Making sense of mud: the use of benthic foraminifera in mudstone sedimentology, Sabah, North Borneo

Jon Noad[1] and Rachel Preece[2]
[1]*Husky Energy, 707 8th Avenue SW, Calgary T2P 1H5, Alberta, Canada*
[2]*Chevron Upstream Europe, Chevron House, Hill of Rubislaw, Aberdeen, AB15 6XL, UK*

ABSTRACT

The use of microfossils in the dating of sedimentary rocks is commonplace, and well documented. However, the use of these fossils, particularly benthic foraminifera, in the interpretation of depositional environments has received less attention. A series of mudstone samples collected from five formations outcropping in eastern Sabah, NE Borneo, ranging in age from Eocene to Pliocene in age, has yielded more than 80 species of calcareous and agglutinated foraminifera. These have been interpreted to give both stratigraphical and depositional information.

The microfossil assemblages are interpreted to represent conditions ranging from those inhabiting mangroves, very shallow marine to paralic coastal settings, through to open marine, relatively anoxic settings. These interpretations are supported by the interpreted sedimentology of measured outcrop sections. The preservation, size of individual tests, species diversity and diagenetic signatures have been combined to provide a detailed picture of conditions extant at the seabed during deposition of these sediments. This includes oxygen and energy levels, as well as evidence of post mortem dissolution. Around 60% of the samples yielded a very limited fauna, or were barren. Among the assemblages identified are deep marine 'flysch-type faunas' that are also comparable to the Agua Salada Fauna of Northern Venezuela.

The synthesis of foraminiferal and sedimentological data provides a powerful tool in identifying depositional environments in seemingly homogenous mudstone beds. Hence it can be used as a correlation tool. Through applying the process described here to hydrocarbon exploration, it is possible to extrapolate additional information on depositional settings from core, and hence provide sequence stratigraphic architectural trends. These can be used to predict source rock distribution. This approach may also be applied to cuttings data in the absence of well logs or core.

INTRODUCTION

It is not uncommon to see a table or range chart of reported microfossils from a particular formation listed in a scientific paper, and the formations exposed in eastern Sabah are no exception (Fitch 1958; Hutchison 2005). These data are typically used for the dating of sedimentary rocks, while the composition of the tests may also be used for a variety of geochemical analyses. However the opportunity also exists to use foraminiferal assemblages to examine conditions during deposition, such as oxygen level at the seabed. This may have implications for the identification of potential source rock intervals. Collecting samples for microfossil analysis, in conjunction with an ongoing sedimentological study of the sediments, allows the diverse assemblages of foraminifera to be tied to particular depositional settings. Local variations in species diversity, test size and numbers of specimens can then be attributed to more subtle variations in water depth and oxygenation levels.

Foraminifera are separated into two types based on their mode of life, either benthic or planktonic. Benthic foraminifera may be agglutinated, usually with tests fabricated from quartz grains cemented by calcitic or organic cement, or their tests may be primarily secreted and composed of calcite, aragonite, or rarely silica (Boersma 1978). They may also be subdivided into smaller and larger benthic foraminifera, of which only the former are examined here. In the study area, larger benthic foraminifera have only been recorded from the Gomantong Formation (BouDagher et al., 2000), and are not discussed in this paper. Instead the focus is on the agglutinating and calcareous foraminifera, which were recovered from a series of samples collected from outcrops of selected formations in eastern Sabah (Figure 1). Identifications of all the foraminifera detailed in this paper were made by the second author.

GEOLOGICAL OVERVIEW

The regional geology of Sabah is complex, and formed in response to the relative motion and interactions of the Indian, Australian, Pacific and Eurasian plates (Hamilton 1979; Hutchison 1989; Daly *et al.* 1991). This paper focuses on Eastern Sabah, which is floored by Cretaceous to Eocene

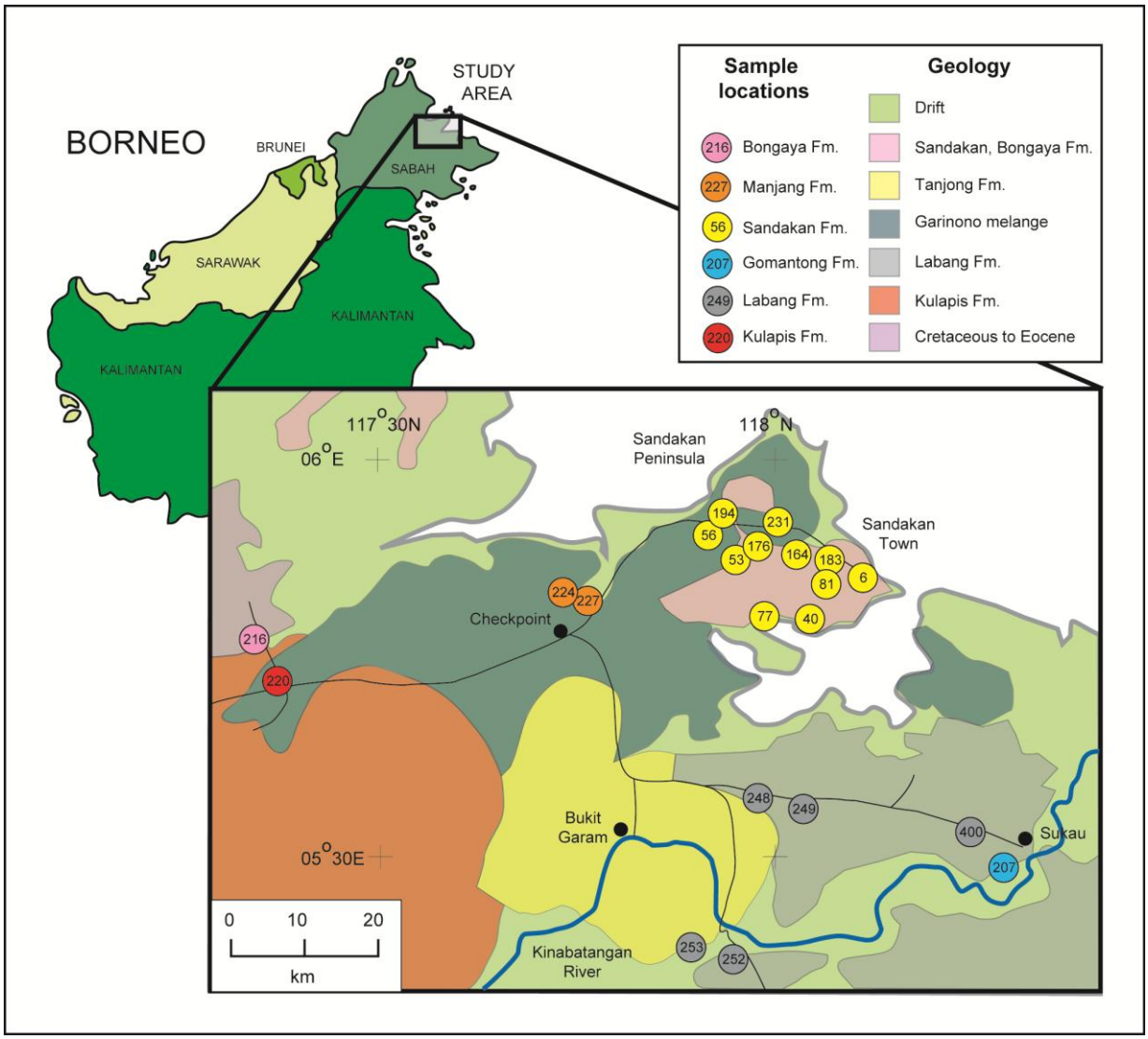


Figure 1. Map of geology and sample localities in eastern Sabah (after Yin 1985).

