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The sedimentology of Miocene shallow marine clastics of the Sandakan Formation of eastern Sabah

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Abstract: The Sandakan Basin lies on the east coast of Sabah and contains some excellent exposures, resulting in part from the steep topography of the region and from the recent development of housing estates and road construction. These often spectacular outcrops allow examination of the Miocene succession, which has not previously been feasible. A total of 4 months has been spent collecting sedimentological data throughout the c. 25 km by 15 km basin. Over 70 measured sections have been logged across the basin and this, in conjunction with numerous macrofossil, microfossil and ichnofacies studies, has allowed the differentiation of the interbedded sands and clays, previously described as a marginal marine succession, into facies associations ranging from continental to shallow shelfal in origin. Seven main facies groups are identified which range from mangrove deposits cut through by fluvial channels, through delta top with channels into facies deposited in a lagoonal/interdistributary bay environment. These pass into shoreface trough or planar crossbedded sands with common *Ophiomorpha* or *Skolithos* trace fossils and finally into offshore marine muddy facies. Palaeoseismicity is suggested by synsedimentary deformation, often confined in discrete horizons which can be traced over several kilometres. Detailed palaeontological studies of these rocks will allow development of this facies scheme and further division of these systems into sub-environments.

These well exposed marginal marine facies present an exceptional opportunity to develop a sequence stratigraphic framework of the Sandakan Basin through the Miocene. Examination of the eustatic/tectonic control of the system will then be applied to hydrocarbon-bearing strata in adjacent basins. Furthermore this study will constrain palaeogeographic reconstructions of the region.

INTRODUCTION

A study of the Tertiary sedimentary rocks of eastern Sabah is important to constrain tectonic models for the evolution of Northern Borneo and the Sulu Sea. Several workers have presented sedimentological data from the Eocene to Pliocene strata exposed in the region, but few detailed studies have been undertaken. Furthermore, such studies are often of a reconnaissance nature and have not addressed the regional significance of individual formations. In this paper we present new and detailed sedimentological data from the Sandakan Formation, which has formerly been described as consisting of fluvio-deltaic to estuarine (Hutchison, 1992) or shallow marine and deltaic sediments (Lee, 1970; Stauffer and Lee, 1972).

The considerable urban development in progress in the region around Sandakan Town makes this project particularly timely and has allowed the measurement of numerous stratigraphic sections, previously unexposed, throughout the area. Some of the sections examined reach dimensions rarely encountered in SE Asia (e.g. Taman Inda Estate where cliff exposures are 300 x 100 metres) and allow detailed reconstructions of bedform geometry and lateral facies variations. Reconnaissance work might suggest there is a paucity of fossiliferous material in the Sandakan Formation. The preservation of fauna/flora is very variable through the formation, although Lee (1970) has documented numerous localities with fossils in the region; we also have been able to collect a good deal of fauna from certain intervals within these rocks. Dissolution of carbonate may be responsible for barren horizons in some cases, whilst other intervals contain little fauna for environmental reasons. Many of the faunal assemblages have not been previously recorded from NE Borneo and include new species which constrain the sedimentological interpretation for the deposits.

New faunal and sedimentological information from the excellent exposures in the Sandakan region will allow the construction of a sequence stratigraphic model for the succession. This model will provide valuable analogues for potential hydrocarbon provinces in adjacent regions such as the Baram Delta, and will constrain tectonic models for the region.

REGIONAL SETTING

Oceanic spreading of the South China Sea began in the Palaeogene and ceased around 17 Ma, when the Dangerous Grounds block collided with Northern Borneo (Clennell, 1996). In Western Sabah this led to the uplift of the Crocker Formation, comprising turbidites floored by ophiolitic basement (Tongkul, 1991). To the east the collision is thought to have initiated the development of the extensive melanges found there (Clennell, 1996). Extension of the Southeast Sulu Sea in the very early Miocene, by rifting of the pre-existing ophiolitic terrane, led to limited oceanic spreading (Tongkul, 1991). Eastern Sabah lay at the hinge of a spreading system (Hutchison, 1992), though stretching was not sufficient to generate oceanic crust (Clennell, 1996). Extensional forces, together with compression caused by the collision of the Dangerous Grounds block, was accommodated by wrench faulting, opening a series of sedimentary basins (Maliau, Malibau, Bukit Garam) in eastern Sabah during Miocene times (Fig. 1). These basins overlie large areas of melange or distal Crocker turbidites, and are filled with a mixture of siliciclastics and volcaniclastics with limited carbonates. Whilst basin evolution was controlled by regional tectonic events, their internal architecture and fill was controlled by local, gravity-driven subsidence and basement uplift which often resulted in circular basin development (Tongkul, 1993; Clennell, 1996).

SANDAKAN FORMATION LITHOFACIES

Seven lithofacies/lithofacies associations are defined from over seventy measured sections in the region surrounding the town of Sandakan. We present detailed sedimentological logs from three sections, Leila Road, Bird Quarry and Taman Inda (Figs. 3, 4 and 5), the locations of which are shown in Figure 2. These outcrops have been selected to illustrate the facies encountered within the Sandakan Basin. A detailed description of each of the lithofacies/lithofacies associations is given below. For the purposes of this paper only the end members of each facies are described, though in reality an almost complete spectrum of facies can be observed in the field.

