Microfossil assemblages as proxies for precise palaeoenvironmental determination – an example from Miocene sediments of northwest Borneo

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Abstract: Hydrocarbon reservoirs in northwest Borneo are often developed in 'paralic' depositional settings, although current exploration is evaluating relatively deep-water turbiditic plays. In the absence of conventional core, and with only ambiguous wireline log and seismic signatures being available, the use of microfossil data is considered to determine precise depositional setting. This is important because different depositional settings imply different reservoir qualities in terms of architecture, connectivity, heterogeneity and poroperm characteristics.

Equivalents of the reservoir succession are well exposed in northwest Brunei, and contain well-preserved sedimentary features and ichnofossils to determine precise depositional setting. Microfossil assemblages (both palynomorphs and foraminifera) have been sampled from each depositional environment identified at outcrop and by using an iterative approach, and incorporating data on modern distributions, diagnostic microfossil assemblages and taxa have been identified which can be used as precise palaeoenvironmental proxies. By using this approach distal turbidite, proximal turbidite, open shelf with slumping, open shelf, lower shoreface, upper shoreface, tidal flat with tidal channels, lower distributary channel, lagoon–distributary channel margin and upper distributary channel depositional environments can be recognized.

The discovery of oil at Miri in northeast Sarawak in 1910, followed by the discovery of the Seria Oilfield in Brunei in 1929 (Harper 1975), signalled the establishment of northwest Borneo as a world-class hydrocarbon province. In Brunei, exploration moved offshore in the 1960s leading to the discovery of numerous fields such as Champion, Magpie and Iron Duke (Sandal 1996). All these onshore and offshore discoveries were in 'paralic' (i.e. marginal marine) sediments of Miocene age. At the time of writing, exploration is moving into the deeper water offshore, searching for hydrocarbons in the turbidite equivalents of the existing paralic plays. In offshore Sarawak, the Miocene-aged Luconia carbonates also provide exploration and production opportunities, although will not be referred to further herein.

Biostratigraphy has always played an important role in exploration studies in the region. The reservoir and adjacent sediments are normally rich in spores and pollen, allowing for exploration-scale biozonation using pollen lineages such as the mangrove *Florschuetzia* (Morley 1991; Sandal 1996). Broad-scale chronostratigraphic calibration is achieved using the

occasional occurrence of calcareous nannofossils and planktonic foraminifera in sediments representing more open marine settings. Benthonic foraminifera assemblages have been used to establish broad palaeoenvironmental interpretations (James 1984; Sandal 1996).

As well as exploration in the deeper water offshore, the industry in northwest Borneo, as in many other parts of the world, is interested in maximizing recovery from existing fields. To do so requires a precise understanding of the depositional setting of the reservoir, so as to assess reservoir architecture, connectivity and compartmentalization, in order to locate horizontal and multilateral production wells efficiently. In the absence of cores, depositional setting is often interpreted from log signatures and seismic facies. However, in northwest Borneo, these are often ambiguous, it being difficult, for example, to distinguish shoreface sands from distributary channel sands, which have differing reservoir properties. It is our contention that biostratigraphy could hold the key, in combination with other subsurface methods, for determining precise depositional environment, which is so important for effective production strategies. Whilst biostratigraphy has always been used to determine depositional setting of subsurface samples, these interpretations have often been too broad for use in detailed reservoir interpretation. Samples have often been described as 'fluvio-marine', 'paralic' or 'deltaic'. These limited interpretations result from the following uncertainties.

- There is little information on the environmental distribution of the modern-day equivalents of the microfossils occurring in the reservoir succession.
- In terms of benthonic foraminifera, the assemblages are dominated by agglutinating forms, which are often difficult to interpret in terms of depositional environment. Such assemblages are often interpreted as indicating either low-oxygen, deep-marine environments, or freshwater-influenced, marginal marine environments. To hedge their bets, some biostratigraphic contractors have given interpretations of such assemblages as 'marginal marine to bathyal marine' – obviously an interpretation of limited value! The problem is further compounded in that because of the pressure of time constraints on the reporting of subsurface studies, many agglutinating foraminifera are identified to generic level only. For example, '*Trochammina* sp.' will have a (palaeo)environmental range of marginal marine to bathyal marine, but it

may be possible to identify species of *Trochammina* which are restricted to more precise depositional environments. R. W. Jones (pers. comm.) reports that in the Neogene basins of eastern Venezuela, speciation of *Trochammina* is indeed useful for such precise palaeoenvironmental definition.

In order to overcome these uncertainties we have conducted a study on the outcrop analogues of the subsurface reservoirs in northwest Borneo. There are extensive outcrops of the equivalents of the subsurface reservoirs in Brunei, in northeast Sarawak and on the island of Labuan (Fig. 1). These outcrops are broadly age equivalent to the reservoir successions (see the section on 'Chronostratigraphic results' below) and encompass the range of depositional environments known to occur in the subsurface. Sedimentary structures and trace fossils are often very evident at outcrop, permitting a precise and accurate interpretation of depositional environment (Lambiase *et al.* in press). A range of depositional environments from fluvial, through tidally influenced distributary channel, lagoon, estuarine, upper and lower shoreface, open inner shelf, deep shelf and proximal and distal turbidite are all recognized. We have sampled a representative set of outcrops encompassing the full range of depositional environments noted above. Each sample has been processed and prepared for the study of its content of foraminifera and palynomorphs. By undertaking an iterative approach, whereby the interpretations of depositional environment from the microfossils, sedimentology and ichnology are combined, we have been able to recognize microfossil assemblages which characterize each of the depositional environments recognizable from sedimentology. We believe that this will have great practical value in the subsurface where, in the absence of core, detailed sedimentology is not possible. Microfossils, as recovered from cuttings and sidewall cores, can now be used as precise palaeoenvironmental proxies for interpreting the reservoir succession, thus permitting biostratigraphy to be a valuable tool when applied to production and development geology. A very similar approach has been adopted in the palaeoenvironmental interpretations of the deltaic sediments of Miocene–Pliocene age of the East Venezuela basin (Jones *et al.* 1999).

Geological background

Excellent descriptions of the geology of Brunei and northwest Borneo can be found in the recent publication by Brunei Shell Petroleum (Sandal
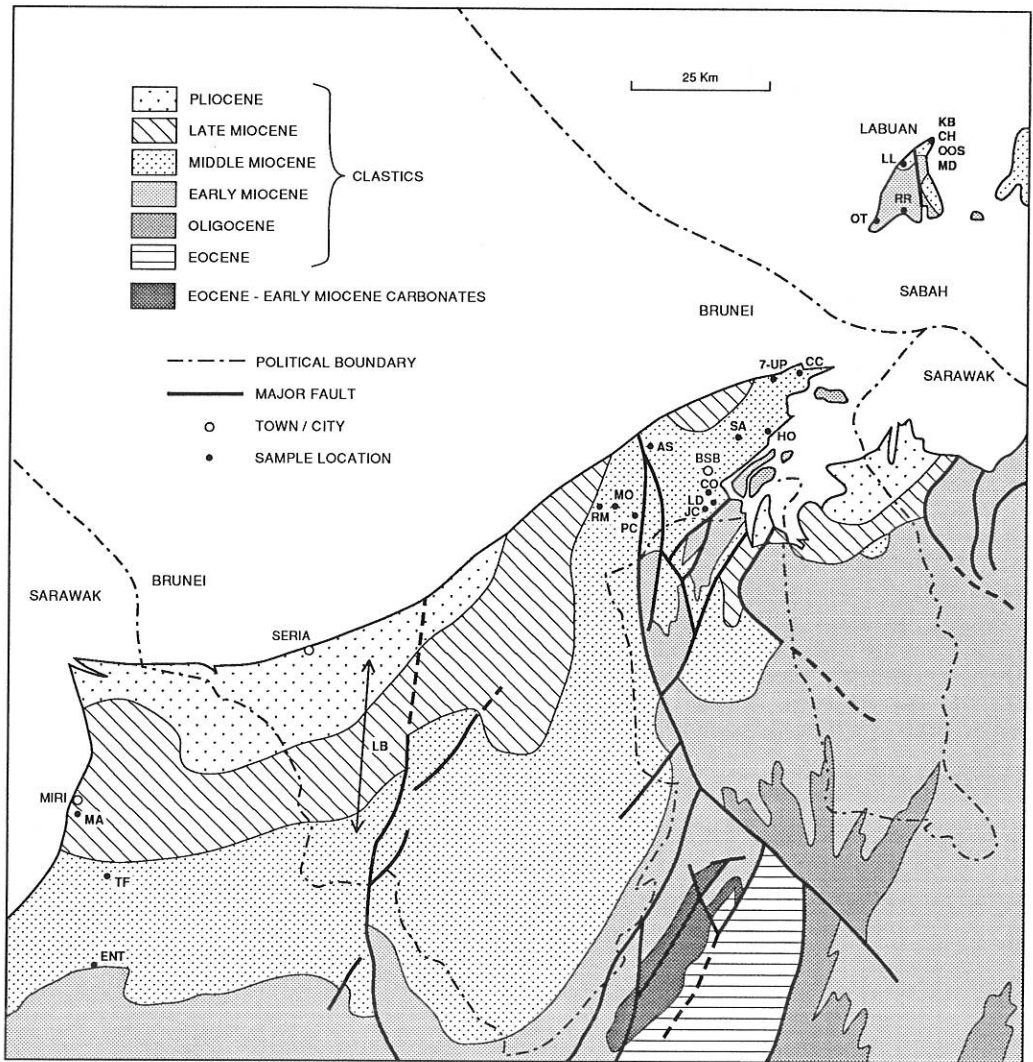
Fig. 1. Geological map of northwest Borneo (modified after Sandal 1996), showing the location of outcrops sampled during this study and referred to in the text. Political boundaries are approximate.

1996) and its predecessor (James 1984). As noted above, the main reservoirs of northwest Borneo were developed in a 'paralic' setting (see also Prosser & Carter 1997). The collision of the Sundaland plate and South China Sea portion of the Eurasian plate in the Late Palaeogene–Neogene led to the development of the Crocker–Rajang mountain belt. This uplifted sediments of the former Crocker–Rajang accretionary complex, subsequent erosion of which caused several rapidly prograding clastic depositional systems to develop. These are usually referred to as 'deltas', but we prefer to refer to them as

prograding clastic systems as they represent a more complex set of depositional environments than can be envisioned within a deltaic model. Initially, an Early Miocene Melingan prograding clastic system was deposited, followed by a Middle–Late Miocene Champion system and a Late Miocene–Quaternary Baram system. Sediments of the Champion prograding clastic system are the focus of this study as they form the sediments at outcrop and the majority of subsurface reservoirs.

As noted above, the Neogene depositional systems are much more complex than can

be characterized by envisaging three progradational delta complexes. First, a complex interaction between tectonics and sedimentation resulted in the progressive partitioning of the Neogene deltaic depocentres into sub-basins. A number of diapir-cored structures grew episodically and simultaneous with deposition (Morley *et al.* 1998), which profoundly altered depositional settings on a local scale. Secondly, high-frequency changes in sea level caused not only progradation, aggradation and retrogradation, but also marked changes in the profile of the coastline. In terms of a general depositional model for the studied sediments, analogy with parts of the coastline of modern-day northwest Borneo (e.g. Brunei Bay) is likely, as is analogy with the sub-Recent Baram delta, which was flooded *c.* 5400 years BP (Caline & Huong 1992). A coastline with variable wave, tidal and fluvial dominance (as in modern Brunei Bay) seems likely, into which major river systems were feeding. In times of falling relative sea level these formed progradational clastic systems ('deltas'). At times of relative sea-level rise, large estuaries were formed. Our studies of the outcrops (see Lambiase *et al.* in press) suggest that classical deltaic sequences are rarely observed. Instead, much of the Miocene

sedimentation falls more readily into a model dominated by large estuaries such as modern-day Brunei Bay. The palaeogeographies of north-west Sabah presented by Rice-Oxley (1991) support this contention.