aged cherts and spilites and associated basalt and sediments, outcropping in the Bidu Bidu Hills and to the west of Lahad Datu (Noad 1999; Hutchison 2005). In the early Eocene an accretionary wedge (the Rajang Prism of Bénard *et al.* 1990) was uplifted on the NW Borneo margin, related to the subduction of the proto-South China Sea beneath northern Borneo (Taylor and Hayes 1980; Hall 1996), and to the consequent opening of the South China Sea around 32 Ma (Daly *et al.* 1991). The wedge shed clastic sediments southeast-ward into the Central Sabah Basin foredeep from the early Eocene, depositing the Kulapis and Labang Formations (Hutchison 1992; Noad 1999; 2001).

Sedimentation continued through the Oligocene, towards the end of which the Labang High was uplifted, allowing carbonate sedimentation of the Gomantong Limestone to develop. In some areas the Labang Formation was subaerially exposed, and weathered material was incorporated into the succeeding limestones. A reorganisation of plate movements in the early Miocene led to the deposition regionally of the Garinono mélange, as olistostrome blocks of Kulapis and Labang Formation rocks. This may also relate to the cessation of sea floor spreading in the South China Sea in the mid Miocene, due to the collision of buoyant, micro-continental rifted blocks (the "South China Sea micro-continent" including the Palawan, Reed Bank and Dangerous Grounds blocks) from the southern China margin, and the Rajang Prism (Taylor and Hayes 1980; 1983).

The initiation of seafloor spreading in the Sulu Sea led to extension in eastern Sabah (Rangin and Silver 1990; 1991), and to the rejuvenation of the Central Sabah Basin (Noad 1999). The clastic dominated Tanjong Formation was deposited mainly as tempestites cut by channel-confined debris flows, on a regionally extensive open marine shelf, part of which was later uplifted. Eroded material then fed northwest-ward into the Sandakan Peninsula area. This was incorporated into the Sandakan Formation deposits, which range from mangroves, deepening to the north from shallow marine sandstones into shelfal deposits (Noad 1999). The Sandakan Formation unconformably overlies Oligocene volcanics which are related to subduction of the Celebes Sea (Rangin 1989; Noad 1999), and is dated as Middle to Upper Miocene in age (Hutchison 2005). The Bongaya and Manjang Formations are also clastic in character, and were deposited in sub basins coeval with, and to the northwest of, the Sandakan Formation.

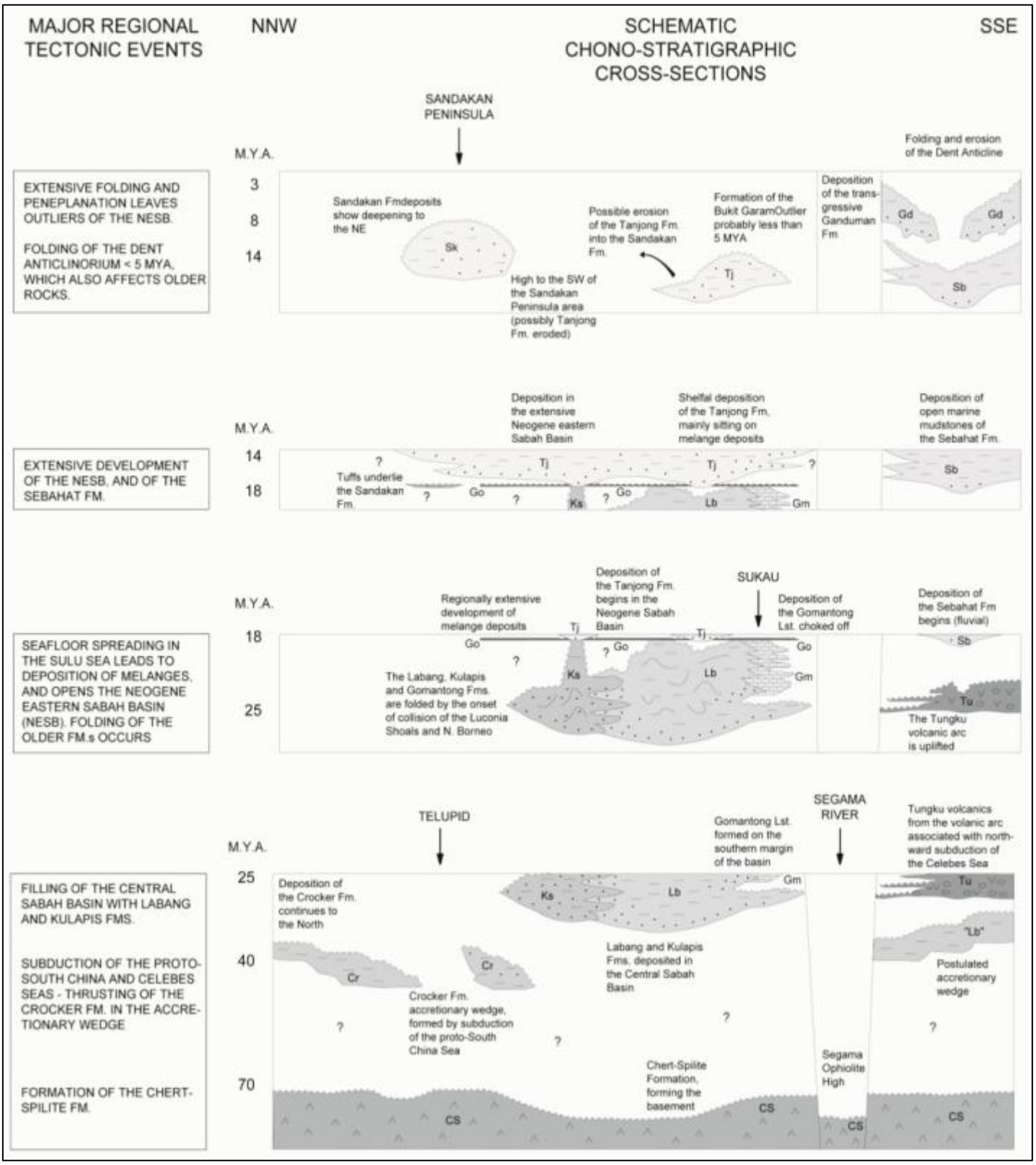


Figure 2. Four chronostratigraphic cross-sections through eastern Sabah. Intermittent tectonic activity through the Oligocene to Recent has necessitated the use of several subsections. This is because uplift and erosion, particularly associated with the onset of spreading in the Sulu Sea around 16 Ma, and also around 4 to 1 Ma (possibly related to the interplay of continued collision along the northern Borneo margin, and rotation of the Philippines Sea Plate), has led to truncation of many of the older formations prior to the deposition of younger sediments.