1. Dark grey muds with abundant logs and carbonaceous detritus

Sections: Leila Road, Bird Quarry

Description. Thick cohesive dark grey muds, with an abundant fauna. Typically the muds contain large logs, which are either silicified, or more commonly carbonaceous with a black charcoal-like appearance thought to be due to diagenetic alteration (Fig. 6). The logs may are often bored by bivalves or worms. There are also occasional thin coaly bands, scattered smaller pieces of wood and rare rooted trunks. Well preserved impressions of leaves can be recovered from the muds, and stems of smaller plants are also observed. A small amount of subrounded dark amber clasts up to 5 cm in size may be present in some localities.
Palaeontology. Both bivalves and gastropods occur in all outcrops of this type. These are sometimes well preserved, with original shell material, but more commonly only as a partially rotted internal cast in ironstone. Around 15 species have been identified (Table 1), and the biota is dominated by a fauna typical of a brackish water environment. A good example is *Hiatula*, which prefers a marine environment, but lives directly below freshwater runoff, as well as other brackish forms such as *Corbicula*. This is supported by the presence of rare fragments of the carapace of *Trionyx*, a freshwater turtle (pers. comm., Feb. 1996, Colin Patterson, Natural History Museum, London). Other fauna includes keeled worm tubes of an unknown species, and insects preserved within the amber. Types of insects include ants, parasitic wasps, thrips and spiders, all forms typical of tropical conditions.
Interpretation. See Facies No. 2

2. Channelised sands with trough-cross bedding

Sections: Bird Quarry/Leila Road

Description. Generally fine grained sands, with very channelised bases. These channels tend to pinch out laterally, and they vary from a few metres to at least 100 m in width (Fig. 7). The sands are trough crossbedded, with the troughs usually in fairly thin sets i.e. 30 cm to 50 cm. Mud drapes are observed in trough-cross bedded sands forming channel fills. These pass up into finer silty sands commonly exhibiting climbing ripples, the ripples having the typically asymmetric form of current ripples, and an average wavelength of

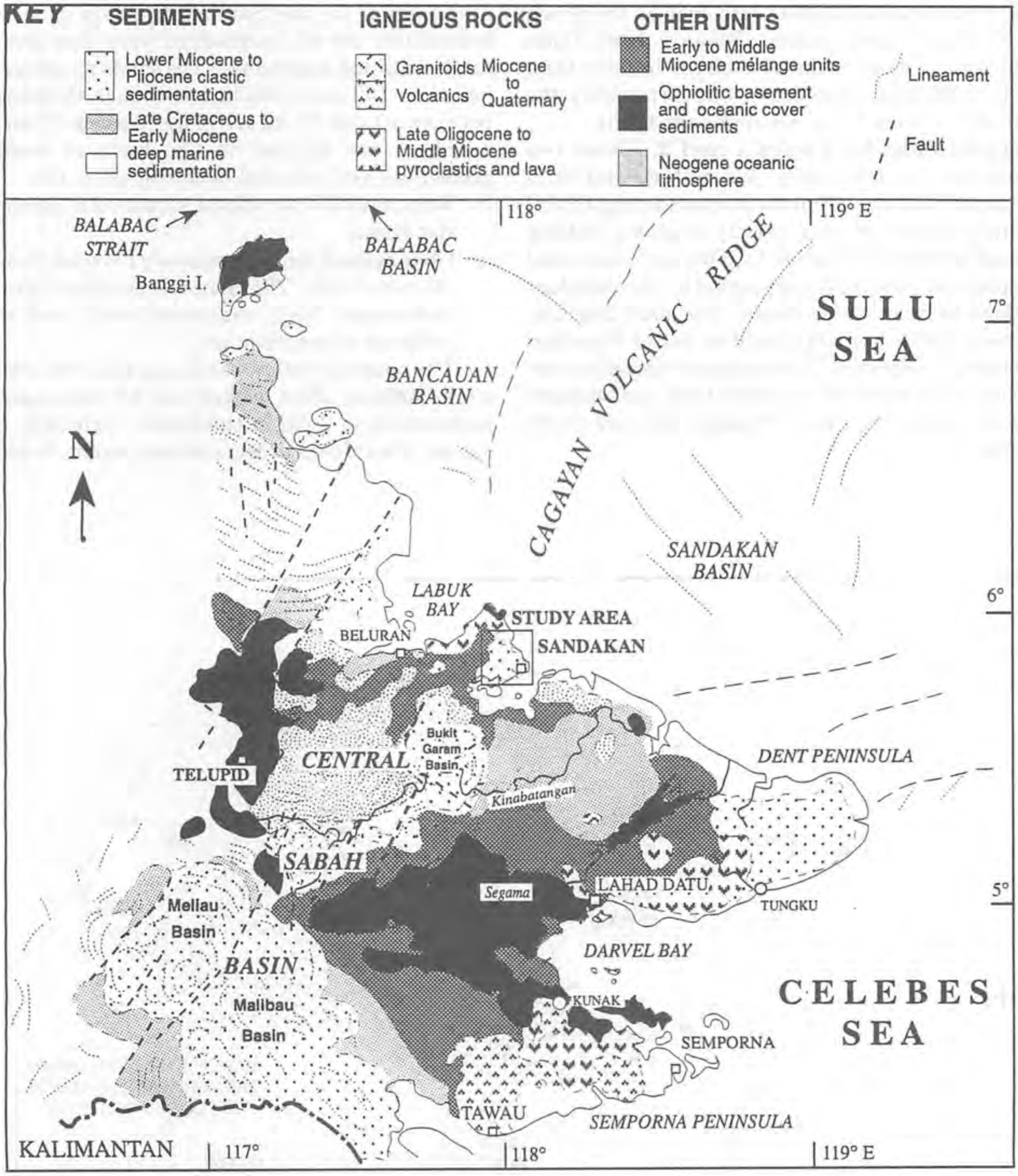

Figure 1. Simplified geological map of north-east Sabah and the adjacent marine region. After Clennell 1996. Based on Tongkul, (1991, 1993, 1994), Clennell, (1991, 1992). Offshore information from Hinz *et al.* (1989), Lee and Tham (1989), Hinz and Block (1990) and Wong (1993).

approximately 20 cm (Fig. 8). This upper portion is commonly bioturbated, generally by mainly horizontal burrows.