In terms of lithostratigraphy (Fig. 2) these sediments are assigned to the Belait Formation in Brunei and Labuan, which prograges over the older, basinal Setap and Temburong formations. In northeast Sarawak and western Brunei, the progradational complex includes the Sibuti, Lambir and Miri formations. This lithostratigraphic separation of northeast Brunei and northeast Sarawak reflects a further complication of the Neogene depositional systems in that the Lambir and Berekas sub-basins had independent controls on deposition, much like at present where in the west the Baram delta is being deposited, whilst in the east the large estuary of Brunei Bay occurs. In the Lambir sub-basin sedimentation tends to be wave-dominated, whilst in the Berekas sub-basin sedimentation is more tidally influenced. Geological maps published by James (1984) and Sandal (1996) indicate the occurrence of the Miri Formation in northeast Brunei, suggesting the need for a fundamental revision of the lithostratigraphy of the region.
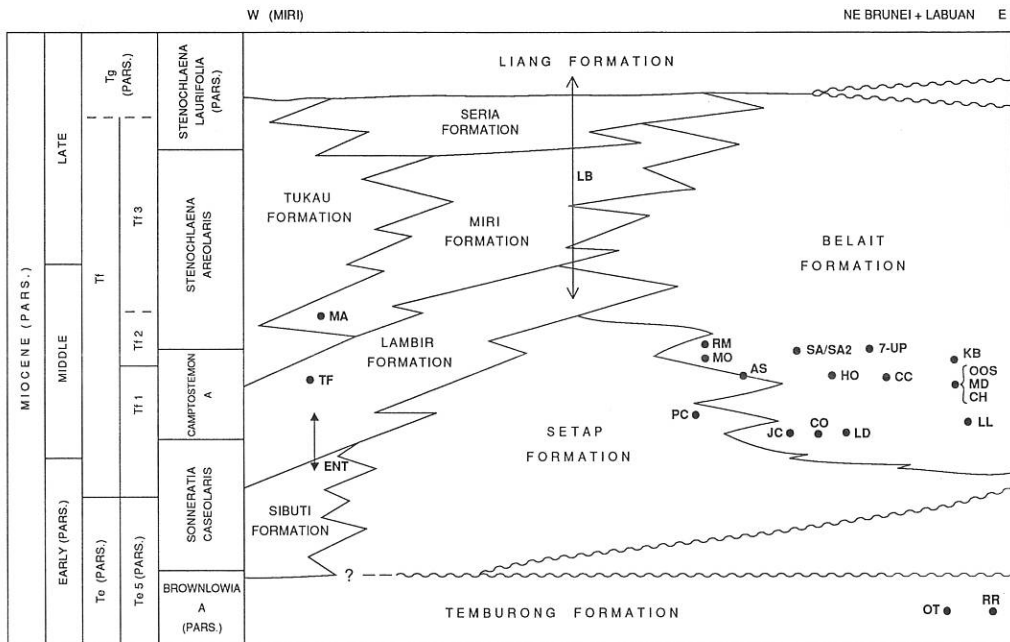

Fig. 2. Stratigraphic summary diagram of northwest Borneo, showing lithostratigraphy v. local biostratigraphy and chronostratigraphy (modified after Sandal 1996), and the stratigraphic position of outcrops sampled during this study and located in Fig. 1.

Sample locations

Figure 1 shows the geographic locations of the outcrops sampled during this study and Fig. 2 their stratigraphic position (see also discussion of chronostratigraphy below). Over 200 samples from 28 different localities have been studied in the course of this project.

Three localities were studied south of Miri in Sarawak. The ENT section in the Lambir Hills represents the transition from the Sibuti facies of the Setap basinal succession, into the wave-dominated prograding shoreface sediments of the overlying Lambir Formation. The lower part of the succession represents open shelf sedimentation (Sibuti Formation/facies), whilst the upper part (Lambir Formation) represents storm-influenced lower and upper shoreface deposition. The TF section, also in the Lambir Hills, represents upper shoreface deposition of the Lambir Formation cut by major distributary channels. The MA section represents a sand-rich tidal flat–beach succession in the Miri Formation, exposed in the crest of the Miri anticline, just south of the town of Miri.

Eighteen different outcrops were visited in Brunei, the most significant of which are as follows. CC is from an outcrop near the abandoned Brookerton Colliery where a tidally influenced estuarine succession is cut by a distributary channel, which is subsequently infilled by tidal flat deposits, culminating in coal deposition. 7-UP is from the 7-UP beach succession, which exposes a muddy embayment sequence punctuated by sand-filled tidal channels and tidal flats. AS, near Jerudong, represents the transition from the basinal Setap Formation to the prograding deposits of the Belait Formation. Open shelf sediments are well exposed. The nearby PC outcrop also represents open shelf deposition, but where syn-depositional tectonics have led to slumped blocks being redeposited on the margins of an open shelf environment. Lower shoreface deposits of the Belait Formation are well exposed at the MO locality to the west of Jerudong, whilst at RM there are good exposures of upper shoreface deposits. The SA2 succession along the Sungai Akar road presents a good succession of upper shoreface sediments, whilst the underlying SA succession represents a tidal flat–tidal channel complex. The HO succession on the Kota Batu road is also a tidal flat–tidal channel succession, cut by distributary channels and with an embayment succession culminating in coal deposition.

Seven outcrops were studied on the island of Labuan which represent a variety of depositional settings. OT is from the oil terminal at the southwest corner of the island, and is in proximal turbidite facies of the Temburong Formation. RR is from a temporary outcrop at Rancha-Rancha on the southern coast of the island and is the distal turbidite equivalent of OT. LL is Lyang-Lyang Beach on the west coast of the island were the basinal Setap Formation (in distal delta front/lower shoreface facies) is abruptly overlain by fluvial sediments of the Belait Formation equivalent. A similar situation occurs at Kubong Bluff (KB) on the northern tip of the island, although there the Belait Formation equivalent includes fluvial, tidal flat and lower shoreface facies. Further lower shoreface deposits are exposed at the MD outcrop close to KB, along with upper shoreface, tidal flat and tidally influenced distributary channel deposits. CH and OOS are further small outcrops of the lower shoreface facies of the Setap Formation at the northern end of the island.

Chronostratigraphic results

The paralic Belait, Lambir and Miri formations, which are the focus of this study, generally lack microfossils suitable for high-resolution chronostratigraphic determinations. Planktonic foraminifera and calcareous nannofossils are almost absent, whilst most benthonic foraminifera species tend to be long ranging, or are new species of uncertain age range. Age determinations thus tend to be based on spore and pollen palynology, as originally defined by Muller and co-workers (Muller 1964, 1969, 1972; Germeraad et al. 1968) and refined by Morley (e.g. Morley 1991). Age-significant forms include the lineage of mangrove pollen of the genus *Florschuetzia*, and the pollen *Camptostemon*, *Dacrydium*, *Praedapollis* and *Piceapollenites*. Within the open marine Setap Formation (and equivalents), beneath the Belait and Lambir formations, and in the offshore facies equivalents of the proximal facies of the Belait and Lambir formations, in addition to age significant spores and pollen, some age-significant planktonic foraminifera (Eckert 1970) and dinoflagellates (Besems 1993) occur.

At all the outcrops studied the Setap Formation and its equivalents, directly beneath the Lambir and Belait formations, is of Early Miocene age, based on the presence of *Florschuetzia trilobata* and the absence of *Camptostemon* sp. At the ENT section in the Lambir Hills a transitional section between the Setap Formation ('Sibuti facies') and the Lambir Formation is exposed. Here the Sibuti Formation contains planktonic foraminifera indicative of an Early

Miocene age (presence of *Globigerinoides obliquus*; absence of *Orbulina* spp.), whilst the presence of *Florschuetzia levipoli* and *Florschuetzia meridionalis* suggests a late Early Miocene age (the association of the calcareous nannofossils *Sphenolithus heteromorphus* with *Reticulofenestra haqii* and *Reticulofenestra minuta* also supports this age assignment). The overlying mudstones and sandstones of the Lambir Formation are no older than intra-Middle Miocene based on the co-occurrence of *F. trilobata* and *Camptostemon* sp. This suggests that there is an unconformity between the Setap and Lambir formations at this locality, with the earliest Middle Miocene being absent. The presence of slight angular disconformity in the outcrop and abrupt change in depositional environments supports this possibility. On the island of Labuan a similar situation exists where the uppermost Setap present (outcrop LL) is Early Miocene in age based on the abundance of *F. trilobata*, presence of *Praedapollis* sp. and absence of *Camptostemon* sp., whilst the lowest paralic sands (outcrop KB) are intra-Middle Miocene based on the presence of *Camptostemon* sp.

It appears that at all the localities studied, in the Lambir, Belait, Berakas and Labuan sub-basins (outcrops AS, ENT, KB, MO, PC and RM), the onset of paralic sedimentation (i.e. progradation of the various delta systems) is approximately synchronous within the resolution of biostratigraphy. These initial deltaic sands are all intra-Middle Miocene in age, corresponding to the stratigraphic inception of *Camptostemon* sp. *Florschuetzia meridionalis* also occurs in relatively large numbers, as opposed to *Florschuetzia trilobata* or *Florschuetzia levipoli*. It seems likely that an intra-Middle Miocene tectonic event caused uplift of the Crocker Range in central Borneo, and caused simultaneous progradation of clastic depositional systems into the South China Sea from both southeasterly and southwesterly directions.

Stratigraphic differentiation within the Belait, Lambir and Miri formations is hampered by the lack of chronostratigraphically significant microfossils. However, outcrops known to be in the upper part of the Belait Formation (at the SA–SA2 sections in Brunei) are regarded as being distinctively younger, no older than late Middle Miocene, based on the co-occurrence of *F. trilobata* and *Dacrydium* sp.

Turbiditic sediments of the Temburong Formation exposed on the southern part of Labuan Island (outcrops OT and RR) form the oldest sediments studied herein, being of early Early Miocene age based on the presence and abundance of *F. trilobata* and *Piceapollenites* sp. One clast from the OT locality demonstrates the reworking of Middle Eocene pelagic sediments with abundant Middle Eocene planktonic foraminifera, dinocysts and calcareous nannofossils being present. In other samples from these localities reworking of Oligocene sediments is evident.