CS: Chert-Spilite Fm., Cr: Crocker Fm., Lb: Labang Fm., Ks: Kulapis Fm., Gm: Gomantong Limestone, Go: Garinono Fm., Tj: Tanjong Fm., Sd: Sandakan Fm., NESB: Neogene eastern Sabah Basin.
Dent Peninsula: Tu: Tungku Formation, Sb: Sebahat Fm., Gd: Ganduman Fm.

The chronostratigraphic evolution of eastern Sabah is summarised in Figure 2.

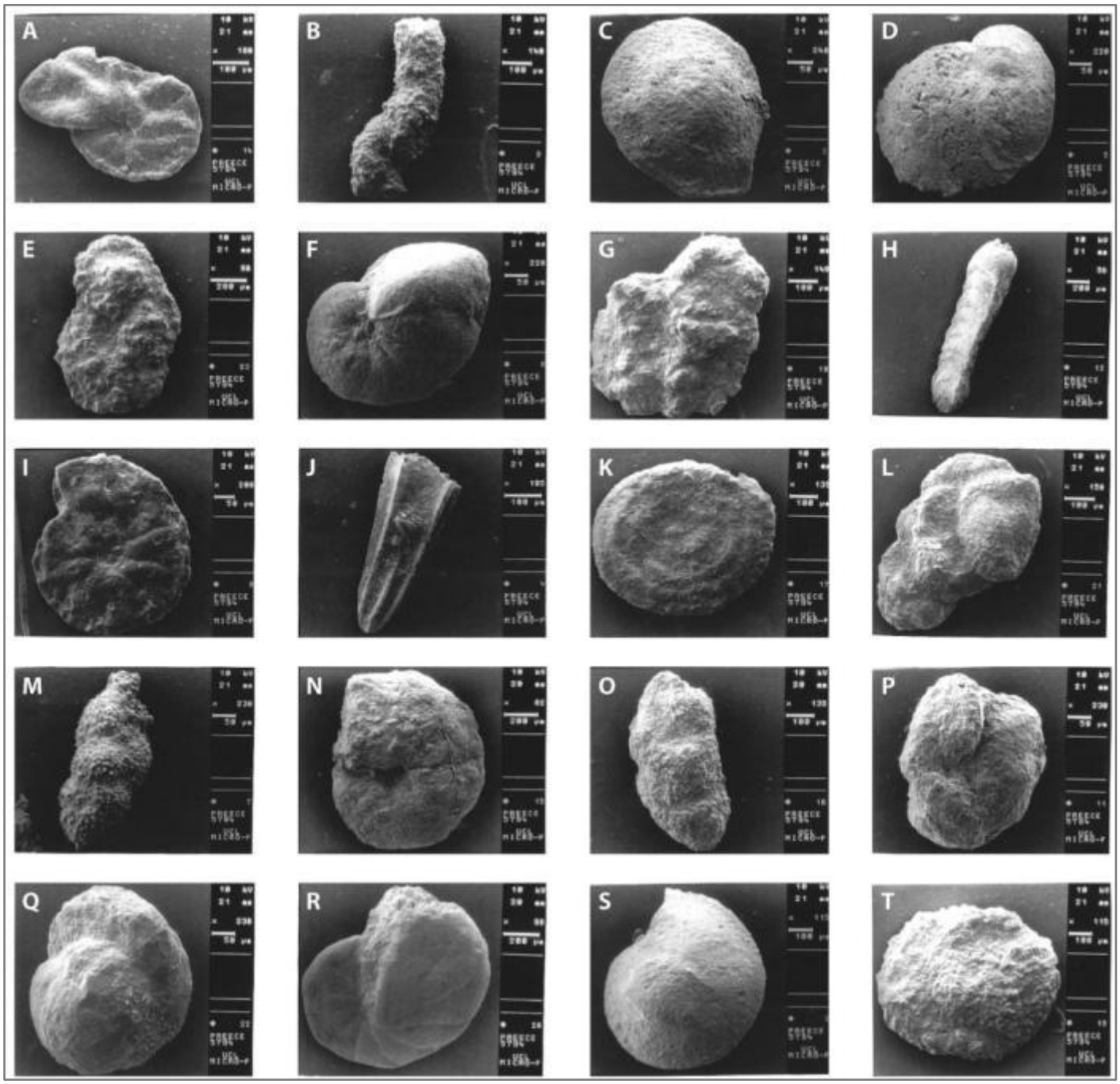


Figure 3. Photomicrographs of foraminifera with corresponding sample numbers (refer to Table 1). Note that (c) signifies a calcareous foraminifer. A. *Haplophragmoides carinatus*; B. *Rhizammina* sp.; C. *Gyroidinoides venezuelana* (c); D. *Cancris panamensis* (c); E. *Reticulophragmium venezuelana* (coarse grained); F. *Nonion incisum* (c); G. *Ammobaculites agglutans*; H. *Clavulina cubensis*; I. *Haplophragmoides wilsoni*; J. *Plectofrondicularia californica* (c); K. *Ammodiscus tenuissimus*; L. *Valvulina flexilis*; M. *Uvigerina hispida* (c); N. *Cyclammina acutidorosata*; O. *Karriella coniformis*; P. *Haplophragmoides obliquicameratus*; Q. *Budashevaella multicameratusi;* R. *Cyclammina cancellata*; S. *Karriella microgranulosa*; T. *Saccamina* sp.

SAMPLING RESULTS

Sampling strategy

More than 1000 samples of mudstone were collected during the course of this study (Noad 1999), and efforts were made to dig at least 50 cm into the substrate to collect fresh, relatively unweathered samples. More than 50 samples were selected for processing and micropalaeontological evaluation, concentrating on the Miocene Sandakan Formation, but including samples from five other formations. The samples were washed and then picked at 250 microns, 125 microns and 62 microns sieve mesh sizes. The resulting concentrate was described and then picked for foraminifera. It should be noted that almost all of the barren samples were from the Sandakan Formation and from the Tanjong Formation, the latter being barren in all samples.

The results of the sample processing are provided for the 21 samples that yielded calcareous and/or agglutinated foraminifera (Figure 3). These include

Table 1. Descriptions of processed samples which yielded foraminifera.

