Keys. The abandonment surfaces have been extensively bioturbated by ambulatory organisms. Lithofacies A3 is interpreted to represent open areas ("broads"), also recorded as occurring within Floridian mangroves, and possibly swept clear of vegetation during storms.

Lithofacies B: Thinly laminated heterolithic facies

This lithofacies comprises thin, millimetre scale interbeds of silty sandstone and highly bioturbated mudstone, with abundant muddy drapes and occasional rootlets (Plate 3). Small fossil rooted plants with trunk diameters of less than 10 cm have been observed. This lithofacies directly overlies Lithofacies A1. Occasionally these laminae are capped by 20 to 40 cm thick, fine grained sandstone beds with planar cross-beds, and channelized margins, extending typically for 10 to 20 metres laterally in outcrop.

Interpreted depositional setting:
These sediments are thought to have been deposited on a mixed to muddy tidal flat, characterised by lenticular bedding, and by finely interbedded sands and thicker mudstones. The sandstone beds are interpreted to represent small, meandering tidal channels crossing the flats.

Lithofacies association C: Thick stacked sequences of sandstone beds

A series of stacked 2 m to 5 m thick sharp, flat based fine to medium grained sandbodies, with each sandbody featuring trough cross-beds, grading up from medium grained to fine grained sandstone (Plate 4). Each sandstone bed is capped with a very distinctive, ironstone-cemented, rippled horizon (Plate 5). Weathering exposes fields of, often strongly peaked, wave ripples that may extend for hundreds of metres, often showing interference patterns and ladderbacks. The rippled horizons are overlain by a thin grey mudstone bed, and then by the next sandstone bed. Rarely the sandbodies are made up of planar cross-beds, with sets on a metre scale, and cross-beds dipping at up to 30 degrees.

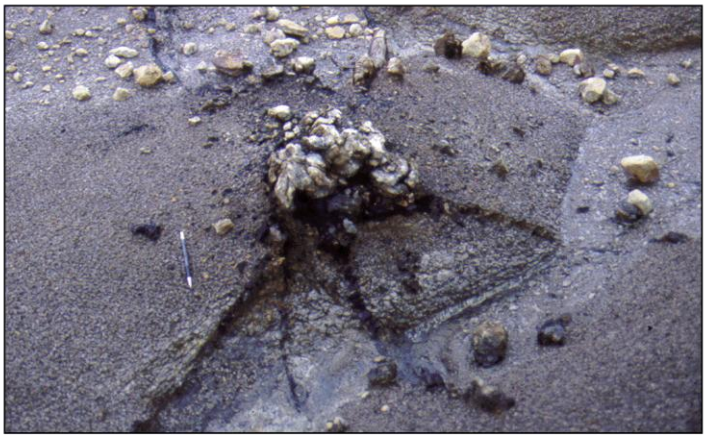


Plate 1. *Fossil mangrove tree with buttresses. Note that the core is petrified, the outer integuments vitrainised.*

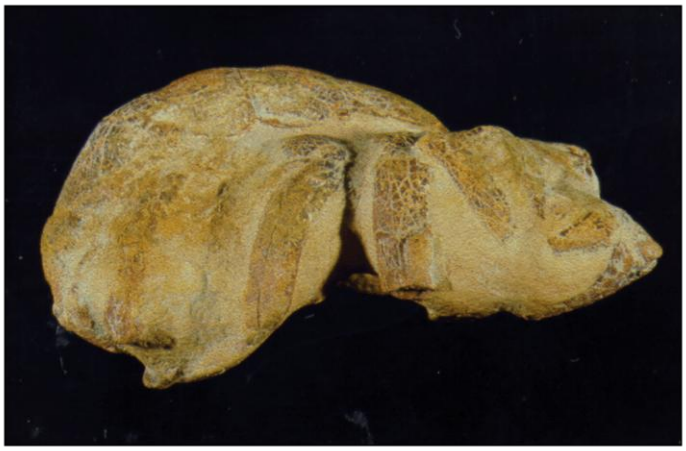


Plate 2. *Fossil Thalassina (mangrove lobster, length 10 cm), collected from mangrove mudstone beds rich in plant debris.*