It is clear that high-resolution correlation within the Belait, Lambir and Miri formations will not be possible using microfossil inception and extinction events. Quantitative studies such as those proposed by Chow (Shell Sarawak internal reports) for offshore Sarawak may be of value, using ratios of climatically sensitive pollen taxa to detect a high-resolution climatostratigraphic signal. However, the strong palaeoenvironmental control on microfossil assemblages as described below needs to be borne in mind, as this may result in correlations of similar depositional environment being confused with chronostratigraphically significant correlations. Studies of whole-rock geochemistry to recognize geochemical correlations may prove useful, although, once again, palaeoenvironmental (and also diagenetic) controls will have to discounted before correlations can be regarded as truly chronostratigraphic.
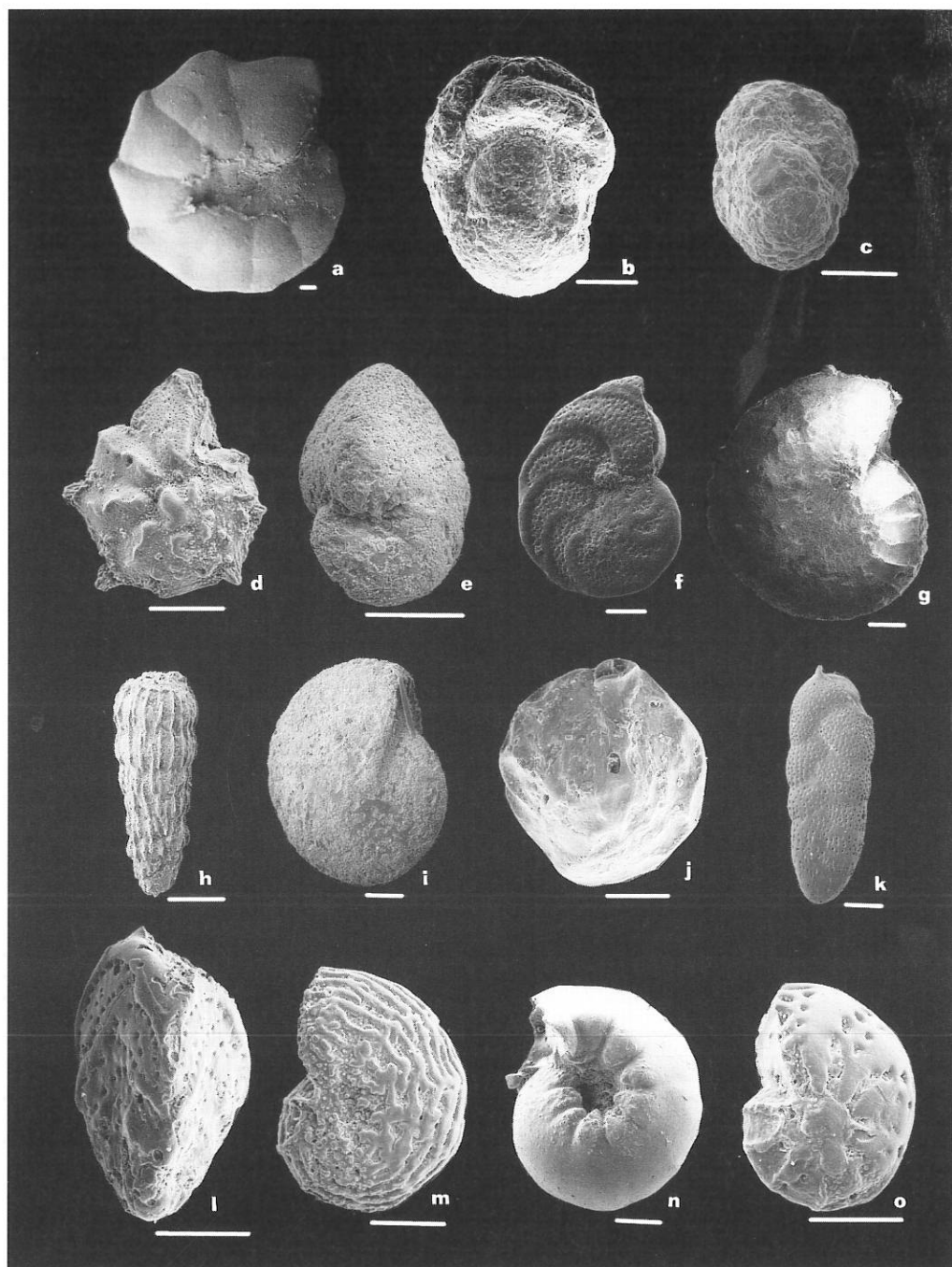
Palaeoenvironmental proxies

As noted above, the Miocene sediments of northwest Borneo are reasonably rich in palynomorphs and foraminifera. Foraminiferal assemblages are typically dominated by agglutinated forms, but in open marine shelfal settings calcareous forms are relatively common, including sparse planktonics. Comparison with the coeval faunas of Sabah (Whittaker & Hodgkinson 1979), Indonesia (Van Marle 1991) and the Sunda Shelf (Biswas 1976) is possible. The seminal review of the Recent foraminifera collected on the Challenger Expedition of the last century by Jones (1994) provides an invaluable guide for identification of taxa encountered in this study.

The taxonomy and palaeoenvironmental significance of the agglutinating foraminifera present in the studied sediments has recently been assessed by Bidgood *et al.* (in press), in a study allied to that presented here. Knowledge of the agglutinated foraminifera occurring in the Neogene–Recent sediments of northwest Borneo is relatively limited (although see Bronnimann & Whittaker (1993) for a discussion of Recent agglutinated foraminifera from the Malay Archipelago). It is clear from the work of Bidgood *et al.* (in press) that several undescribed taxa

ENVIRONMENT OF DEPOSITION	PALYNOLOGY											FORAMINIFERA													
	MANGROVE	BACK-MANGROVE	COMPETACEAE	FRESHWATER SWAMP	DIPTEROCAPACEAE	PALMS	GYMNOSPERMS	FRESHWATER ALGAE	DINOCYSTS	SPORES	REWORKING	PLANKTONICS	CALCAREOUS BENTHONICS	CALCAREOUS AGGLUTS	AGGLUT DIVERSITY	FINE 'TROCHAMMINA'	WHITE SUGARY 'TROCHAMMINA'	COARSE 'TROCHAMMINA'	'TEXTUKURNUBIA'	'PSEUDOEPISTOMINA'	'CYCLAMMINA'	KARRERIELLA	TREMATOPHRAGMOIDES	MILIAMMINA	HAPLOPHRAGMOIDES CF. EGGERI
DISTAL TURBIDITE	VR	O		O		O	O		VR	C-A					LOW	C-A									
PROXIMAL TURBIDITE	C-A									C-A	Abt				LOW	C-A					R				R
OPEN SHELF WITH SLUMPS	O	O		O-C		O-C			VR	C		R	Abt	C	MOD	C			C						
OPEN SHELF	R-O	R		R-O		R-O			R-A	C-A		R-C	C-A	O	MOD		C					O			
LOWER SHOREFACE	R-O	R		R		O-C			VR	C-A					MOD		C			R-C					
UPPER SHOREFACE	R	R		R		O-C				C		VR	VR		MOD		C					O			
TIDAL FLAT + TIDAL CHANNEL	C	R	(C)	R	(C)	C		O	VR	C					MOD			C							
LAGOON OR DISTRIBUTARY CHANNEL MARGIN	Abt									R					LOW			R			·		C	C	
LOWER DISTRIBUTARY CHANNEL	C	C				C			VR	O-C					MOD			C		R					
UPPER DISTRIBUTARY CHANNEL + FLUVIAL	VR	C		C		VR		O		Abt					NIL										

Fig. 3. Distribution of groups of microfossils recognized within this study v. deposition environments recognized at outcrop and thought to occur in the subsurface. This chart is the basis for the discussion in the palaeoenvironmental proxies part of this paper.

occur. This observation, together with the differentiation of forms of common genera such as *Trochammina*, *Recurvoides* and *Cyclammina*, permits the use of agglutinating foraminifera as reasonably precise palaeoenvironmental indicators. This is further supported by the work of Bronniman & Keij (1986) in reviewing the occurrence of modern agglutinated foraminifera in the estuaries and bays of Brunei, whilst the work of Dhillon (1968) and Ho (1971) provides useful information on the modern distribution of all groups of foraminifera in northwest Borneo.

Palynomorphs are often abundant in the studied material and can be used for palaeoenvironmental interpretation (see also Haseldonckx 1974). However, most samples contain material redeposited from hinterland environments, thus initial interpretations of palynological assemblages can result in interpretations which are significantly more proximal than when the whole microfossil assemblage and sedimentology are considered.

In the discussion of palaeoenvironmental proxies below, palynomorphs are grouped into categories based on their general environmental preferences and taxonomy.

Mangrove belt – including *Zonocostites* (=modern *Rhizophora*), *Avicennia* and *Florschuetzia* (= modern *Sonneratia*).

Back-mangrove – including *Acrostichum* and Combretaceae.

Coastal gymnosperms – including *Casuarina*.

Freshwater swamp – including *Blumeodendron*, *Calophyllum*, *Dicolpopollis*, *Lanagiopollis*, Dipterocarpaceae, Pentace, *Camptostemon* and *Marginopollis concinnus* (=modern *Barringtonia*).

Coastal and mangrove palms – including *Oncosperma* and *Spinizonocolpites echinatus* (=modern *Nypa*).

Hinterland gymnosperms – including *Dacrydium* and *Pinus*.

Freshwater algae – including *Pediastrum* and *Botryococcus*, the later also being present in saline waters such as those present in lagoons and intertidal regions.

Marine dinocysts – including *Spiniferites*, *Systematophora* and *Operculodinium*.

Hinterland spores – including *Laevigatosporites*, *Verrucatosporites*, *Leiotriletes*, *Selaginella* and *Lycopodium*.

This gives the broad environmentally controlled elements of any palynological assemblage within the studied samples. Obviously, most pollen and spores can be dispersed from the location of the plant they originate from. In our attempt to nominate palaeoenvironmental proxies, we consider the relative abundance of these elements in the context of the production rate of pollen or spores from the parent plant. Thus, for example, we consider the abundance of freshwater swamp elements and back-mangrove elements even in sedimentary environments we know to be relatively distal.

Anderson & Muller (1975) concluded that palynological assemblages from a Miocene coal within the Belait Formation were similar to those from a Holocene peat. Although the Miocene coal sampled by these authors may be from a different locality to those sampled by us, we cannot concur with their conclusions relating to the origin of the Belait Formation coals. All the coals we have sampled are extremely rich in mangrove pollen (to the exclusion of other types) (see further discussion below), and we suggest that these coals formed by infilling of distributary channels by mangrove swamps during late highstand, or by accumulation of mangrove swamp vegetation on windward or current protected edges of distributary channel mouths as happens in modern Brunei Bay.

From the outcrops noted earlier, 10 distinct depositional environments can be recognized on the basis of their integrated sedimentology,