Formation	*Locality*	*Sample number*	*Interpreted depositional setting*	*Description of sample*	*Overview of faunal contents*
Bongaya	216	614/4	Open marine mudstone.	Large residue, common quartz grains, pyritized burrows. 18 forams.	Planktonic fauna only.
Manjang	227	616/9	Open marine mudstone.	Mostly quartz grains, forams often broken, fines sideritic.	All agglutinates, but varied fauna, stressed environment but not extreme.
Manjang	224	616/5	Open marine mudstone.	Common quartz grains, occasional forams.	Mainly calcareous forams.
Sandakan	56	84/8	Open marine mudstone.	Uncommon sand grains, gritty, off white, minor amber.	Well preserved fossils, 115 agglutinates, marginal conditions.
Sandakan	194	531/11	Open marine mudstone.	Mostly very fine quartz grains, gastropod fragments, many forams, some pyritized. Some siderite.	Very varied fauna shows well oxygenated during life, with pyritization showing post mortem reducing conditions.
Sandakan	53	84/6	Open marine mudstone.	Some siderite, quartz grains, minor pyrite and amber.	Very limited fauna shows barely habitable conditions.
Sandakan	231	616/12	Open marine mudstone.	Echinoid plates, rare pyritized burrows, lots of carbonaceous material, minor quartz grains.	Poor preservation.
Sandakan	164	529/2	Open marine mudstone.	Quartz grains and charcoal, small residue, more than 100 forams.	Fauna is reduced in size showing stress. Preservation is good. Associated macrofauna.
Sandakan	176	530/5	Lower shoreface with rip current channels.	Gritty sand grains, minor amber, rare pyrite, few seeds.	Limited fauna, all agglutinates, possible post mortem dissolution.
Sandakan	183	531/1	Lower shoreface heterolithic beds.	Little sediment, granular sand, charcoal, amber.	Many rusted foram remnants, suggesting post mortem dysoxia. Poor preservation.
Sandakan	6	716/8	Middle shoreface tempestites.	Lots of clay and quartz grains, some calcite.	Conditions barely habitable, forams may be washed in (usually deeper water)
Sandakan	81	824/2	Lower shoreface heterolithic beds.	Siderite and grey quartz grains, heterogeneous in finer fraction.	Reduced diversity fauna shows low oxygen conditions.
Sandakan	77	821/3	Mangrove.	Common sand grains, charcoal and rolled amber. Siderite crystals.	Fauna is reduced in size showing stress, lack of calcareous fauna shows poorly oxygenated conditions. Varied fauna.
Sandakan	40	81/5	Mangrove.	Lots of charcoal, fine grained quartz grains, some siderite, common forams.	Fauna is reduced size showing stress, lack of calcareous fauna shows poorly oxygenated conditions.
Gomantong	207	66/7	Lime mudstone, shallow marine, low energy.	Very common forams, including *Lepidocyclina*. Too many to pick, no other matrix.	Deposited above the CCD, resilicification of some specimens. Varied fauna, favourable conditions.
Labang	400	97JL3/3	Shallow marine mudstone in hybrid setting.	Foram sample from Labang interbedded with Gomantong Limestone.	Internal moulds of planktic forams. Pyritised tubes. Worn fauna suggests high energy, shallow marine.
Labang	252	623/11	Shallow marine, heterolithic beds.	Lots of light grey quartz grains, some iron stained, 18 forams.	Reduced size, well preserved, with stressful, low oxygen conditions. Robust forms suggest possibly washed in from high energy conditions.
Labang	248	621/29	Open marine mudstone with thin turbidite sandstone beds.	Many burrows composed of sand grains. Rare amber. Sample rich in quartz grains and mica.	Fauna is reduced in size showing stress. Preservation is good, and limited fauna suggest low oxygen conditions.
Labang	249	621/30	Open marine mudstone with thin turbidite sandstone beds.	Some quartz grains, pyritized burrows common.	Pyritised tubes and burrows, reducing conditions and planktic forams only.

Formation	*Locality*	*Sample number*	*Interpreted depositional setting*	*Description of sample*	*Overview of faunal contents*
Labang	253	623/13	Open marine mudstone.	Few clear sand grains and lots of forams.	Sample contains Agua Salada assemblage. Varied fauna, favourable conditions. Several forms with alveola suggest marginally habitable conditions with low oxygen. Mid shelf, relatively deep water.
Kulapis	220	614/5	Massive turbidites interbedded with thin mudstone.	Ironstone in coarse fraction, some wood fragments, little clear quartz, pyrite fragments.	Very limited fauna.

Table 2. Distribution chart showing calcareous foraminifera from processed samples.

| Locality | Formation | Setting | Lithology | Planktonic | | | | Calcareous foraminifera | | | |

Table 3. Distribution chart showing agglutinated foraminifera from processed samples.

Locality	220	252	253	249	248	400	207	40	77	81	6	183	164	231	176	53	194	56	224	227	216	
Formation	Kulapis	Labang	Labang	Labang	Labang	Labang	Gomantong	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Sandakan	Marjang	Marjang	Bongaya	
Setting	flysch	open marine	open marine	open marine	open marine	open marine	reef	mangrove	nearshore	shoreface	shoreface	open marine	open marine	open marine	open marine	open marine	open marine	open marine	open marine	open marine	deep marine	
Lithology	sand/mud	sand/mud	mud	mud	mud	mud	lime mud	mud	sand/mud	sand/mud	sand/mud	mud	mud	mud	mud	mud	mud	mud	mud	mud	mud	
Agglutinating foraminifera																						*Alveovalvulina suteri*
																						Budashevella multicameratusi
																						Egerella karamatensis
													A					A	A			*Haplophragmoides obliquicameratus*
		A											A									*Haplophragmoides cf. wilsoni*
																						Jarvisella karamatensis
																		A				*Recurvoides contortus*
																						Saccamina sp.
																						Trochammina squamata
																						Clavulina sp.
																						Cyclammina cancellata
																						Egerella forestensis
		A																				*Haplophragmoides carinatus*
									A				A									*Haplophragmoides coronatum*
																			A			*Recurvoides obseletum*
																						Trochammina altispira
																						Ammomargulina sp.
																						Karriella microgranulosa
																						Saccamina sphaerica
																						Rhizammina sp.
																						Ammobaculites cf. strathernensis
																						Haplophragmoides cf. narivaensis
																						Alveovalvulina pozonensis
																						Ammobaculites sp.
																						Haplophragmoides emaciatum
																						Spiropsammina uhligi
																						Trochammina pacifica
																						Rusted agglutinate remains
																						Haplophragmoides sphaeriloculous
																						Trochammina cf. squamata
																						Bathysiphon sp.
																						Spiropsammina sp.
																						Cyclammina placenta
																						Glomospira gordialis
																						Milammina sp.
																						Ammomargulina sp.
																						Clavulina cubensis
																						Rheophax acosta
																						Rheophax duplex
																						Ammodiscus incertus
																						Sigmoilopsis schlumbergeri
																						Rhabdammina sp.
																						Spiroplectammina carinate
																						Ammobaculites aggutans
																						Valvulina flexilis
																						Ammodiscus aequispiris?
																						Ammodiscus tenuissimus
																						Cyclammina acutidorosata
																						Cyclammina cancellata
																						Egerella cf. bradyi
																						Guppyella sp.
																						Haplophragmoides discus
																						Karriella apicularis
																						Karriella coniformis
																						Reticulophragmium venezuelana
Pyrite																						*Astrorhiza sp. nov.*

Sample Interpretation

The extremely limited species diversity indicates highly stressed conditions, with the pyrite suggesting reducing conditions with low oxygen levels. This suggests that the turbidites were deposited in deep water with little bottom circulation. The trace fossils also indicate a deep water setting.