Palaeontology. One of the channels examined had bird footprints preserved at the base of the sand, from a coastal wading bird such as the Green Plover (Fig. 9; pers. comm., Febuary 1996, Colin Patterson). Other fauna is thought to have been lost to carbonate dissolution, but fortunately the associated Facies 1 has an abundant fauna.

Interpretation for Facies 1 and 2. These two lithofacies are commonly associated, and it is postulated that they represent meandering fluvial channels (Facies 2) on a variety of scales, cutting through mangroves (Facies 1). This environmental interpretation is strongly supported by the abundant brackish to fresh water fauna. The most laterally extensive sands probably could be better described as estuarine deposits. The mangrove deposits were probably more sparsely vegetated than some modern ones, as coals are rare, although logs are fairly common.

3. Heterolithic sediments

Sections: Taman Inda (Fig. 10)

Description. One of the most striking lithofacies associations in the Sandakan Basin is a very heterolithic set of interbedded very fine grained sands, silts and mudstones. The sands are generally less than 150 cm in thickness, though thicknesses between 10 and 50 cm are more common. Two end members are defined on the basis of bedding geometries and internal bedforms (Fig. 10):

i) Very laterally persistent sands with extremely flat bases.
ii) Channelised sands, commonly between 2 m and 30 m in width. The channels cut down into the beds below fairly indiscriminately and show evidence of reactivation.

The cream to yellow sands usually show swaley cross-laminae, often picked out by carbonaceous material up to 2 cm in thickness. Generally only one set of swales is present in each sand. In places

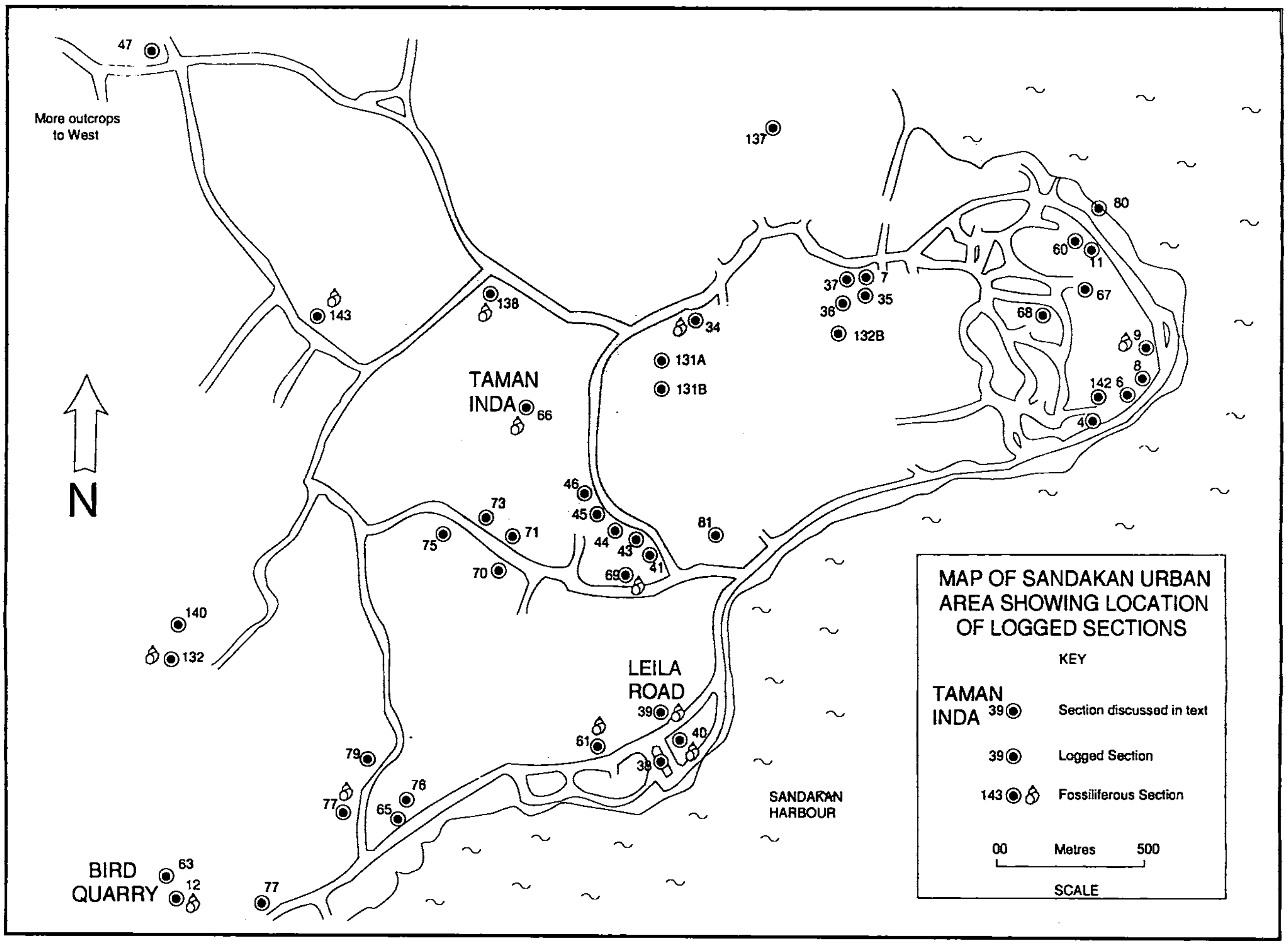

Figure 2. Detailed location map of the Sandakan area.