Fig. 4. Some representative foraminiferal taxa from various palaeoenvironments from the northwest Borneo area. All scale bars = 100 μm. (**a**) '*Cyclammina*' sp. Characteristic of proximal turbidite settings. Recorded so far from offshore borehole material only. Generic character (alveolar wall) unclear. (**b**) '*Recurvoides*' sp. Form characteristic of proximal and distal turbidite settings. Note the fine-grained agglutinated wall structure. Generic character (streptospiral coiling) unclear. (**c**) '*Trochammina*' sp. Form characteristic of proximal and distal turbidite settings. Note the fine-grained agglutinated wall structure. Apertural position unclear. (**d**) *Asterorotalia* sp. Characteristic of 'normal' open shelf and open shelf with slumps settings. (**e**) *Nonion* sp. Characteristic of 'normal' open shelf settings. (**f**) *Planulina* cf. *wuellerstorfi* (Schwager). Characteristic of 'normal' open shelf and particularly open shelf with slumps settings. (**g**) *Operculina* sp. Characteristic of 'normal' open shelf settings, probably deeper parts of the shelf. (**h**) *Rectuvigerina ?striata* (Schwager). Characteristic of 'normal' open shelf settings. (**i**): *Lenticulina* sp. Characteristic of 'normal' open shelf settings. (**j**) *Quinqueloculina parkeri* (Brady). Characteristic of 'normal' open shelf settings, probably shallower parts of the shelf. (**k**) *Bolivinita spathulata* (Williamson). Characteristic of 'normal' open shelf and open shelf with slumps settings. (**l**) *Reusella simplex* (Cushman). Characteristic of 'normal' open shelf settings. (**m**) *Lenticulina* sp. nov. Characteristic of 'normal' open shelf settings. (**n**) *Hanseniisca neosoldanii* Brotzen. Characteristic of 'normal' open shelf and open shelf with slumps settings. (**o**) *Elphidium* sp. Characteristic of 'normal' open shelf and open shelf with slumps settings.
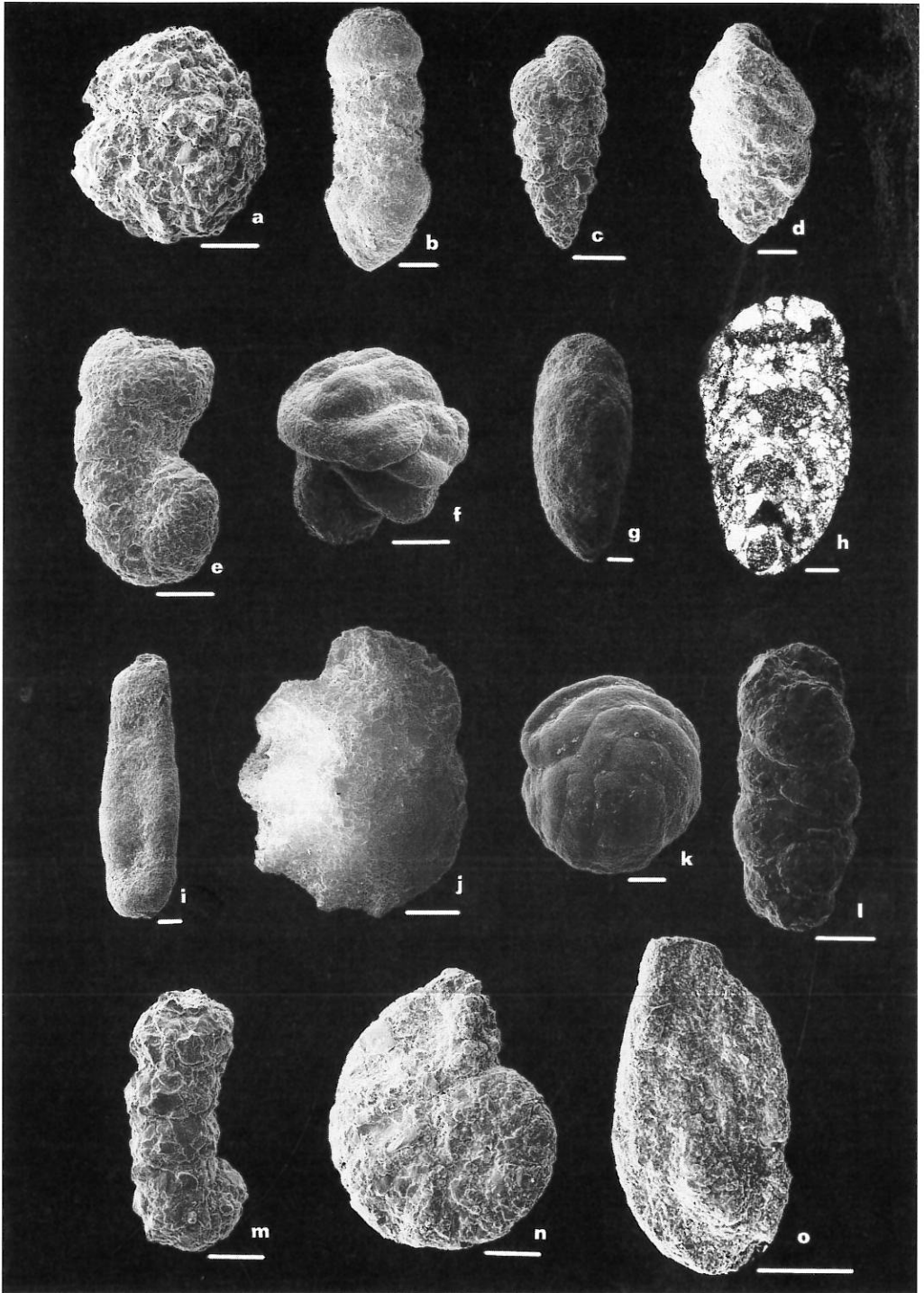
ichnology, micropalaeontology and palynology. These are: distal turbidite; proximal turbidite; open shelf with slumping; open shelf; lower shoreface; upper shoreface; tidal flat with tidal channels; lower distributary channel; lagoon–distributary channel margin; and upper distributary channel. We believe that each of these depositional environments has its own distinctive microfossil assemblages based on our empirical observations of the outcrops and our (limited) knowledge of the modern-day distributions of the equivalents of the microfossils occurring in these assemblages. An important point to stress is that it is essential to study palynology in conjunction with foraminifera. Neither discipline alone will give unequivocal results, whilst the combination of palynological data with foraminiferal data is a powerful tool for interpreting depositional environments. These results are summarized in Fig. 3 and considered in more detail below. Figures 4–13 illustrate the key microfossils and microfossil assemblages referred to in the text.

Distal turbidite

Distal turbidite deposits of northwest Borneo contain microfossil assemblages which differ markedly from what might be expected from similar-aged deposits from other parts of the world. Contrary to expectations, planktonic foraminifera and dinocysts are very rare or absent. The reason for this is that in the modern day the Baram, Temburong and Brunei rivers, and others, input immense amounts of freshwater onto the northwest Borneo shelf, causing a freshwater plume to be developed which extends far out into the South China Sea. Such freshwater plumes are thought to have been present during the Miocene and would have severely impacted upon the occurrence of stenohaline marine plankton such as planktonic foraminifera and most dinocysts. Other examples of this phenomenon have been described by Brenac & Richards (1998) and Dunay et al. (1998). Palynological assemblages are thus rather impoverished, containing very rare or occasional back-mangrove elements, gymnosperms, palms and freshwater swamp species. Mangrove pollen and dinocysts are extremely rare. However, spores can be common–abundant, testifying to their marked abilities for dispersal, and leading to possible misinterpretation of such assemblages as representing more proximal, marginal marine environments.

Foraminiferal assemblages are rather distinctive, containing abundant agglutinating forms especially fine-grained and often deformed specimens of 'Trochammina/Recurvoides'. The fine-grained nature of the wall (individual agglutinated particles typically no more than 2–3 μm in