The *Astrorhiza* were scattered through the massive beds in no preferred orientation, and are thought to have been transported down slope by turbidity currents from an original location on a sandy, high energy shelf. They typically have six arms, and have used very coarse sand grains to construct their tests, which may reach more than a centimetre in diameter. This species has not previously been recorded in rocks of this age or from this region (pers. comm. M. Kaminski, UCL). Although ranging in age from the Jurassic to the present day, and common to temperate coastal waters, very little appears to be known of the biology of any member of the family Astrorhizidae.

Labang Formation

Sedimentology

The Labang Formation (Figure 4C) is interpreted to have been deposited in a variety of settings ranging from shallow marine, sandy, high energy shelf passing seaward into a muddy, open marine system with occasional, thin turbidite sandstone beds. The sandstone beds exhibit grooved bases and a deep water trace fossil assemblage including graptoglyphids (Clennell 1996,; Noad 1999). In contrast to the possibly coeval Kulapis Formation, the Labang sediments comprise thick grey mudstone beds and unstructured, yellow sandstone beds. There is some evidence that the Formation becomes more sand prone upwards (Clennell 1996), and generally individual exposures are made up either of sand- or mud-dominated facies (Noad 1999). These have been interpreted to represent the deposits of a small precursor basin to the Central Sabah Basin (Hutchison 1992; Clennell 1996), with sandy shelfal deposits around the basin margin

and deeper marine deposits in the centre (Noad 1999). The Labang Formation has been dated as Oligo-Miocene in age (Haile and Wong 1965; Clennell 1991) and as early Eocene at least in part (Table 4). The presence of *Orbulina universa* in Sample 400 (Table 2) suggests a Middle Miocene or younger age, but reworking of Labang Formation mudstone clasts into the Gomantong Limestone indicates an Eocene to early Oligocene age.

Sample description
The sample from Locality 400 contains a mixed fauna of deep marine (*Gyroidinoides, Laticarinina*) and shallow marine (*Amphistegina*) calcareous benthics, with indications of some dissolution (of the planktonic forms). This may indicate unusually calcareous-rich sediment rather than a different faunal biota. The shallow marine forms may have been washed downslope in turbidity currents.

The sample from Locality 400 is in contrast to the sample from sediments of Locality 252, which were devoid of calcareous foraminifera but contained abundant agglutinated benthic foraminifera. This may well indicate that, through much of the Labang Formation, the former have been dissolved out through diagenesis.

The deep marine mudstones showed a fascinating and contrasting array of foraminifera, often from adjacent outcrops. At Locality 249, the limited calcareous fauna of *Globobulimina* spp. suggests low oxygen conditions, with the redox level very close to the sediment surface, possibly in a seabed depression with little circulation just above the CCD. Agglutinated forms were absent, possibly due to a lack of sandy material in deep water. Former acidic conditions here are shown by pyritised burrows. The reduced size of the foraminifera suggests a stressed setting. At Locality 248 there are several tube-like, benthic foraminifera, suggesting very quiet conditions, which have been colonised by the opportunist *Reophax* spp. Oxygen levels were probably very low, as shown by the alveolar forms, with no dissolution of calcareous foraminifera. The low abundance of foraminifera in this sample may reflect a location in the channel axis, as opposed to a lower energy location on the channel levee bank.

Locality 253 hosted a very rich faunal assemblage with 31 agglutinated forms, including several forms with alveola. Such assemblages are commonly termed 'flysch-type faunas', and are generally associated with lower slope- basin floor submarine fan deposits (e.g. Jones, 1996). In NW Borneo these agglutinated foram assemblages were first described by Keij (1964), who noted great similarities between the Borneo faunas and those from European Paleogene flysch deposits. The presence of foraminifer *Valvulina flexilis* and others also points to similarities with the Agua Salada Formation of Venezuela (Preece 1999; Preece *et al*, 1999). Once again the absence of calcareous forms probably indicates post depositional dissolution, while the presence of a number of elongate forms is sometimes taken to indicate low oxygen levels, as does the presence of several alveolar forms (*Reticulophragmium, Cyclammina, Alveophragmium*). *Reophax* spp. are early colonisers and always occur in fairly low oxygen to reducing conditions.

Gomantong Formation

Sedimentology
The overall depositional setting is interpreted as shelfal, made up of reefal limestones with associated bryozoans and common large benthic foraminifera, overlain by a muddier, open shelfal succession

Table 4*. Distribution chart showing palynoflora from processed samples, identified by Robert Morley, Palunova.*

Locality	Formation	Setting	Lithology	Palynoflora																																				
				Florschuetzia levipoli	*Calophyllum sp.*	*Monoporites annulatus*	*Dacrydium sp.*	*Florschuetzia clavicolpata*	*Monoporites diversus*	*Florschuetzia ovalis*	*Discoidites borneensis*	*Zonocostites ramonae*	*Florschuetzia trilobata*	*Florschuetzia semilobata*	*Myrtaceae*	*Korthalsia sp.*	*Proxapertites hammenl*	*Liliacidites regularis*	*Spiniziconocolpites baculatus*	*Proxapertites cursus*	*Homotrybium plectilum*	*Spiniziconocolpites echinatus*	*Odontochitina operculata*	*Areoligera sp.*	*Ranitomeya variabilis*	*Psilatricolpites kayanensis*	*Adnatosphaeridium multispinosum*	*Psiladiporites sp.*	*Triorites festatus*	*Triorites minutipori*	*Heraclium pallidum*	*Cicatricosisporites sp.*	*Pinus sp.*	*Camptostemon sp.*	*Picea sp.*
353	White Pebble	fluvial	sand/mud	A	A																																			
301	Ganduman	shallow marine	sand/mud																																					
12	Sandakan	mangrove	mud								A																													
144	Sandakan	shoreface	sand/mud	A	A							A																													
143	Sandakan	shoreface	sand/mud								A																													
66	Sandakan	open marine	mud																																					
123	Tanjong	open marine	mud			A					A																													
130	Gomantong	reworked Labang	mud																																					
400	Labang	shallow marine	mud																																					
127	Labang	open marine	mud																																					
248	Labang	open marine	mud																																					
13	Kulapis	flysch	sand/mud																																					

indicating a regional deepening event. Near the base the Gomantong Limestone includes reworked green clasts of the underlying Labang Formation, and may be interbedded with thin green mudstone beds, which are thought to be reworked (Noad 2001). The single Gomantong sample was taken from open shelfal mudstone beds (Figure 4D) exposed close to Sukau. The Gomantong Limestone is dated as Chattian to Burdigalian in age based on larger foraminiferal data (BouDagher *et al.* 2000), as Early Miocene (zone Te5) by McMonagle *et al.* (2012) and as latest Oligocene (NP25) based on nannofossil data (pers. comm. J. Young, BMNH, based on the presence of *Sphenolithus ciperoensis* in the absence of *Sphenolithus distentus*).