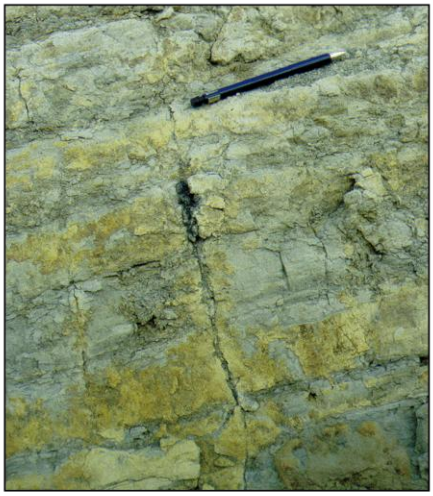


Plate 3. *Tidal flat deposits, with a well preserved rootlet.*



Plate 4. *Detail of upper shoreface sandstones with low angle bedset boundaries, rich in carbonaceous debris.*

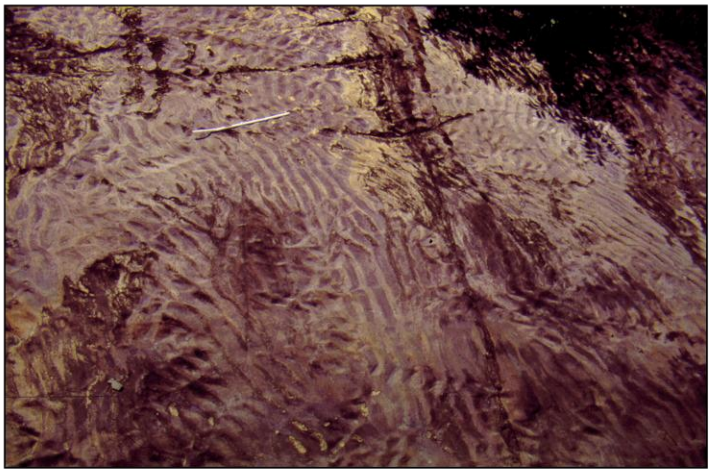


Plate 5. *Ironstone-cemented wave ripple horizon. The varying orientation of the crests suggests shallow water depths.*

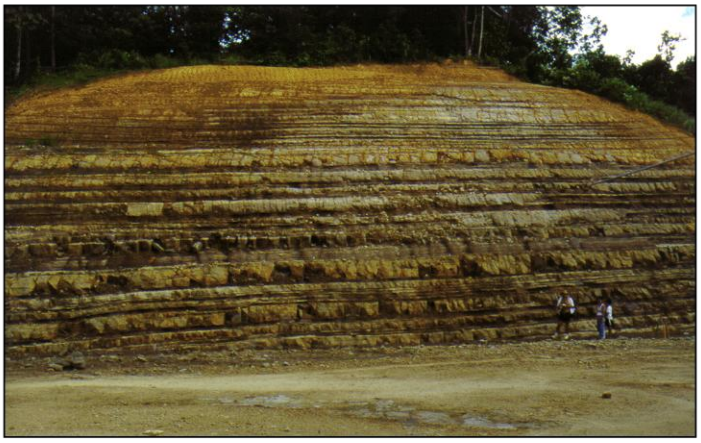


Plate 6. *Tabular heterolithic interbeds of swaley cross-bedded sandstone and mudstone, interpreted to represent sporadic storm events on the middle shoreface.*



Plate 7. *Rip-current channels incising into thick, middle shoreface mudstone beds.*