Fig. 5. Some representative foraminiferal taxa from various palaeoenvironments from the northwest Borneo area. All scale bars = 100 μm. (**a**) 'Trochammina' sp. Note the coarse agglutinating wall structure which is often white and 'sugary' in texture. This is a characteristic of this taxon in open shelf and, particularly, shoreface assemblages. (**b**) Martinoltiella? sp. 1 (sensu Bidgood et al. in press). Characteristic of open shelf and upper shoreface settings. (**c**) Textularia agglutinans. Characteristic of open shelf and open shelf with slumps settings where Textulariidae are fairly diverse. This particular form is also found, rarely, in tidal channel and shoreface settings. (**d**) Textularia sp. 2 sensu Bidgood et al. (in press). Characteristic of open shelf and open shelf with slumps settings. (**e**) Ammobaculites sp. 1a (sensu Bidgood et al. in press). Characteristic of lagoonal depositional settings. (**f**) Glomospira gordialis (Jones & Parker). Characteristic of fully marine environments. (**g**) 'Textukurnubia' sp. sensu Bidgood et al. (in press). This large highly distinctive cigar-shaped form has been found commonly in marine shelf with slumps settings. (**h**) 'Textukurnubia' sp. sensu Bidgood et al. (in press). Thin-section photograph showing predominantly biserial chamber arrangement. (**i**) Uncertain genus No. 1 (sensu Bidgood et al. in press). This distinctive form of as yet unproven affinity is found in association with 'Textukurnubia' and other agglutinants in open shelf with slumps settings. (**j**) 'Pseudoepistomina' sp. sensu Bidgood et al. (in press). Another distinctive agglutinant which displays characteristic sunken chamber walls. It is found in shoreface and lower distributary channel–estuarine settings. (**k**) 'Glomospira' glomerata (Hoeglund). This glomospirid is recorded from open marine (both shallow and deep) settings, as well as being found in lower shoreface environments. (**l**) Karreriella sp. Karreriella is recorded from most marine environments from deep waters up to shoreface settings. It displays changes in wall structure with fine-grained and coarse-grained forms (such as that illustrated here) recorded from offshore and nearshore waters, respectively. (**m**) Ammobaculites exiguus Cushman & Bronnimann. This species appears to have a preference for shallow-marine and shoreface settings but has also been recorded from lagoonal samples. It is commonly