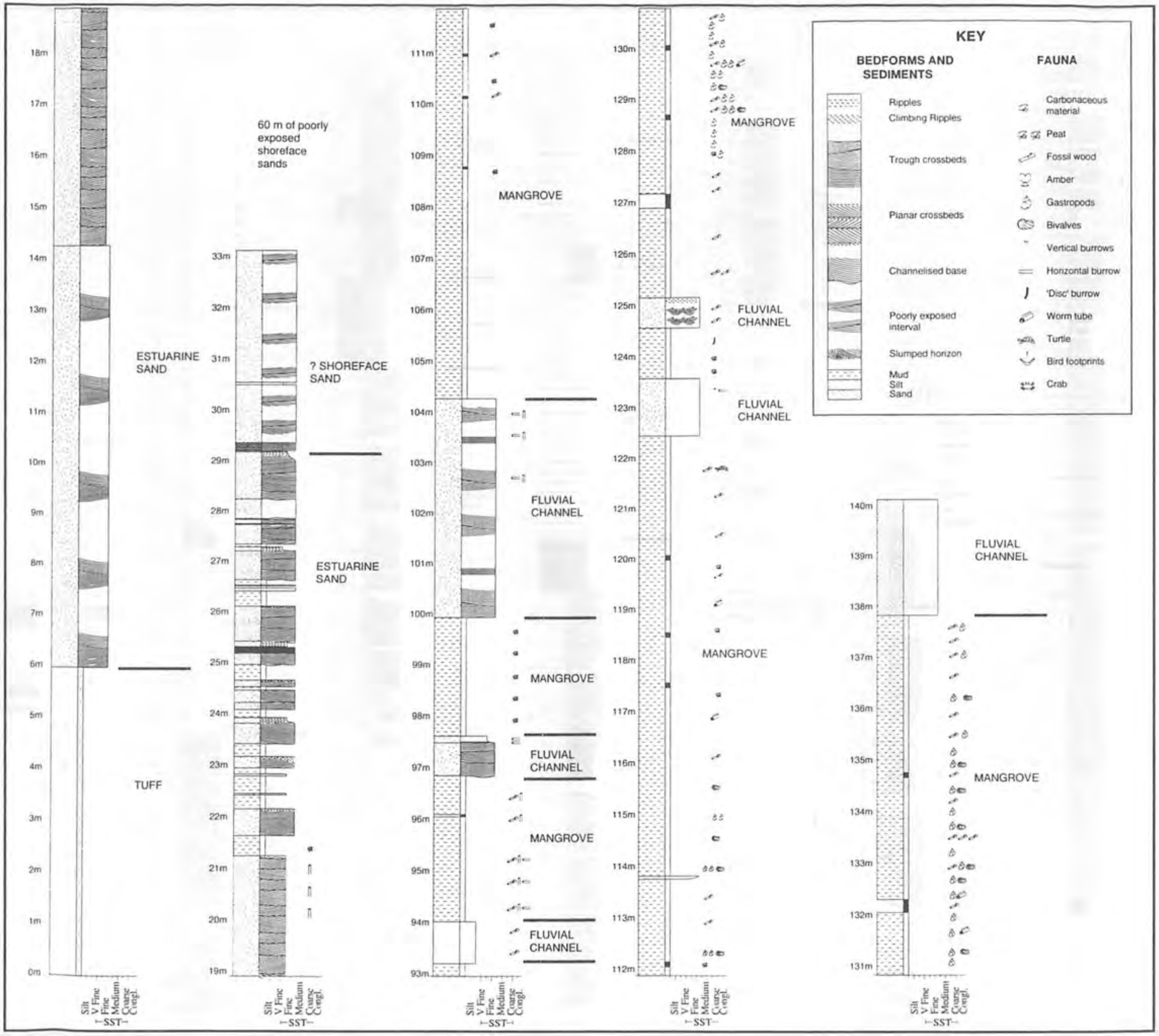

Figure 3. Leila road measured section .