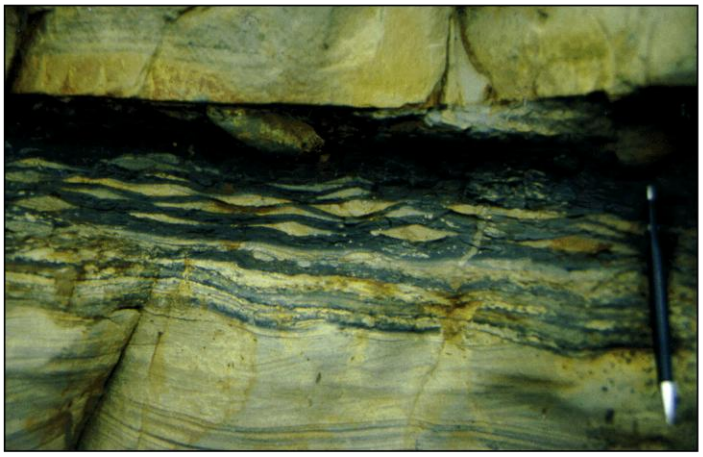


Plate 8. *Starved ripples, overlying hummocky cross-bedded sandstone beds.*

Few body fossils have been found in these beds, apart from moulds of bivalve and gastropod fragments, but *Ophiomorpha* burrows are very common, along with *Rhizocorallium*. Some outcrops have abundant *Skolithos* burrows.

Interpreted depositional setting:
The thick sandstone deposits are believed to have been deposited in the shallow marine, upper shoreface zone, supported by the textural maturity of the sandstone and abundant wave ripples. The trough and planar cross-beds are interpreted to indicate subaqueous dunes migrating across the seabed. The great lateral extent of many of the ripple fields shows that deposition occurred on a wide, flat, sand-dominated platform. The interference patterns suggest water depths of less than five metres, and the sharply peaked ripple crests may show semi-emergent conditions. *Ophiomorpha* may indicate a sandy shoreline sedimentary environment, and *Skolithos* generally indicates intertidal or foreshore deposits.

Lithofacies association D: Heterolithic interbedded sand and mudstone beds on a sub metre scale

One of the most prevalent lithofacies associations in the Sandakan Formation is a very heterolithic set of interbedded very fine grained, carbonaceous sandstone, siltstone and mudstone beds. The sandstone beds range from very laterally persistent, tabular sandstone beds with extremely flat bases (Plate 6), normally less than 50 cm in thickness, to channelised sandstone beds, commonly between 2 and 30 metres in width, and with an erosional relief of up to around 2 metres into the underlying beds (Plate 7). These are all interbedded with mudstone beds. The sandstone beds are generally very fine grained, and usually contain hummocky cross-laminae. The channelized sandbodies have very steep channel margins, and show reactivation surfaces. Each sandstone passes up into more silty beds, with climbing ripples often extending to the top contact. The overlying mudstone beds may feature starved sandy ripples (Plate 8). Dewatering and loading structures are particularly common in this lithofacies association.

A wide variety of ichnofauna are present through most of the beds that make up this lithofacies association. Apart from *Ophiomorpha* and occasional *Skolithos*, fifteen or more other ichnospecies have been delineated, some not previously recorded.