Sample description
Previous work has identified many large benthic foraminifera (BouDagher-Fadel *et al* 2000), as well as an abundant macrofauna (Noad 1999). The fauna and sedimentology have helped to elucidate a variety of depositional settings. The varied and abundant fauna in the samples indicate well oxygenated, favourable conditions above the Carbonate Compensation Depth (CCD), with re-silicification of some specimens but little clastic input. The presence of a (somewhat) brackish water, agglutinated foraminiferal assemblage supports a proximal setting, with the foraminifera possibly washed into a fully marine setting during storms.

Sandakan Formation

Sedimentology
The clastics-dominated Sandakan Formation outcrops across the Sandakan Peninsula over an area of around 200 km^2 (Noad 1999; Noad 2013). Mangrove deposits on the southern margin of the basin ((Figure 4E) overlie Oligocene volcanics. The palaeo-water depth deepens northwards passing through upper shoreface stacked sandstone beds and into heterolithic lower shoreface tempestites (Figure 4F). These comprise thin, hummocky cross-stratified sandstone beds interbedded with thin mudstones with starved ripples. Further to the North the depositional setting is open marine with thick mudstone beds rich in ironstone casts of small fossil crabs (Collins *et al* 2003). The Sandakan Formation has been variously dated as Middle Miocene (*Globorotalia fohsi* zone; Ujiie 1977) or Middle to Upper Miocene in age based on foraminifera; Noad 1999), nannofossils (Clennell 1992) and as Early Miocene based on palynology (Table 4; Clennell 1992).

Sample description
The Sandakan Formation was used to test the model that different depositional settings would yield different foraminifera assemblages (Simmons *et al.*, 1999). A total of 11 of 22 washed samples yielded foraminifera from three distinct environments. Samples from deposits interpreted as ancient mangrove deposits were devoid of calcareous fauna, suggesting dissolution in (sometimes highly) acidic conditions. It is worth noting that molluscs are also preserved as internal casts in this setting (Noad 1999). Agglutinated foraminifera were from varied species but typically dwarfed, indicating stressed conditions, and were sometimes etched and abraded. Some samples had a very limited fauna indicating low oxygen levels (e.g. Locality 81), while others were more diverse, but with alveolar forms showing that conditions were still marginal in terms of low oxygen levels.

The middle to lower shoreface (shelfal) samples were also devoid of calcareous fauna, suggesting dissolution. Trace fossils are abundant and diverse in this setting (Noad 1999), so conditions were clearly favourable for life. The faunal diversity is limited, suggesting possibly stressed and poorly oxygenated conditions, particularly at Locality 35. The presence of several species of *Bathysiphon* (Locality 6) demonstrates that low energy conditions were extant between storms, allowing tubes to be constructed, although the presence of only one species at Locality 35 may be due to more frequent storms which limit the opportunities for foraminiferal communities to become established. Post mortem dysoxia is likely.

The open marine mudstone facies generally yielded well preserved foraminifera, which were often faunally diverse. Both agglutinated and calcareous forms dominated individual samples from this setting. Pyritization shows post mortem reducing conditions, and some samples show anoxia at the sediment/ water interface (Locality 183). Overall the deeper, muddy conditions were clearly conducive to better preservation of a variety of foraminifera.

Variations in local conditions, or potentially diagenetic alteration, definitely lent a bias to the preserved fauna, as in a comparison between Locality 194 (many calcareous and 6 agglutinate species) and Locality 164 (many agglutinates yet devoid of calcareous forms). The lack of dissolution in the former sample may suggest a more distal, mud prone setting, and the faunal diversity shows well oxygenated conditions and an abundant food source. Severe dysoxia at the sediment/water interface encouraged the development of the agglutinated foraminifera, and attributed to the post mortem pyritisation of the calcareous component.

The sometimes stressed conditions are demonstrated by the dwarfed nature of the foraminifera (as at Locality 164), and the often very limited diversity of species in some samples (as at Localities 53 and 176). Evidence of mobilisation of fauna during storms is provided by the sample from Locality 231, which contains relatively shallow water forms including *Entosolina, Elphidium* and *Lenticulina*. This sample also contains a well ventilated, calcareous fauna. Other open marine mudstone samples include ostracod valves and miliolids.

Manjang Formation

Sedimentology
The Manjang Formation is very poorly exposed in an outlier 5 km in diameter located some 30 km to the northwest of the Sandakan Formation. It is considered broadly coeval with the Sandakan Formation, and has been delineated based on SAR (synthetic aperture radar) data. It overlies the Garinono mélange, and basal mudstone beds are overlain by heterolithic sandstone beds with muddy and silty interlaminations, and abundant carbonaceous material. The mudstones are interpreted as open marine deposits, overlain by tempestites and estuarine deposits (Fitch 1958; Noad 1999). One sample was collected just above the contact with the Garinono mélange, the other from the more heterolithic interval above it.

Sample description
Two very similar samples yielded diverse faunal assemblages, one dominated by agglutinates and the other by calcareous foraminifera. Both were deposited in settings with some sand input, but it appears that dissolution was confined to Locality 227. The presence of epifaunal forms shows that oxygen levels were fair, although several species from the sample collected at Locality 227 show low oxygen levels (*Spiropsammina, Alveovalvulina, Alveovalvulinella*). Both samples show lower oxygen elements of the Agua Salada Formation assemblage.

Bongaya Formation

Sedimentology
The Bongaya Formation is exposed in the small Bidu Bidu Outlier to the east of Telupid, which can be delineated using SAR data. This is one of a series of sub basins grouped together under this Formation name, and is slightly larger than the Manjang outlier. It is considered broadly coeval with the Sandakan Formation. The outlier is exposed in several small, heavily weathered outcrops, and one almost complete section of approximately 50m in thickness. Thin sandstone beds are interbedded with 30m thick mudstone beds. The sandstone beds are interpreted as marine, shelfal, lower shoreface tempestite deposits, while the mudstone beds are open marine deposits (Noad 1999). The single sample was collected from the thick mudstone interval. The Bongaya Formation is dated as Lower to Middle Miocene by Hutchison (2005). The presence of *Orbulina universa* in our sample suggests a Middle Miocene or younger age.