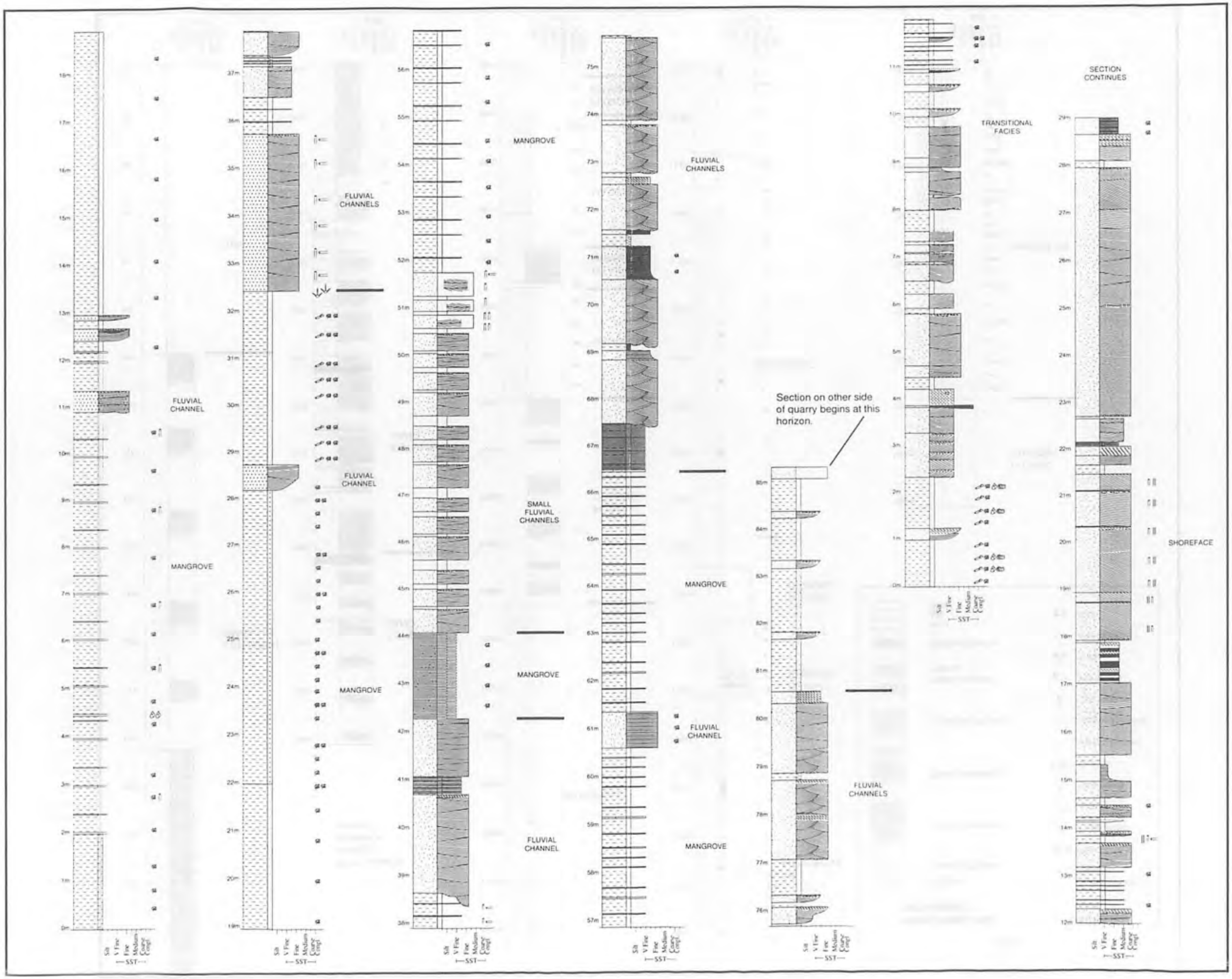

Figure 4. Bird quarry measured section. See Figure 3 for key.

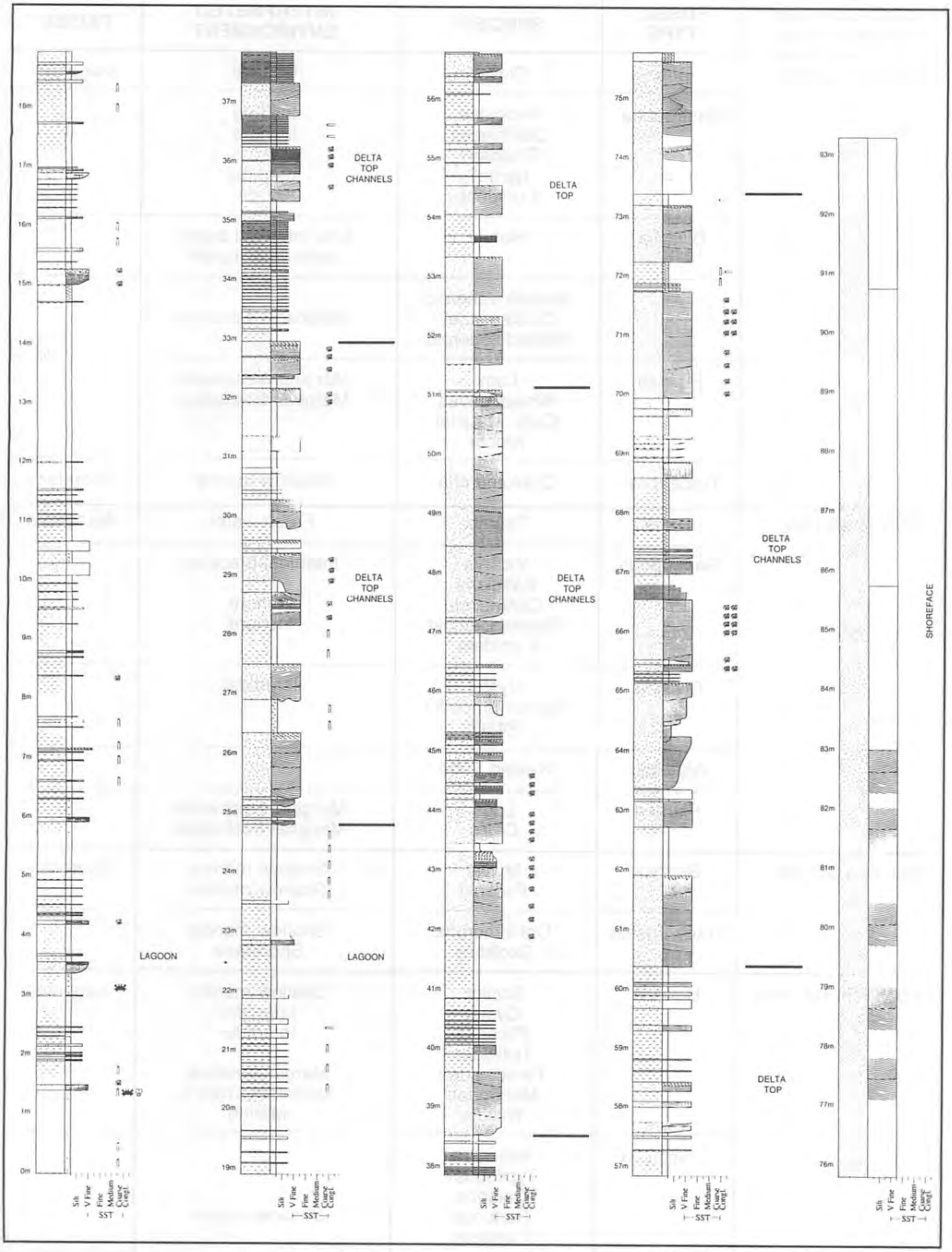

Figure 5. Taman Inda measured section. See Figure 3 for key.