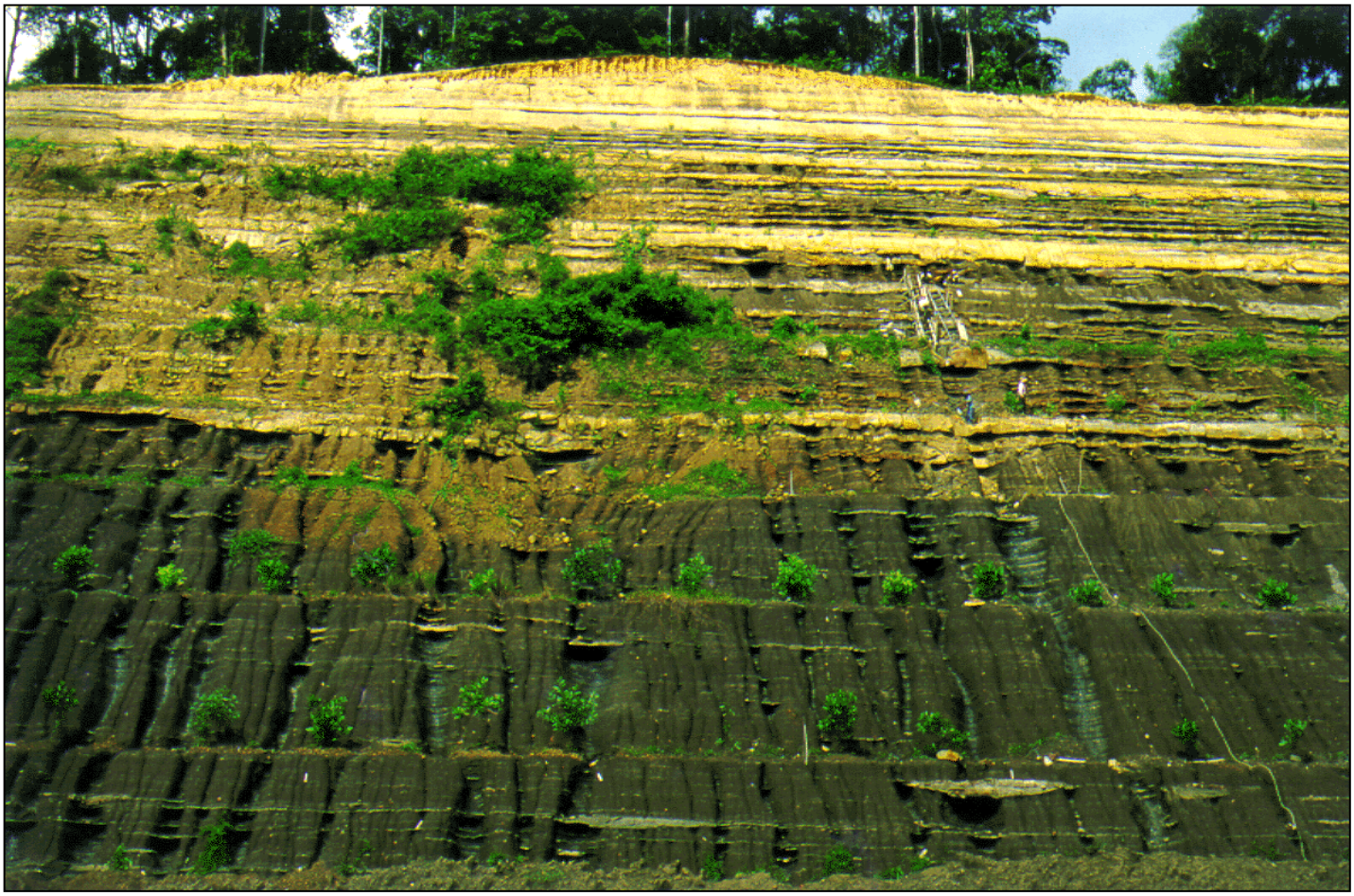


Plate 9. *Superb exposure of the progradational succession at Taman Inda. Lower-middle shoreface mudstones pass up into middle shoreface mudstone cut by rip-current channels, and then into upper shoreface sandstone beds.*

These include *Phycodes*, *Scolicia*, *Scolichnia*, *Teichichnus*, *Olivellites*, *Rhizocorallium*, *Planolites* and *Thalassinoides*.

Interpreted depositional setting:
The very heterolithic nature of these rocks suggests abrupt changes in energy levels. The thinner, tabular sandstone beds are hummocky cross-bedded, and are interpreted as storm deposits (Hobday and Morton 1984). The thicker, more channelized, beds have been cut by fairly strong currents, as evidenced by the steep channel margins, and the reactivation surfaces suggest several episodes of erosion. The presence of numerous dewatering structures, including the striking ball-and-pillow structures, supports relatively rapid deposition. This lithofacies is interpreted as representing tempestite deposits, with the tabular sandbodies indicating deposition on the storm to inner shelf transition zone. The channels are interpreted as having been cut by rip currents (Gruszczynski et al. 1993), with the steep walls suggesting rapid erosion and subsequent fill, supported by the presence of the dewatering structures. Overall these deposits are interpreted as storm dominated, middle shoreface deposits.

Lithofacies E: Open marine mudstone facies

This lithofacies is made up of thick grey mudstone, with occasional very thin but laterally persistent silty siltstone beds (Plate 9). These beds are generally less than 5 cm in thickness, but may extend for at least 300 m with no appreciable change in thickness. Internal structures of many beds are obscured by ironstone cementation during diagenesis but, where visible, hummocky cross-stratification can be discerned. A distinctive and varied fauna preserved as internal casts within the ironstone horizons includes 25 species of fossil crabs (Plate 10), as well as a very varied molluscan fauna and a previously unreported argonaut.