Sample description
The sample was the only one analysed that yielded planktonic fauna, and other foraminifera were absent. This suggests a significantly deeper marine setting than at any other outcrop, or the shallowest if the absence of planktonics in other samples is due to dissolution below lysocline or CCD depth. The common pyritised burrows suggest low oxygen levels or reducing conditions at the seabed, especially post mortem.

PALYNOFLORA

The palynofloras from the region (Table 4) agree well with those reported by previous authors (notably Haseldonckx 1974). Whilst palynofloras reflect vegetation on nearby landmasses, and should not be used for interpretation of marine environments, *Zonocostites ramonae* is most abundant in shoreface deposits of the Sandakan Formation, and *Florschuetzia* spp. were reported from the beds interpreted as mangrove deposits in the virtual absence of other palynomorphs. *Florschuetzia* is produced by *Sonneratia* mangrove plants. The presence of *Spinizonocolpites echinatus* in the Gomantong Limestone, normally a back mangrove coloniser, may suggest that the Gomantong Limestone was deposited relatively close to the shoreline.

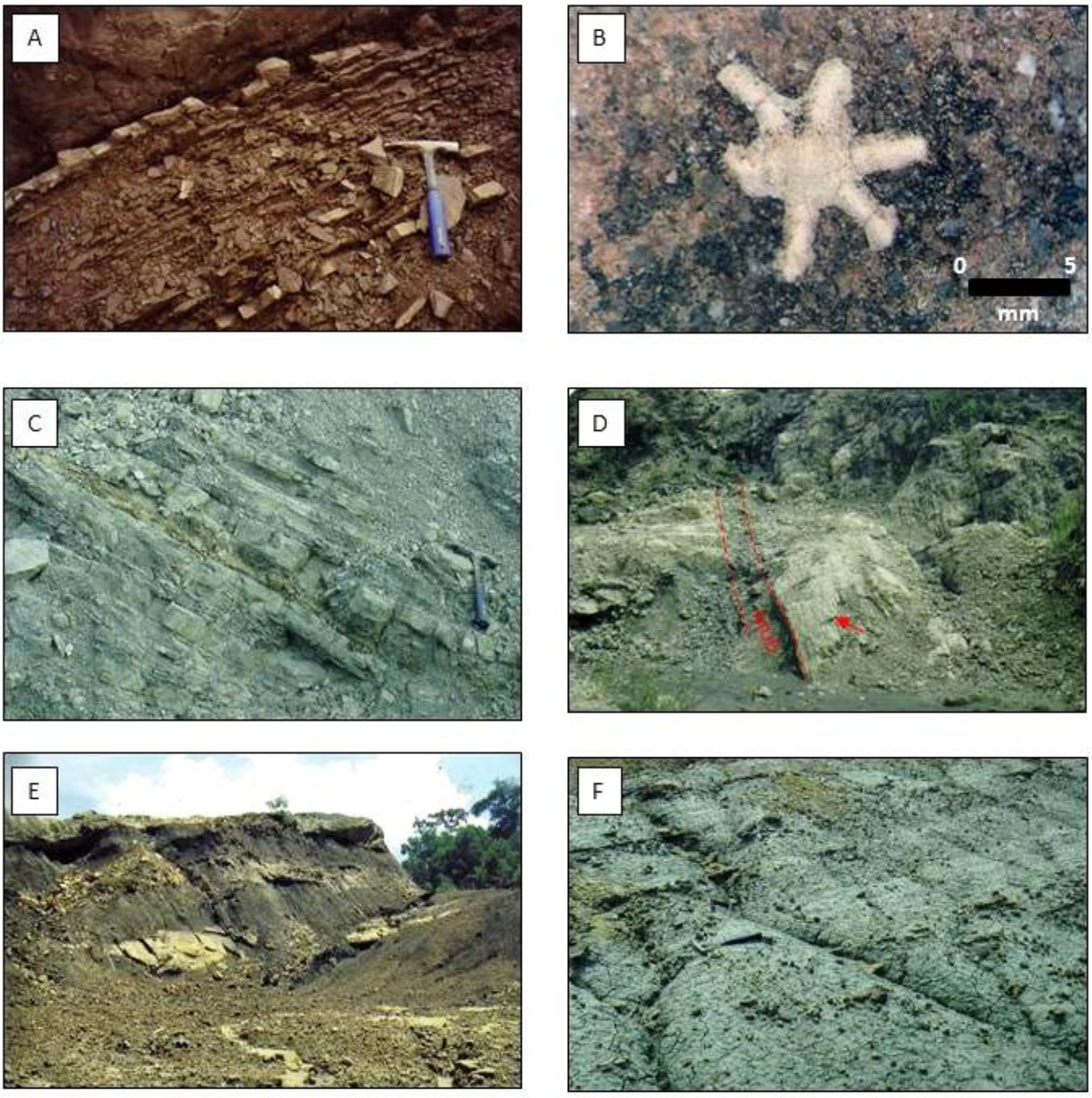
DISCUSSION

Overall the samples yielded a wide variety of both calcareous and agglutinated foraminifera. The former were absent in most samples where agglutinated benthic foraminifera were abundant, which strongly suggests that the calcareous forms in these samples were dissolved out through diagenesis. This appears prevalent through most depositional settings, with only the occasional sample (such as Locality 194) apparently having some kind of chemical buffer to prevent dissolution. Care must be taken when interpreting samples to allow for such diagenetic bias, especially since such dissolution may have taken place in very different settings: (1) in very deep water below the lysocline or CCD (carbonate compensation depth); (2) diagenetic, not uncommon in organic-rich mudstones, or (3) recent tropical weathering of outcrops.

The diversity, size and preservation of the foraminifera could all be utilised to interpret details of the depositional setting. Adjacent outcrops (in an admittedly structurally complex area) showed very different characteristics in terms of faunal abundance and size, particularly in the Labang Formation. Dwarfed fauna show marginally habitable conditions leading to stressed organisms, while reduced diversity also shows that that conditions were challenging for successful colonisation. The condition of some foraminifera, especially when worn or fragmented, showed high energy settings, or downslope transport with turbiditic deposits. Typically such settings also favoured larger, more robust specimens. It is believed that changes through time in patterns in the style of preservation can be used to predict changes in relative sea level, and to correlate between adjacent wells, in areas where the geology is relatively straightforward.