Table 1. Macrofossils in the Sandakan Formation.

LOCALITY (and Locality No.)	FOSSIL TYPE	SPECIES	INTERPRETED ENVIRONMENT	FACIES
Bird Quarry (12)	Bird	Plover	Coastal	Mangrove
	Gastropoda	Naticidae Cerithiacea Thaidae? Nerite? 1 unident.	Inshore Inshore Intertidal	
	Bivalvia	Hiatula	Low intertidal below freshwater runoff	
		Smooth veneroid Corbiculidae? Ribbed veneroid	Brackish-freshwater	
	Plantae	Logs Whole leaves Carb. Material Amber	Marginal-freshwater Marginal-freshwater	
	Trace fossil	Ophiomorpha	Shallow marine	Shoreface
Leila Road (40)	Turtle	Trionyx	Fresh water	Mangrove
	Gastropoda	Vicarya Bathilaria Cerithacea Ribbed Cerithid 6 unident.	Intertidal-brackish Inshore Inshore	
	Bivalvia	Oyster Narrow smooth? Pitar?	Intertidal	
	Annelida	Keeled Tube		
	Plantae	Logs Coals	Marginal-freshwater Marginal-freshwater	
Buli Sim Sim (9)	Bivalvia	Mytilid Pectinid	Shallow marine Shallow marine	Shoreface
	Trace Fossils	Ophiomorpha Skolithos	Shallow marine Shoreface	
Fook Kim Rd (143)	Bivalvia	Scallop Oyster Plicatula Tellinidae Teredinadae Mactrodae Nucula	Shallow marine Intertidal Intertidal Marginal-marine Shoreface marine Marine	Lagoonal
	Crustacea	Iphiculus Typilobus? Calappa Portunus 1 unident.	Shallow marine	
	Annelida	Serpulid		

Table 1. Macrofossils in the Sandakan Formation (cont'd).

LOCALITY (and Locality No.)	FOSSIL TYPE	SPECIES	INTERPRETED ENVIRONMENT	FACIES
St. Monica's (138)	Bivalvia	Oyster Smooth veneroid Glycimeris?	Intertidal Marine	Lagoonal
	Crustacea	Portunus W. Portunus O. Calappa Porthenope Nocia? Panopeus? 1 unident.		
Dog Quarry (69)	Gastropoda	Vicarya Vicarya? Thaid	Brackish Brackish	Mangrove
	Bivalvia	1 unident.		
	Plantae	Rooted trees Amber	Mangrove	
	Insecta	Parasitic wasp Ants Gall Midge Thrips Spiders	Tropical rainforest	
Batu Sapi (77)	Gastropoda	Nerita Muricid? Dosinia? 4 unident.	Intertidal	Mangrove
	Bivalvia	Smooth veneroid Corbiculidae	 Brackish-freshwater	
	Pisces	Teleost		
	Plantae	Logs Amber Carb. material	Marginal-freshwater	

Figure 6. Dark grey muds with petrified logs, Facies 1, Leila Road. See Figure 2 for location and Figure 3 for measured section at this locality.

Figure 7. Channelised sands with trough-cross bedding cutting through grey carbonaceous mudstones. These sands are interpreted as estuarine channels. Locality No. 77 (see Fig. 2).

Figure 8. The lower sand interval is a channelised sand with trough-cross bedding. This is overlain by thin, trough-cross bedded estuarine sands, with mud drapes. These pass up into cross-bedded thick sands interpreted as shoreface/shallow marine sediments containing abundant wave-ripples (Facies No. 5), Bird Quarry. See Figure 2 for location and Figure 4 for measured section at this locality.

some trough crossbedding may develop, and here more than one set of crossbeds is common. Even the thinnest of the sands (5 cm or less) usually contains foresets. The sands within individual beds pass up into more silty sediments, with climbing ripples often extending to the top sand contact. Current ripples have been reworked into symmetrical wave ripples in some intervals. The silty sands are interbedded with grey mudstones, which are often highly bioturbated, with common vertical and horizontal burrows. They contain a spectrum of sandy starved ripples ranging from scattered individual silty ripples to thin beds of sandy wave ripples (Fig. 11).

Palaeontology. Fossils in these sediments are very uncommon, probably due to dissolution, but a few casts of marine bivalves have been found, including modiolids and scallops. In some areas the siltier sediments do not exhibit rippling, and on occasions, these may yield exceptionally well preserved whole leaves. It is hoped that identification of these forms will aid in palaeoenvironmental reconstructions. More commonly, however, the plant material has been comminuted into very fine carbonaceous debris, which picks out the crossbeds.

Figure 9. Bird footprints at the base of an estuarine channel, believed to be made by a plover, Bird Quarry. See Figure 2 for location and Figure 4 for measured section at this locality.

Interpretation. These lithofacies are interpreted as wave-dominated delta top sediments. This is supported by the common wave ripples and very heterolithic beds and is supported by the fauna which indicates a marine environment. The reworked ripples show that there is some current activity, probably near the estuary mouth. The flat based sands are interpreted to have been deposited in parts of the delta top with little topographic variation, while the more channelised portions are interpreted as either feeder channels crossing the delta top or tidal channels. These channels can be distinguished from the fluvial channels (Facies No. 2) by the presence of marine fauna. Where leaves are found, these must have been deposited in a much more protected part of the coast, while the abundant carbonaceous laminae are comminuted plant material probably produced in high energy conditions.

While not a good environmental indicator, it is interesting to note the presence of rare vertically confined contorted or slumped beds within the sands of this lithofacies association. In some cases these may even develop into slump breccias, with remoulded 'clasts' made up of small detached contorted silty sand. These chaotic horizons probably originated by dewatering of individual beds, possibly triggered by palaeoearthquakes. In some areas these contorted beds can be traced over several kilometres at the same stratigraphic interval implying significant, albeit local, ground shaking.