Interpreted depositional setting:
The thin ironstone cemented siltstone beds are interpreted as distal storm deposits, while the fine grained grey mudstone was deposited in open marine conditions in the lower shoreface to offshore transition zone. The very mixed fauna shows well oxygenated bottom conditions.

Summary of facies belts

Extensive fieldwork has enabled the delineation of the major facies belts (Figure 4) of the Sandakan Formation (Figure 6). To the south lie mangrove deposits, passing northward into shallow marine sandstones. The mangrove deposits are cut by fluvio-mangal channels. The interpreted position of the palaeo-coastline is believed to run along the boundary between these two facies belts, although this position is at best an approximation due to the limited outcrop and interpreted northward

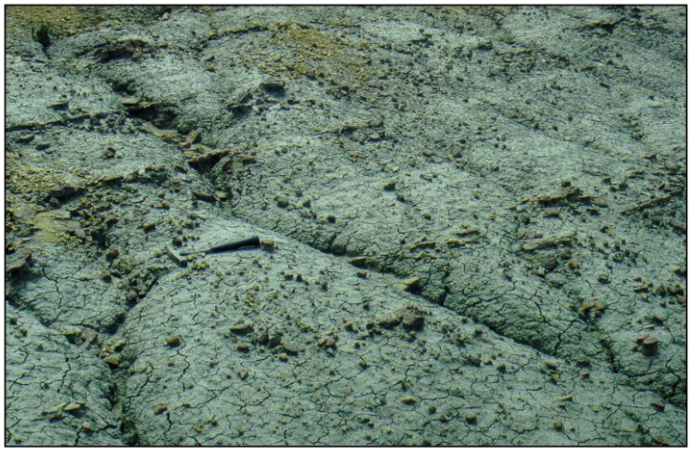


Plate 10. *Thin distal, ironstone-cemented siltstones set in highly fossilifereous, lower shoreface mudstone beds.*



Plate 11. *A selection of fossil crabs (clockwise from top left): Portunus, Dorippe, Ranina, Calappa and Rhinolambrus, preserved in lower shoreface silts.*

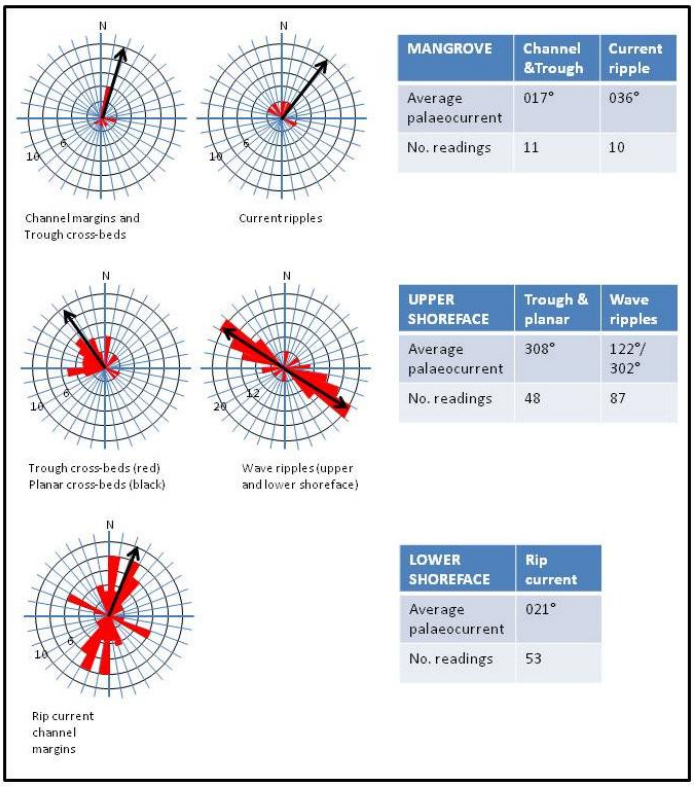


Figure 5. *Details of palaeocurrent data for lithofacies associations.*

progradation of the Formation. The humid conditions appear to have been conducive to rapid colonisation of any tidal flats, explaining their limited extent.