regarded throughout the area as a general 'fluvio-marine' indicator. (**n**) Trematophragmoides bruneiensis Bronnimann & Keij?. This form has been recorded from brackish (lagoonal, mangrove swamp or overbank) settings. (**o**) Miliammina fusca (Brady). This form has a wide environmental preference (brackish hypersaline marshes to upper bathyal) according to Murray (1991). However, in the northwest Borneo study area it is a commonly recorded component of marsh and lower distributary channel environments where it is often associated with abundant mangrove pollen.
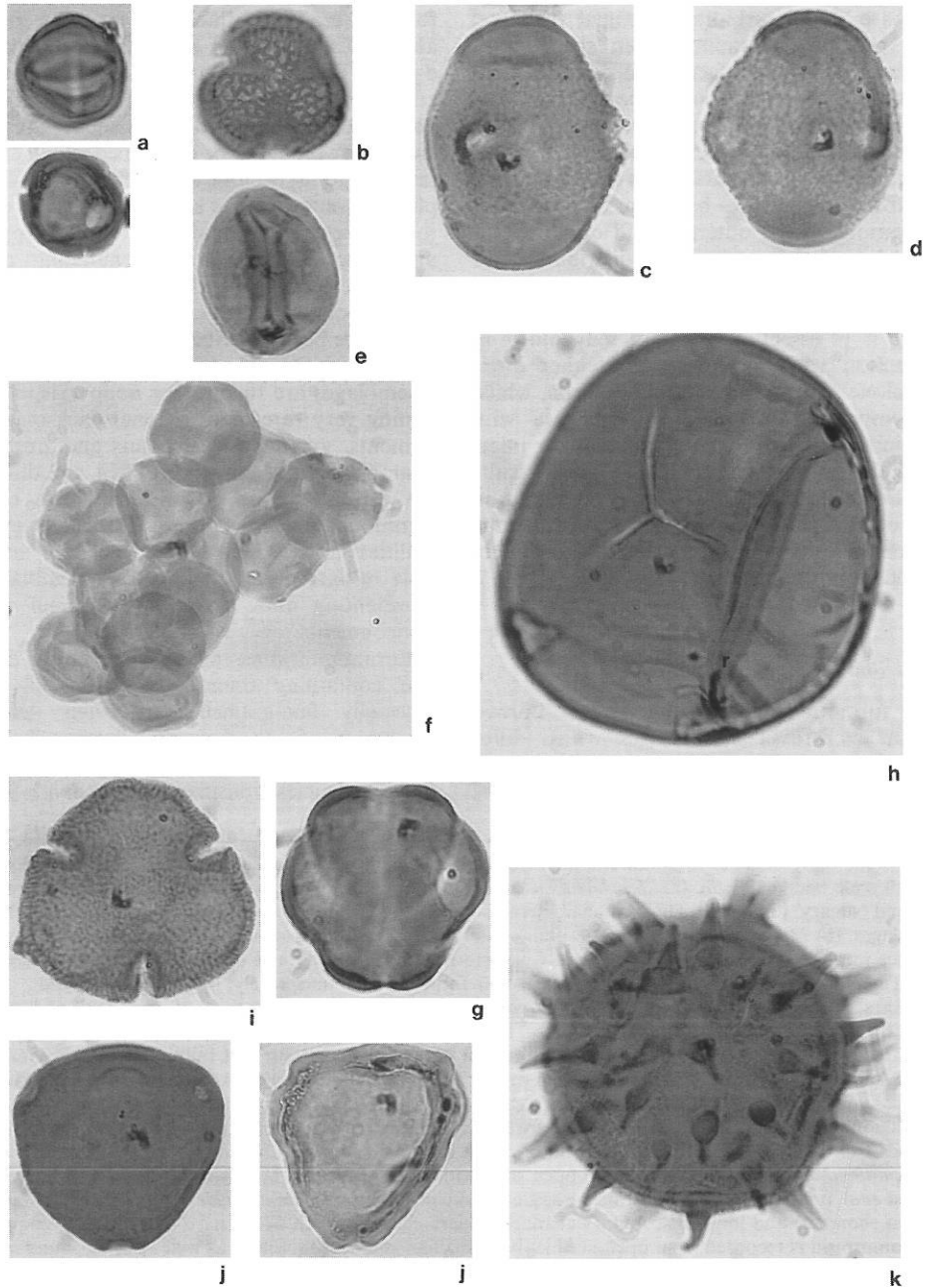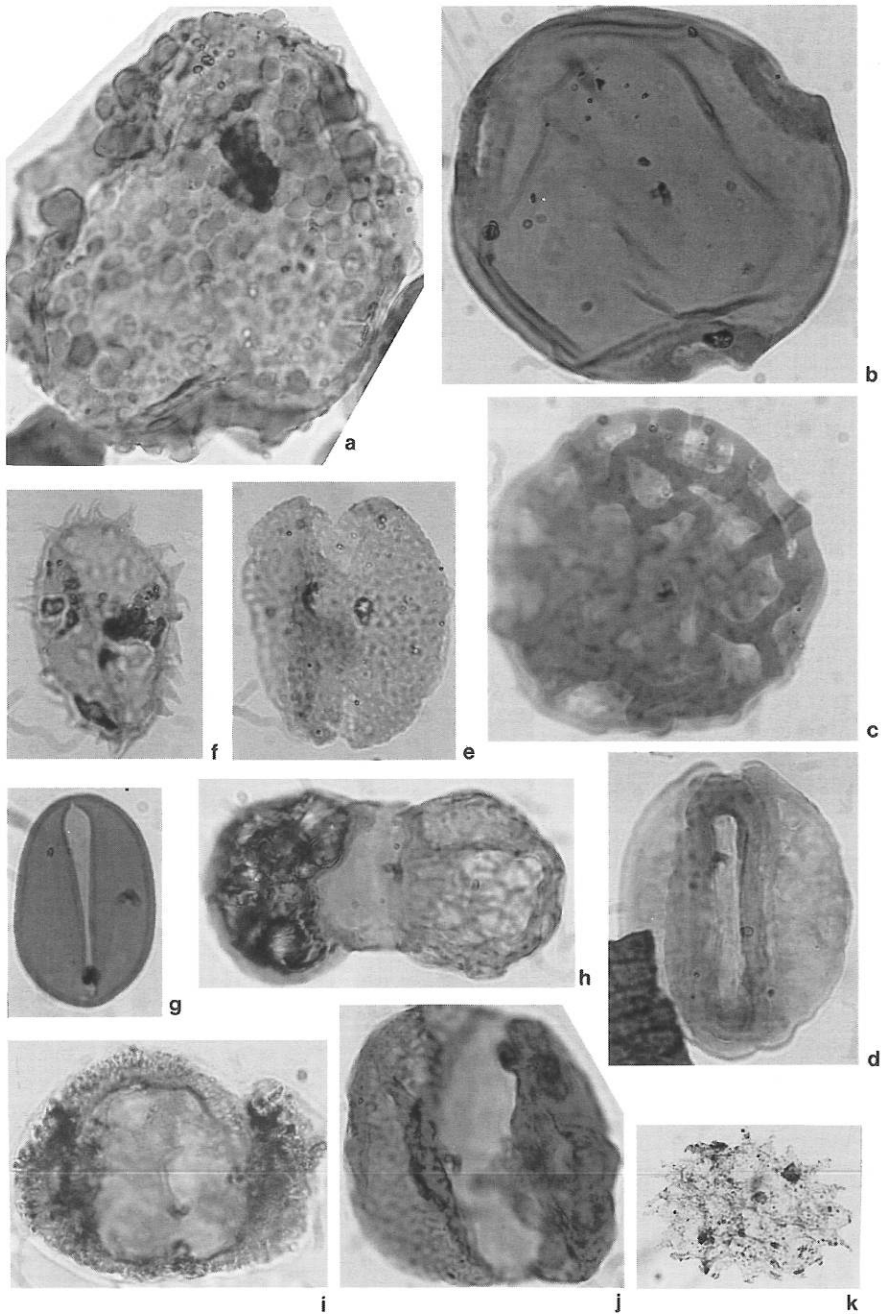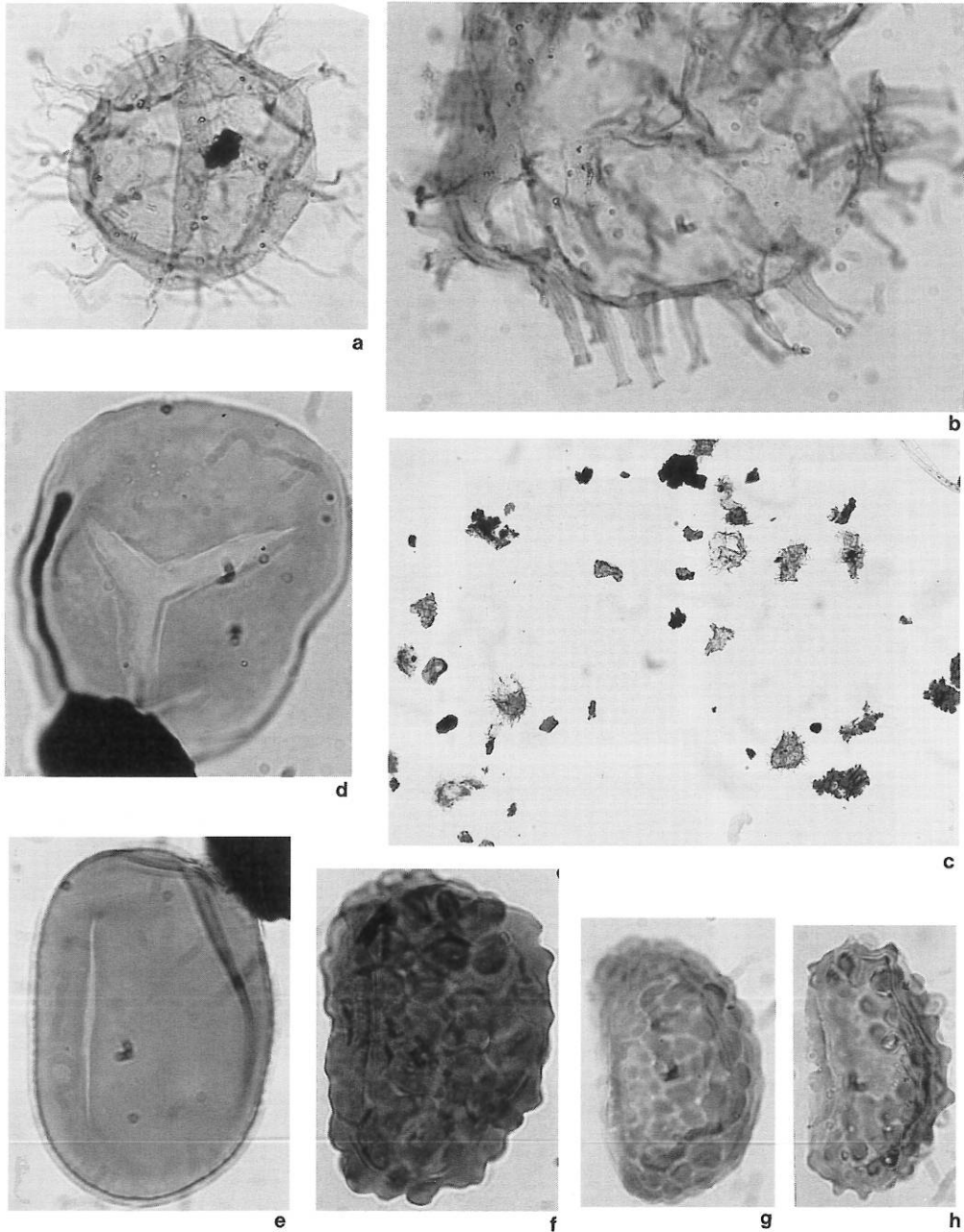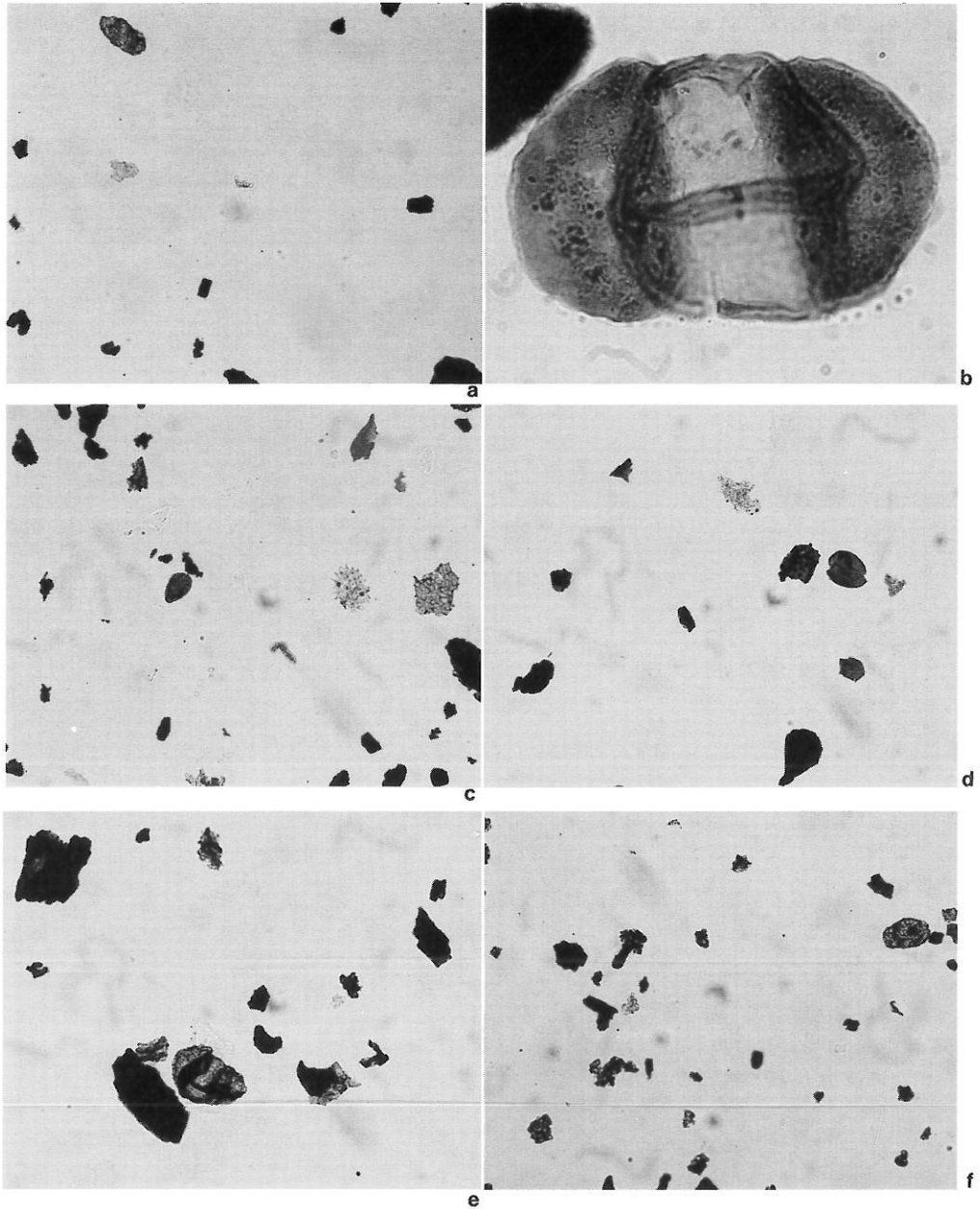
Fig. 6. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Mangrove pollen assemblage*: (**a**) *Rhizophora* type (*Zonocostites ramonae*) – equatorial and polar views ×1000; (**b**) *Avicennia* sp. – polar view ×1000; (**c**) *Sonneratia caseolaris* (*Florschuetzia levipoli*) – equatorial view ×1000; (**d**) *Sonneratia alba* (*Florschuetzia meridionalis*) – equatorial view ×1000; (**e**) *Florschuetzia trilobata* – equatorial view ×1000. *Backmangrove miospore assemblage*: (**f**) Combretaceae–pollen massulae – different views ×1000; (**g**) *Lumnitzera* type–Combretaceae – subequatorial view ×1000; (**h**) *Acrostichum aureum* – proximal view ×1000; (**i**) *Brownlowia* type (*Discoidites bomeensis*) – polar view ×1000. *Coastal gymnosperm taxa*: (**j**) *Casuarnia* type *equisetifolia* – polar view ×1000. *Freshwater swamp pollen assemblage*: (**k**) *Camptostemon* sp. – subpolar view ×1000.
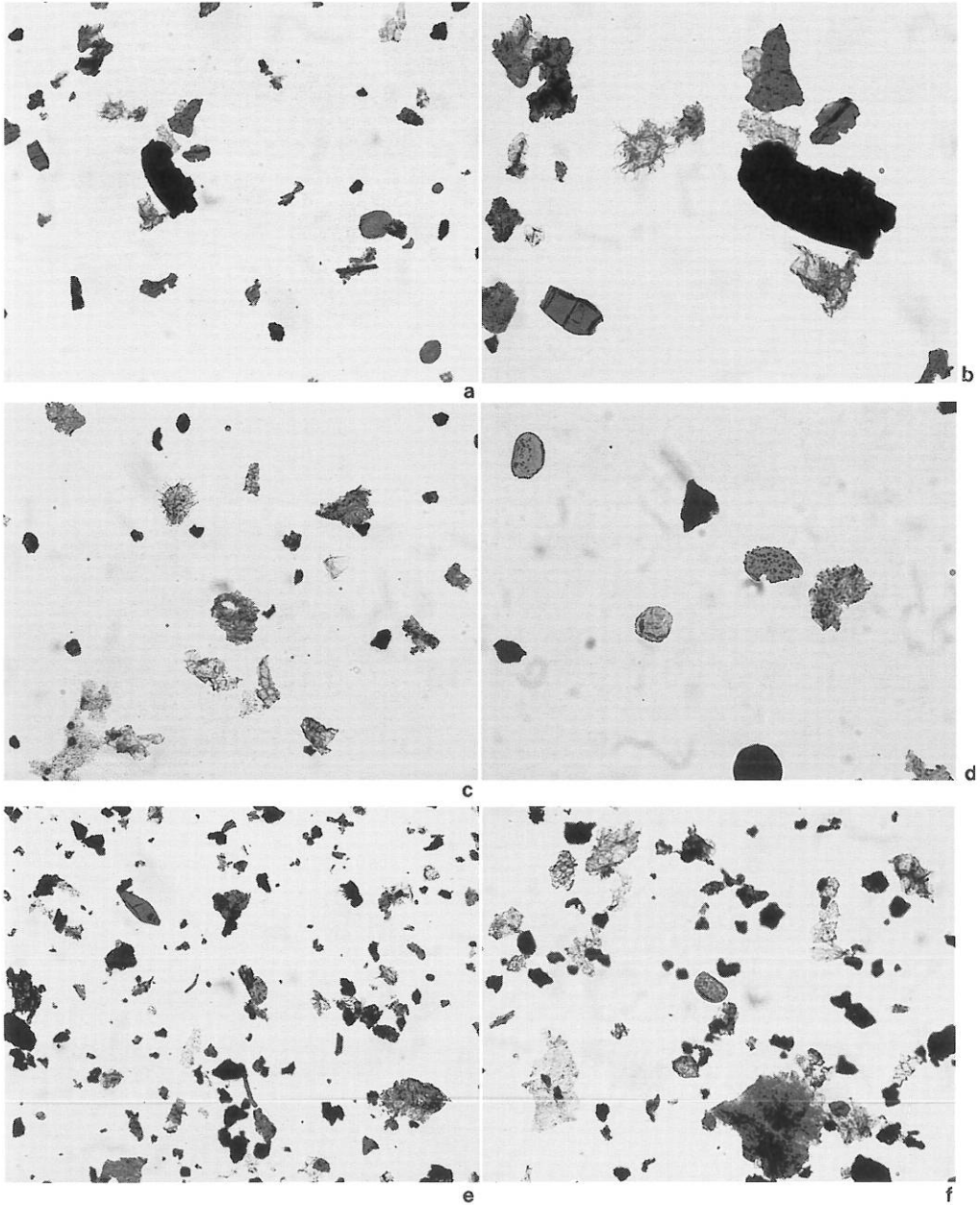
Fig. 7. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Freshwater swamp pollen assemblage*: (**a**) *Alangium* sp. (*Lanagiopolis* spp.) – polar view ×1000; (**b**) *Durio* type – polar view ×1000; (**c**) *Intsia* type – subequatorial view ×1000; (**d**) *Barringtonia* sp. (*Marginipolis concinnus*) – equatorial view ×1000; (**e**) *Calamus* type (*Dicolpopolis* spp.) – distal view ×1000. *Coastal and mangrove palm pollen assemblage*: (**f**) *Nypa* sp. (*Spinizonocolpites echinatus*) – proximal view ×1000; (**g**) palmae undifferentiated – proximal view ×1000. *Hinterland gymnosperm pollen assemblage*: (**h**) *Podocarpus polystachius* ×1000; (**i**) *Dacrydium* sp. ×1000; (**j**) *Pinus* sp. ×1000. *Freshwater algae*: (**k**) *Pediastrum* sp. ×400.