4. Grey clays with rare silty sands

Sections: Taman Inda

Description. These sediments comprise thick grey clays, with occasional very thin but very laterally consistent silty sands. These have flat bases but may show low angle crossbeds and slightly rippled tops. Internal structures of many beds are obscured by development of ironstone during diagenesis. They commonly have thin carbonaceous laminae. There are also small winged channels, up to at least 50 cm in thickness, but generally less than 3 m in width. These show trough, or more rarely swaley crossbedding.

Palaeontology. The fauna recovered from this facies is very distinctive, and indeed helps to define this lithofacies. The most common constituent is small crabs, up to about 3 cm in length, beautifully preserved as casts within the diagenically developed ironstone layers. At least 15 species have so far been identified, the commonest of which are

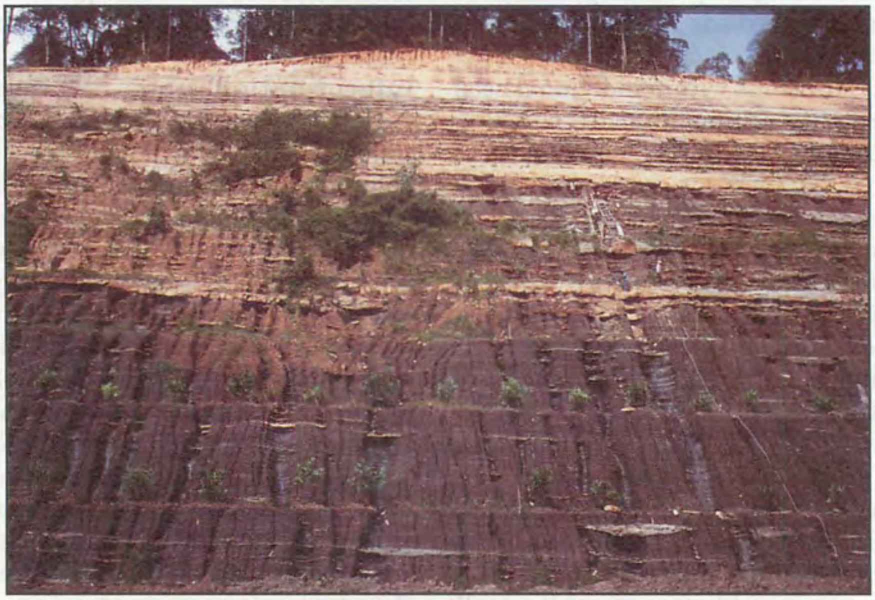

Figure 10. General view of the section at Taman Inda. A prograding sequence of three lithofacies associations can be distinguished in this excellent exposure. The lower interval comprises structureless mudstones containing abundant fossil crabs and rare winged channels, interpreted as having been deposited in a sheltered shallow marine environment (Facies 4). This unit is overlain by a heterolithic set of interbedded very fine grained sands, silts and mudstones (Facies 3). The uppermost interval consists of thick shoreface sands with abundant *Ophiomorpha* (Facies 5). See Figure 2 for location and Figure 5 for measured section at this locality.

Figure 11. Starved sand ripples in mudstone from the heterolithic facies, Facies 3, Taman Inda. See Figure 2 for location and Figure 5 for measured section at this locality.

swimming crabs (Table 1). There are also scallops, scattered oysters and other marine bivalves; gastropods, echinoids and worm tubes are common. Occasionally large but infrequent well rounded amber clasts occur.

Interpretation. These sediments are interpreted as shallow marine lagoonal or interdistributary bay facies, which lay in a relatively sheltered location, protected from open marine conditions. The fauna is marine, but the fine grain size and common swimming crabs show that the current energy was low. The fragments of oysters may have been washed in during storms, though it is possible that oysters colonised harder areas of the seabed.

5. Cross-bedded thick sands

Sections: Bird Quarry/Taman Inda

Description. Thick sand dominated sequences occur in much of the Southern and Eastern Sandakan Peninsula. These weather to form large scarps, which may reach more than 100 m in height. The typical succession is a 2 m to 5 m thick, flat based, fine occasionally medium grained sand, with trough or more rarely planar crossbedding on a metre-plus scale (Fig. 9). The sand grades up slightly to a very fine grained sand, which may show rippling, and is capped by a very distinctive ironstone-cemented rippled horizon. This commonly weathers out to show wave ripples ranging from megaripples with a wavelength of around 50 cm to fields of smaller wave ripples showing interference patterns typical of shallow marine seas washing over an undulating seabed. Ladderback ripples are also developed in places. The rippled horizons are in turn overlain by thin but laterally persistent plastic grey clays, which give way vertically to the next sandbody.

Palaeontology. No body fossils have been recovered from the this facies. *Ophiomorpha* burrows are generally abundant.

Interpretation. The bedforms and *Ophiomorpha* burrows in this facies suggest it was deposited in a shallow marine shoreface setting, either located offshore or adjacent to a beach. Smaller wave ripples are typical of shallow marine seas with an undulating seabed.

6. Thin to medium bedded sands with *Skolithos*

Sections: Section No. 9/142

Description. These sediments are composed almost entirely of sands, with interbedded mudstones usually absent but occasionally reaching a few centimetres in thickness. The sands are thin-medium bedded, with individual beds around 10 cm to 20 cm in thickness. The sands are flat based, and bedding is swaley and undulating, but rarely cuts down into the beds below. The most distinctive feature of these beds is the abundant vertical burrows, picked out by erosion as small sand pillars between beds. These burrows are thought to be the trace fossil *Skolithos*.

Palaeontology. Most of the fauna has been lost to dissolution, but occasional bivalve casts are of marine forms (see Locality 9, Table 1).