Northward the shallow marine sandstone beds pass into heterolithic tempestite deposits, indicating an unsettled climatic regime. Sheet-like storm deposits are cut by rip current channels, suggesting a significant fetch to the north, generating strong storm surges in a southward direction, which then reflect to the north. This facies belt passes gradually into more muddy, open marine sediments, with only thin storm siltstone interbeds and a varied fauna.

Plate 11 shows a classic coarsening upward sequence passing form open marine, mudstone beds with scattered distal rip current channels up into a heterolithic, lower shoreface succession with common hummocky cross-stratified sandstone beds and common rip current channels, ovcerlain in turn by stacked upper shoreface sandstone beds. This succession is interpreted to indicate progradation of a sandy deltaic system, and demonstrates, using Walther's Law, the lateral changes in lithofacies across the Miocene Sandakan Basin.

SYNTHESIS OF PALAEOCURRENT DATA

It has proved possible, through the measurement of more than 200 palaeocurrent orientations (Figure 5), to build up a detailed picture of sediment movement through the Sandakan sub-basin (Figure 6). The mangrove channels flow in a generally NNE-ward direction whereas the shoreface sandstones are characterised by a more complex palaeocurrent pattern. A coastline can be mapped, running WNW-ESE, where the mangrove deposits interfinger with, and pass laterally into, thick scarp-forming sandstone beds. Wave ripple crests covering the top surfaces of these beds run parallel to this coastal orientation, suggesting swash and backwash. However planar and trough cross-beds within the sandstone beds show a dominantly NW-ward vector, indicating along shoreline transport by strong tidal currents. The clastic material is sourced from an inferred major river system comparable in size to the Kinabatangan River, located to the east of the current Sandakan Peninsula.

Further offshore, the rip current channels are oriented NNE-SSW, parallel to the trend of the mangrove channels. This supports a model where storm currents are reflected back offshore towards the north, passing seaward into sheet-like tempestites, which pinch out northwards. The source of the large volumes of relatively fine grained, clastic sediment is thought to be from the river system described above, flowing NE-ward into the sea. Overall, the Sandakan Formation is interpreted to have been deposited in a supply-dominated regime, and provides an excellent example of the