Fig. 8. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Marine dinocyst assemblage*: (**a**) *Spiniferites ramosus* – proximal view ×1000; (**b**) *Polysphaeridium subtile* – half cyst ×1000; (**c**) palynofacies with numerous *Polysphaeridium subtile* (outcrop ENT sample 4) ×200. Open shelf environment characterized by this almost monospecific dinocyst assemblage. *Hinterland spore assemblage*: (**d**) *Leiotriletes* spp. (also called *Deltoidospora* spp.) – proximal view ×1000; (**e**) *Laevigatosporites* spp. ×1000; (**f**) *Verrucatosporites* spp. (robust form) ×1000; (**g**) *Verrucatosporites* spp. ×1000; (**h**) *Stenochlanea palustris* (*Verrucatosporites usmensis*) ×1000. Note: spores are generally very resistant to decay, oxidation and transport, generally more resistant than pollen. They are produced in large quantity and for these reasons are found in all types of environments, even relatively deep marine where they are transported.
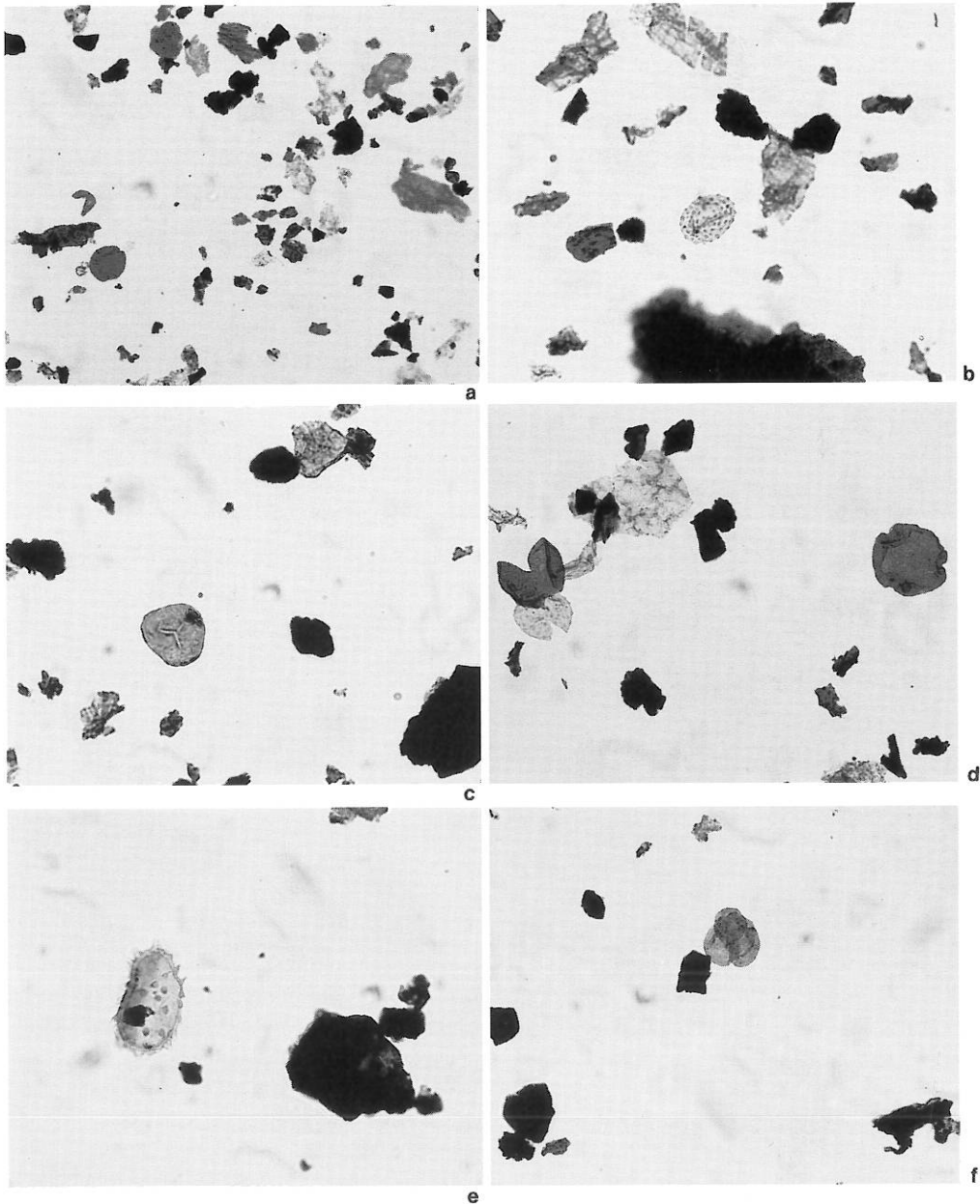
Fig. 9. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Distal turbidite*: (**a**) palynofacies with altitude conifer *Pinus* sp. (outcrop RR sample 1) ×200; (**b**) *Pinus* sp. (outcrop RR sample 1) ×1000; (**c**) palynofacies with freshwater algae *Pediastrum* sp. (outcrop RR sample 4). Note: the palynofacies is characterized by rare kerogen particles, mainly dark (vitrinite and inertinite). The presence of *Pinus* sp. and other bisaccates reflects a deposition relatively far offshore. This taxon is generally easily transported in comparison to other palynomorphs. *Proximal turbidite*: (**d**) palynofacies with freshwater swamp *Calamus* type (*Dicolpopolis* spp.) and *Stenochlanea palustris* (*Verrucatosporites usmensis*) (outcrop OT sample 1) ×200; (**e**) palynofacies with *Pinus* sp. (outcrop OT sample 3) ×100; (**f**) palynofacies with *Pinus* sp. (outcrop OT sample 3) ×200. Note: the palynofacies is characterized by dark kerogen particles and the presence of bisaccates. The relative increase in particles or richer residue reflects a more proximal depositional setting.
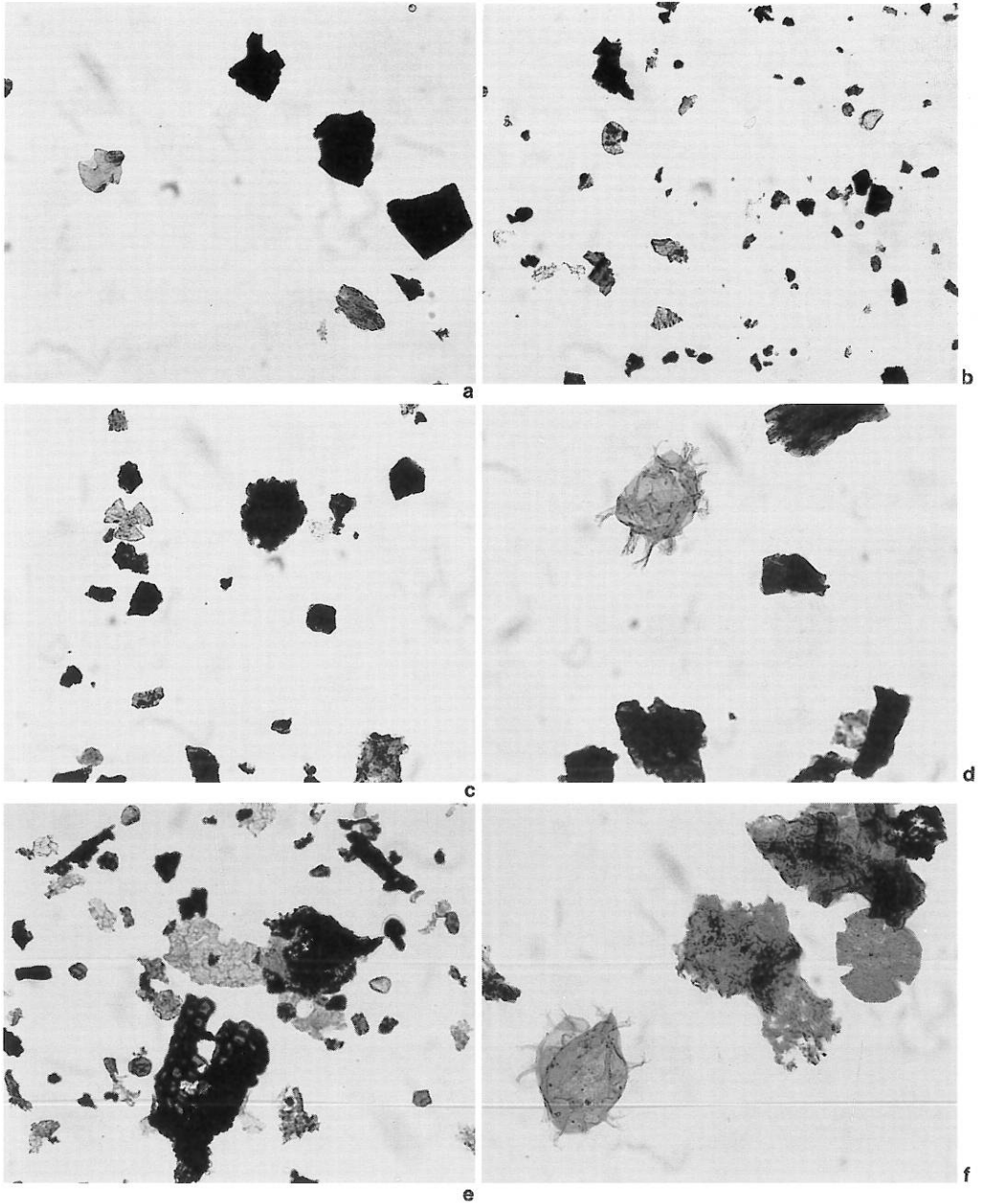
Fig. 10. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Open shelf*: (**a**) palynofacies with rare dinocyst *Spiniferites ramosus* (outcrop ENT sample 14) ×100; (**b**) palynofacies with rare dinocyst *Spiniferites ramosus* (outcrop ENT sample 14) ×200; (**c**) palynofacies with dinocyst *Polysphaeridium subtile* (outcrop ENT sample 24) ×100; (**d**) palynofacies with spores (outcrop ENT sample 24) ×200. Note: the palynofacies is characterized by less numerous dark particles and the presence of more common dinocysts, although rare. Spores are common but not as abundant as in terrestrial environments located behind the mangrove belt. *Open shelf with slumps*: (**e**) palynofacies (outcrop PC sample 2) ×100; (**f**) palynofacies (outcrop PC sample 1) ×100. Note: the palynofacies is characterized by a mixing of numerous particles of different spore coloration and size. This probably reflects the sediment mixing itself while the slumping is active and the importance of transport of allochthonous material.
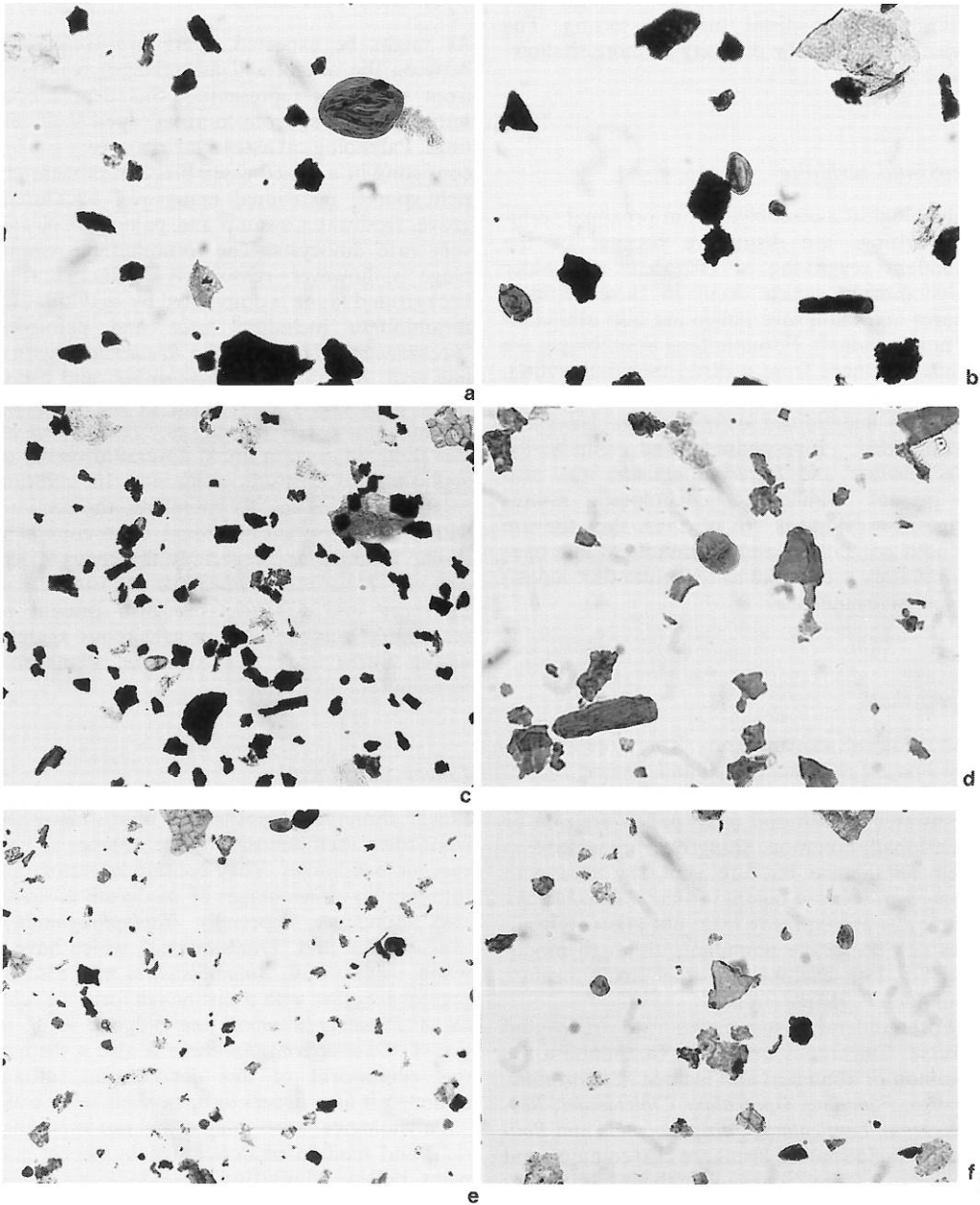
Fig. 11. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Lower shoreface*: (**a**) palynofacies with freshwater swamp *Alangium* sp. (*Lanagiopolis* sp.) (outcrop OOS sample 1) ×100; (**b**) palynofacies with freshwater swamp *Stenochlanea palustris* (*Verrucatosporites usmensis*) (outcrop OOS sample 2) ×200; (**c**) palynofacies with backmangrove *Acrostichum aureum* (outcrop MO sample 3.5) ×200; (**d**) palynofacies with freshwater swamp *Alangium* sp. and spores (outcrop CH sample 2); ×200; (**e**) palynofacies with *Nypa* sp. (*Spinozonocolpites echinatus*) (outcrop MO sample 5) ×400. Note: the palynofacies is characterized by light coloured, as well as dark coloured, particles. There is also increased evidence of relatively large pollen taxa such as *Alangium* sp., *Acrostichum aureum* and other spores, *Spinozonocolpites echinatus*, which source from diverse terrestrial environments connected to the coastline. *Upper shoreface*: (**f**) palynofacies with freshwater swamp *Lophopetalum multinervum* (outcrop RM sample 3.9) ×200. Note: the palynofacies contains freshwater swamp taxa and common spores. The major palynological difference between lower shoreface and upper shoreface environments is the virtual absence of dinocysts in the latter.