Interpretation. The sediments are interpreted as having been laid down as beach deposits, possibly on bar fronts where persistent wave reworking has removed the finer grained material.

7. Thin bedded muds

Sections: West and North of the Sandakan basin

Description. These sediments are represented by featureless mudstones, though some thin silty beds occur, which are generally less than 10 cm in thickness, with slightly erosive bases. Most of these are laterally impersistent, pinching out over a few metres. The silts show cross-lamination and have occasional horizontal and vertical burrows, as well as minor fine carbonaceous material on the bedding planes.

Palaeontology. Fauna removed by dissolution.

Interpretation. These sediments are interpreted as open marine shelf deposits, with the silts possibly representing storm-driven coarser clastic incursions.

CONCLUSIONS

1. The Sandakan Formation comprises approximately 2 km of interbedded sandstones and mudrocks formerly interpreted as undifferentiated marginal marine facies containing little fauna.
2. The Sandakan Formation was deposited in a very large marginal marine system showing a wide range of associated depositional environments (Fig. 12). Sedimentary bedforms and facies associations allow differentiation of fluvial, estuarine and shallow marine deposits.
3. The discovery of new macrofauna has been used to differentiate the various environments. This fauna includes: bird footprints and freshwater turtles, several crab species, gastropods, bivalves and borers, trees, leaves, carbonaceous material and amber containing insects.
4. Further work will involve synthesing the data collected from the Sandakan Formation both spatially and stratigraphically, in the aim of

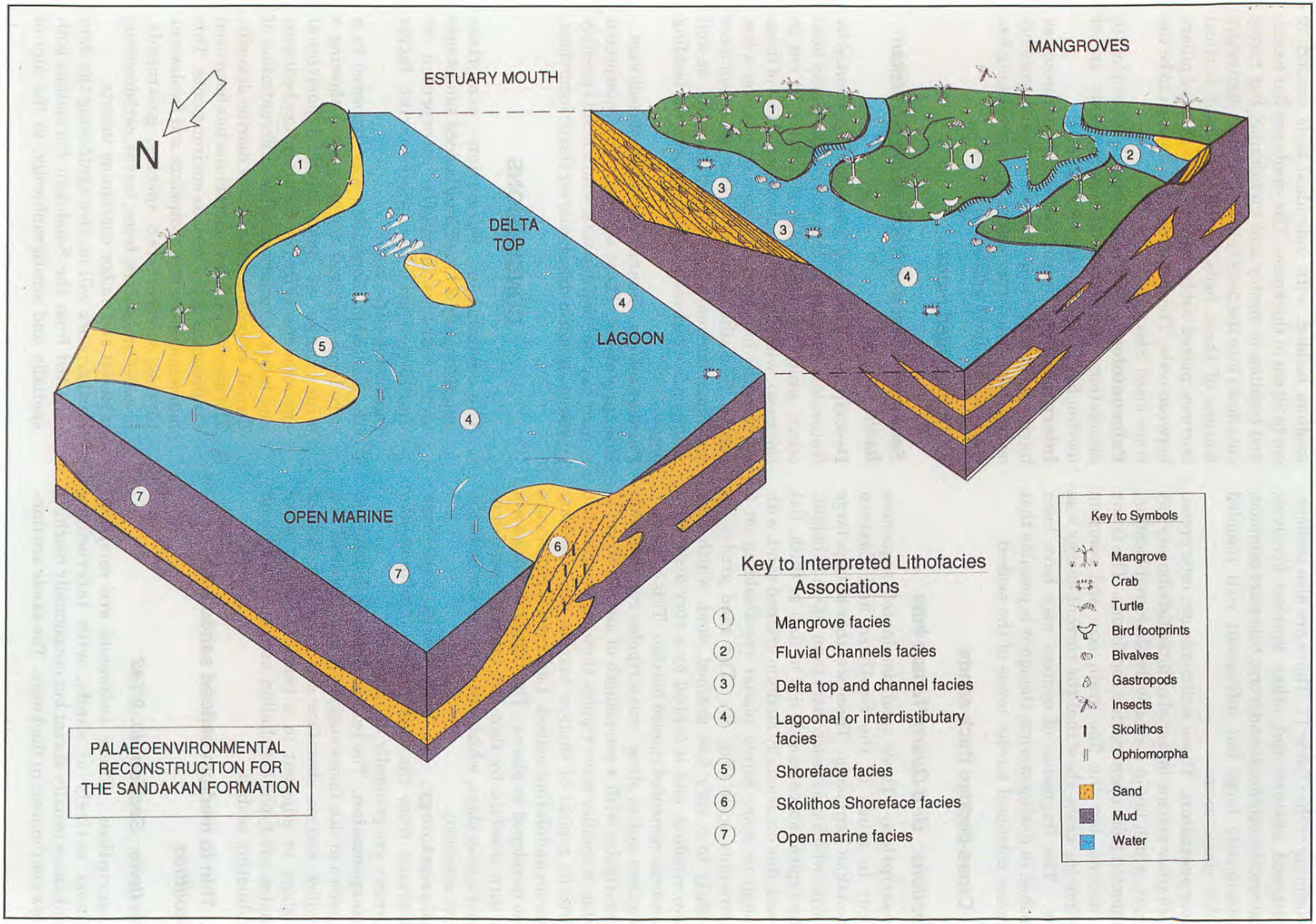

Figure 12. Palaeoenvironmental reconstruction of the Sandakan Formation.

developing a sequence stratigraphic model to explain the sedimentary evolution of the formation. Faunal data will allow the development of a biostratigraphic zonation scheme and help in determining the palaeobathymetry of the Sandakan sediments.

5. The data collected will allow reconstruction of the Miocene palaeogeography of the Sandakan Basin, and correlation with adjacent offshore data.

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