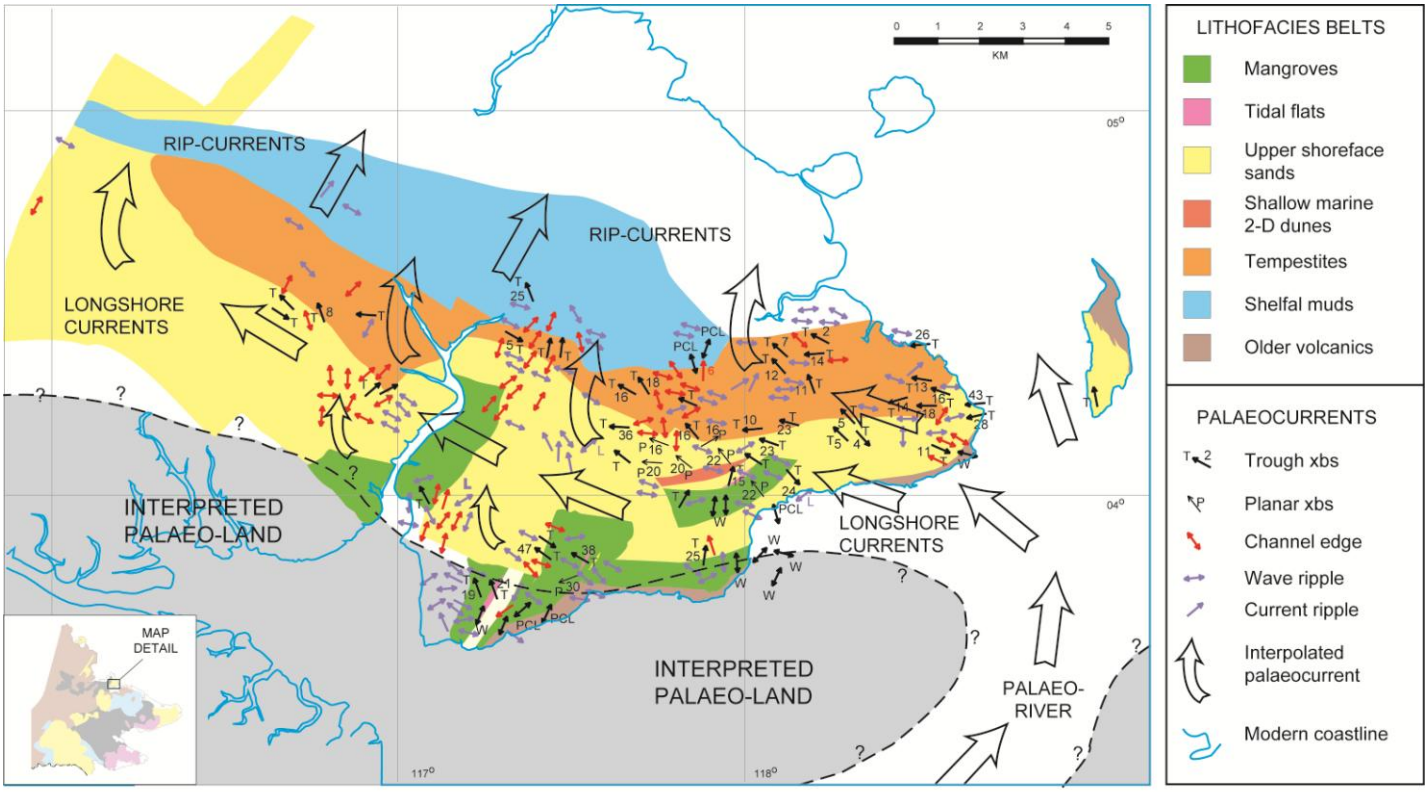


Figure 6. *Palaeogeographic reconstruction of the Sandakan Formation, showing the depositional facies belts identified from field logging. An interpretation of the current pattern ('sediment flux') has been added, using palaeocurrent data collected from outcrop.*

utility of palaeocurrents in palaeogeographical reconstruction.

DISCUSSION ON SEDIMENT FLUX

The total sand volume stored in the Sandakan Formation on the Sandakan Peninsula is estimated at 29,040 million cubic metres (Table 1). The average total thickness of the Sandakan Formation at any one point is estimated at approximately 300 metres. Assuming that the Sandakan Formation was deposited over a period of around 4 million years (based on limited dating using microfossils), this gives a deposition rate of 90 metres/million years. This compares to a figure of 50 to 200 metres/million years of sediment accumulated on the Indochinese shelf (Kukal 1971). Using the figure of 4 million years this suggests that 7260 cubic metres of sand was trapped in the Sandakan depositional system every year, although almost certainly most of the sediment flux passed through the system, mainly through longshore drift to the west.

CONCLUSIONS

A total of five lithofacies associations have been delineated in the Sandakan Formation, namely: mangrove mudstones with sheet and channelized sandbodies; thinly laminated, heterolithic todal deposits, rarely vegetated; upper shoreface sandstone beds; middle shoreface, heterolithic, storm dominated sheet-like sandstone beds cut by rip current channels; and open marine mudstone beds. These show a full transition from paralic deposits out into an open marine setting. The use of palaeocurrent data collected from all five lithofacies associations has allowed a detailed picture to be constructed of the sediment dispersal patterns in the Miocene Sandakan sub Basin. This methodology can be applied to many other basinal settings worldwide.

Environment	Length (m)	Width (m)	Sand thickness (m)	Sand volume (MMm3)
Mangrove	27270	9770	36	9600
Tidal	450	910	2	1
Upper shoreface	25450	5680	125	18100
Lower shoreface	19100	2270	28	1200
Open marine	15000	2270	4	140
TOTAL				29040

Table 1. *Estimated sediment deposition parameters for the Sandakan Formation.*

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