Fig. 12. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Upper shoreface*: (**a**) palynofacies with *Calamus* type (*Dicolpopolis* sp.) (outcrop RM sample 15.3) ×200; (**b**) palynofacies with spores (outcrop RM sample 17.7) ×100. *Upper shoreface, tidally influenced*: (**c**) palynofacies with freshwater swamp Dipterocarpaceae (outcrop MD sample 4) ×200; (**d**) palynofacies with dinocyst *Hystricholpoma* sp. (outcrop MD sample 14) ×400. Note: the combined presence of dinocysts and taxa of freshwater environments indicates environmental zones where terrestrial and marine influences are well matched. *Sandy beach – tidal flat*: (**e**) palynofacies with numerous palynomorphs and fungal remains (outcrop MA sample 6) ×200; (**f**) palynofacies with dinocyst *Spiniferites ramosus* and backmangrove *Brownlowia* type (outcrop MA sample 9) ×400. Note: the presence of numerous and diverse palynomorphs indicates the proximity of terrestrial sources and vegetational environments close to the environment of deposition.

Fig. 13. Some representative palynological taxa and palynofacies from various palaeoenvironments from the northwest Borneo area. *Tidal flat–tidal channel complex*: (**a**) palynofacies with freshwater swamp *Crudia* sp. (*Striatricolpites catatumbus*) (outcrop SA sample 10.5) ×200; (**b**) palynofacies with mangrove *Florschuetzia* spp. (outcrop SA sample 58) ×200; (**c**) palynofacies (outcrop SA sample 58) ×100. Note: the palynofacies is characterized by numerous dark particles, most probably micropieces of peat which generates in freshwater swamps. Mangrove taxa can be locally abundant between channels. *Lagoon–distributary channel margin*: (**d**) palynofacies with *Rhizophora* sp. (*Zonocostites ramonae*) (outcrop HO sample 92.8) ×400; (**e**) palynofacies with *Rhizophora* sp. (outcrop 7UP sample 208) ×100; (**f**) palynofacies with *Rhizophora* sp. (outcrop 7UP sample 208) ×200. Note: the palynofacies is characterized by the absence or paucity of dark kerogen particles which indicates dominance of *in situ* sedimentation within the mangrove belt and lesser influence of transport from other environments, mostly terrestrial but also marine.

diameter) appears to be particularly distinctive of deposition in a distal turbidite setting. The assemblages lack the diversity of more shallow-water settings.

Proximal turbidite

Palynological assemblages from proximal turbidite settings are distinctive because of the abundant reworking of Oligocene and older palynomorphs which occur in these settings. Spores and mangrove pollen are also abundant (if not reworked). Foraminiferal assemblages are similar to those from a distal turbidite setting, containing abundant agglutinating foraminifera, especially fine-grained, deformed '*Trochammina/Recurvoides*'. Fine-grained and thin-walled '*Cyclammina*' and *Haplophragmoides* may also be present. Unlike the palynological assemblages, reworking is not obvious, thus the use of both palynology and foraminiferal micropalaeontology is essential to recognize this depositional environment.

Open shelf

Palynological assemblages from open shelf deposits are reasonably rich and diverse. Spores are common–abundant, whilst back-mangrove, freshwater swamp and palm pollen are rare or occasionally common. Mangroves are variable in their abundance but are generally rare with *Zonocostites* more common than *Florschuetzia*. Dinocysts are typically rare, but at some localities can be locally abundant, although monospecific. For example, at the ENT locality, abundant *P. subtile* occurs.

Foraminiferal assemblages are rich and diverse. Calcareous benthonic foraminifera are common or abundant and include *Asterorotalia, Nonion, Planulina, Operculina, Cibicidoides, Rectuvigerina, Lenticulina, Quinqueloculina* and *Bolivinita*. Agglutinating forms are also common and '*Recurvoides/Trochammina*' (with a white, sugary wall), *Karreriella, Textularia* and *Ammobaculites* sp. 1/1a. In some sections, for example ENT, planktonic foraminifera are also common.

The open shelf environment may be further subdivided on the basis on the relative proportion of calcareous benthonic taxa. Associations of common *Rectuvigerina/Quinqueloculina* suggest inner shelf palaeobathymetry, whilst those with dominant *Operculina* and with common *Operculina* and *Cibicidoides* represent middle and outer shelf settings, respectively.

Open shelf with slumps

As might be expected, there are similarities between the microfossil assemblages recovered from sediments representing this depositional setting and those from 'normal' open shelf settings. Palynological assemblages are very similar consisting of a mixed assemblage of moderately rich spores, occasional mangrove, back-mangrove, freshwater swamp and palm pollen, and very rare dinocysts. The foraminiferal assemblage is, however, reasonably distinctive. The background fauna is dominated by agglutinating foraminifera including large and deformed '*Recurvoides*', '*Trochammina/Recurvoides*' with a fine wall, *Bathysiphon*, '*Glomospira*', and a distinctive, probably new, form of agglutinating foraminifera we refer to as '*Textukurnubia*' (see Bidgood *et al.* in press). Overall diversity of agglutinating forms is moderate. In addition to the agglutinating foraminifera, the sections with slumps contain abundant calcareous benthonic foraminifera, especially the genus *Asterorotalia, Hansenisca, Planulina* cf. *wuellstorfii, Bolivinita* and *Cibicides* are also present in reasonable numbers, as are calcareous agglutinating forms such as *Textularia*. Planktonic foraminifera are rare.

Lower shoreface

Lower shoreface deposits can be distinguished from open shelf deposits by the absence of calcareous benthonics. They contain agglutinating foraminifera assemblages of moderate diversity and abundance, especially *Haplophragmoides*, '*Recurvoides*' and '*Trochammina*', which have a white, sugary wall. *Ammobaculites* may also be present together with a distinctive form we refer to as '*Pseudoepistomina*' (see Bidgood *et al.* in press). '*Glomospira*' *glomerata* is also a distinctive component of this depositional setting, although it also occurs in open shelf sediments.

Palynological assemblages are not especially rich, and tend to be dominated by spores and palm pollen. Mangroves, back-mangrove elements and freshwater swamp pollen are typically rare. Dinocysts are a very rare component of these assemblages.

Upper shoreface

Upper shoreface deposits are difficult to distinguish from the lower shoreface deposits, as described above, in terms of their microfossil assemblages. Palynologically, the assemblages

are very similar, being dominated by spores and occasional palm pollen with mangroves, back-mangrove and freshwater swamp pollen all rare. In contrast to lower shoreface deposits, dinocysts are completely absent.

Foraminiferal assemblages are also similar to those from lower shoreface deposits, consisting mainly of common and moderately diverse assemblages of agglutinating foraminifera, especially '*Trochammina*', '*Recurvoides*' and *Haplophragmoides* with a white, sugary wall. A distinctive component is the presence of moderately common *Karreriella*.

Tidal flat–tidal channel

Tidal flat–tidal channel deposits can be distinguished from many of the more open marine and more distal environments by their diverse palynological assemblages which include common mangrove and palm pollen, and common spores. A distinctive element is the presence of moderately common *Casuarina*. Dipterocapaceae are also occasionally common, as are algae such as *Botryococcus* which can tolerate low salinity. Dinocysts are recorded in this setting but are very rare.

Foraminiferal assemblages tend to be of low abundance but of moderate diversity, and include coarse-grained '*Trochammina*' and '*Recurvoides*' (wall being coarser than in more distal settings), and occasional *Trematophragmoides* and *Ammobaculites* sp.

Lower distributary channel

Sediments from lower distributary channel deposits contain a distinctive palynological assemblage consisting of common mangrove, back-mangrove and palm pollen. Spores, as in many other depositional settings, are also common. Very rare dinocysts may also occur. Foraminiferal assemblages are of moderate diversity, consisting mainly of coarse-grained agglutinating forms such as '*Trochammina*' and *Trematophragmoides*. '*Pseudoepistomina*', which is common in lower shoreface deposits, also occurs as rare specimens in sediments from this depositional setting.

Lagoon–distributary channel margin

These settings occur where mangrove swamp vegetation is accumulating on windward or current protected edges of distributary channel mouths. They also occur where distributary channels are being infilled by mangrove swamps during falling sea level or due to autocyclic channel shifting. As such they contain palynological assemblages completely dominated by mangrove pollen. Foraminiferal assemblages are also monospecific, being dominated by either *Trematophragmoides* or *Miliammina fusca*.

Upper distributary channel

Upper distributary channel deposits represent near-freshwater conditions and as such are typically barren of foraminifera. Palynologically, they are distinctive, containing superabundant spores, common and diverse freshwater swamp and back-mangrove pollen, and very rare mangrove and palm pollen. Freshwater algae can also be common in this setting.

Discussion

A number of previous studies have noted that foraminifera and/or palynomorphs could be used as palaeoenvironmental proxies, largely based on the observation of the distribution of Recent microfauna/flora, in work which complements our own, outcrop-based, research.

Dhillon (1968) studied the distribution of modern foraminifera in the Lupar and Labuk estuaries of eastern Malaysia, in settings similar to what we describe as lower distributary channel. The Lupar Estuary, which has marked tidal influence, is dominated by what are assumed to be transported stenohaline forms such as *Pseudorotalia*, *Asterorotalia*, *Nonion*, *Lagena*, *Oolina*, *Discorbis*, *Cibicides*, *Amphistegina*, *Triloculina* and other taxa, especially in the distal part of the estuary. Indigenous forms are rare but include *Arenoparella*, *Haplophragmoides*, *Trochammina* and *Ammonia*. The redeposition of stenohaline forms has not been noted in our outcrop material, but the fact that it occurs in Recent sediments suggests that it may also occur in ancient sediments and needs to be taken into account in subsurface studies. In the Labuk Estuary indigenous agglutinating forms are much more common and include *Ammobaculites exiguus*, *Haplophragmoides* spp., *Miliammina* spp., *Arenoparrella*, *Jadammina* and *Trochammina* spp. *Ammonia* is common at the mouth of the estuary. Redeposited stenohaline forms are rare. In comparison to our lower distributary channel outcrop analogues, these assemblages are surprisingly rich and diverse. *Arenoparrella* has often been recorded from modern lower distributary channel sediments, but is difficult to

recognize in our ancient material because of poor preservation of apertural characteristics. Jones *et al.* (1999) have noted *Arenoparrella*, *Haplophragmoides*, *Miliammina* and *Trochammina* in mangrove palaeoenvironments from Neogene sediments of Venezuela.

The depositional setting of the Labuk Estuary more closely fits that envisaged for the Miocene sediments reported upon herein. The estuary is relatively brackish and with a wide mouth opening out into Labuk Bay. Tidal influence is not as strong as in the Lupar Estuary. The dominance of agglutinating foraminifera matches our own results, and also compares well with the work of Ho (1971) who studied the distribution of Recent benthonic foraminifera in inner Brunei Bay. Ho recognized a *Trochammina* cf. *lobata* assemblage in the lower distributary channels, an *Ammobaculites* assemblage over much of Brunei Bay proper, corresponding to our lagoon setting, and an *Asterorotalia trispinosa* assemblage at the mouth of Brunei Bay corresponding to our open shelf setting. The *Trochammina* cf. *lobata* assemblage consists only of coarse-grained agglutinating forms such as *Trochammina* spp., *Miliammina fusca*, *Arenoparrella*, *Haplophragmoides* and *Ammobaculites*. This matches well with the lower distributary channel assemblage described herein. Ho noted that the abundance of *Trochammina* may be related to the abundance of organic matter in the distributary channels.

The *Ammobaculites* assemblage of Ho (1971) has some similarities with the lagoon assemblages described herein. Abundance and diversity are both low and consist of a few species of coarse-grained *Ammobaculites* (including *A. exiguus*), *Haplophragmoides* and *Trochammina*. The *Asterorotalia trispinosa* assemblage is similar in character to elements of the open shelf assemblage described herein. *Asterorotalia* and *Ammonia* are very common, whilst *Elphidium*, *Florilus*, *Ammobaculites*, *Cellanthus* and *Ozawia* also occur alongside transported specimens of more typical outer shelf taxa such as *Operculina*, *Calcarina* and *Triloculina*.

In conclusion, studies of modern foraminiferal distributions appear to confirm our contention that microfossils can be used as precise palaeoenvironmental proxies. Ten precise depositional settings can be identified from microfossil (palynomorph and foraminiferal) assemblages, ranging from distal turbidite through to upper distributary channel. We believe that this opens the possibility to more widespread use of biostratigraphy as a tool in development and production geology in northwest Borneo, by helping to fingerprint the depositional settings of reservoir intervals and so better predict their architecture, connectivity, heterogeneity and poroperm characteristics.

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