In terms of the impact of depositional setting on foraminiferal assemblages, Simmons *et al* (1999)

record from Brunei sediments that calcareous benthonics are restricted to the open shelf, while agglutinated assemblages are moderately diverse in tidal flat to open shelfal settings. This is broadly comparable to this study, using only the most diverse assemblages rather than those thought to have suffered dissolution. Mangrove deposits from the Sandakan Formation yielded six species of agglutinated foraminifera, and shoreface deposits up to nine species. Open marine deposits yielded a



A. Red deep water mudstone and turbidite, Kulapis Formation (Locality 220)
B. *Astrorhiza* sp., agglutinated foraminifera, Kulapis Formation (Locality 220)
C. Deep water turbidites, Labang Formation (Locality 253)
D. Thin mudstone interbedded with Gomantong Limestone
E. Mangrove mudstone, Sandakan Formation (Locality 77)
F. Open marine mudstone, Sandakan Formation (Locality 164)

Figure 4. Outcrop photographs from formations which form part of this study

similarly diverse fauna, although samples from the Labang Fm. yielded up to 30 species. Only one sample, excluding the carbonate dominated facies of the Gomantong Limestone, yielded diverse calcareous foraminifera. This was also from an open marine setting in the Sandakan Formation. However 10 of 16 samples were barren in calcareous forms, suggesting that diagenetic dissolution plays a large role in the preservation of these animals.

The new occurrence of *Astrorhiza* sp. (*arenaria*?) is of palaeontological significance. It is believed to have been washed by turbidity currents from a sandy, shelfal setting into a deeper marine setting, and was found in massive, turbiditic sandstone beds. Future work could involve mapping out the occurrence of this *Astrorhiza* sp and comparing this to palaeocurrents to see if the source was restricted, as it was not seen in any other samples. This foraminifer is unusually large for an agglutinated form, and is believed to be sedentary under normal conditions.

Previous authors demonstrated how mapping benthonic foraminiferal morphogroups and total organic carbon (TOC) levels could reflect variations in the intensity of the oxygen minimum zone (Preece *et al* 1999). Separating out the agglutinate and calcareous faunal groups can aid with this process. Detailed sampling of the Formations examined during this study, in particular the best exposed and least contorted strata (i.e. the Sandakan Formation), would allow the stratigraphic position of potentially high TOC source rocks to be predicted, supported by the development of sequence stratigraphic models. This approach can be applied to other underexplored regions prospective for hydrocarbons.

CONCLUSIONS

A wide variety of both calcareous and agglutinated foraminifera have been recovered from samples collected from five different formations in the Eocene- Miocene deposits of eastern Sabah. Some of the outcrops only yielded agglutinated forms, suggesting that the calcareous forms may have been removed by dissolution. The preservation of the foraminifera ranged from dwarf to normal in size, from limited to high varied species diversity, and from well preserved to worn, suggesting variations in seabed geochemistry, oxygen levels and level of stress suffered by the organisms. The characteristics of the individual assemblages may allow trends to be identified that may relate to changes in relative sea level, climate or levels of oxygen minima and reducing conditions. It may be possible to correlate these intervals, or to use the identified trends to predict potential source rock intervals.

ACKNOWLEDGEMENTS

We would like to thank Robert Morley for identifying the palynomorphs, and the many other palaeontologists who have helped through the course of both authors' doctoral studies. Jim Davy is thanked for all his help with sample preparation, and his always happy and positive approach. We would further like to thank our doctoral supervisors for their support during our studies.

REFERENCES

Bénard, F., Muller, C., Letouzey, J., Rangin, C. and Tahir, S., 1990, Evidence of multiphase deformation in the Rajang-Crocker Range (northern Borneo) from Landsat imagery interpretation: geodynamic implications. Tectonophysics 183, p. 321-339.

Blow, W.H., 1959, Age, correlation and biostratigraphy of the Upper Tocuyo (San Lorenzo) and Pozon Formations, Eastern Venezuela. Bull. American Paleont. 39, p. 67-251.

Boersma, A., 1978, Foraminifera. In: Haq, B.U. and Boersma, A. (eds.) Introduction to marine micropalaeontology. Elsevier, Amsterdam, p. 19-77.

BouDagher-Fadel, M.K., Noad, J.J. and Lord, A.R., 2000, Larger foraminifera from late Oligocene-earliest Miocene reefal limestones of North East Borneo. Revista Espanola Micropal. 32, 3, p. 341-361.

Clennell, M.B., 1991, Origin and tectonic significance of melanges in eastern Sabah, Malaysia. In: Nichols, G. and Hall, R. (eds.) *Orogenesis in Action in London*, J. Southeast Asian Earth Sciences 6, p. 407-429.

Clennell, M.B., 1992, The melanges of Sabah, Malaysia. Unpublished Ph.D. thesis, University of London, 404p.

Clennell, M.B., 1996, Far-field and gravity tectonics in Miocene basins of Sabah, Malaysia. In: Hall, R. and Blundell, D. (eds.) *Tectonic Evolution of Southeast Asia*, Geol. Soc. London,.Spec. Publ. 106, p. 307-320.

Collins, J.S.H., Lee, C. and Noad, J.J., 2003, Miocene and Pleistocene crabs (Crustea, Decapoda) from Sabah and Sarawak. J. Systematic Palaeont. 1, 3, p. 187-226.

Daly, M. C., Cooper, M. A., Wilson, I., Smith, D. G. and Hooper, B. G. D., 1991, Cenozoic plate tectonics and basin evolution in Indonesia. Marine and Petroleum Geology 8, p. 2-21.

Fitch, F.H., 1958, The geology and mineral resources of the Sandakan area, North Borneo. Memoir 9. British Borneo Geological Survey, 189p.

Haile, N. S. and Wong, N. P. Y. 1965. The Geology and mineral resources of the Dent Peninsula, British Borneo Geological Survey, Sabah, Memoir 16. 199p.

Hall, R., 1996, Reconstructing Cenozoic SE Asia. In: Hall, R. and Blundell, D. (eds.) *Tectonic Evolution of Southeast Asia*, Geol. Soc., London,.Spec. Publ. 106, p. 153-184.

Hamilton, W., 1979, Tectonics of the Indonesian Region. U.S. Geol. Survey,. Prof. Paper 1078, 345p.

Haseldonckx, P., 1974, A palynological interpretation of palaeo-environments in S.E.Asia. Sains Malaysiana 3, p. 119-127.

Hutchison, C. S., 1989, The geological evolution of SE Asia. Oxford University Press, Oxford.

Hutchison, C. S., 1992, The Southeast Sulu Sea, a Neogene marginal basin with outcropping extensions in Sabah. *Bulletin of the Geological Society of Malaysia* 32: 89-108.

Hutchison, C. S., 2005, Geology of North-west Borneo: Sarawak, Brunei and Sabah. Elsevier. 421p.

Jones R. W., 1996, Micropalaeontology in petroleum exploration. Oxford University Press, Oxford, 432p.

Kaminski, M.A., Berggren, W.A. and Preece, R.C., 2000, The Agua Salada fauna: a Neogene deep-sea agglutinated foraminiferal fauna adapted to dysaerobic conditions of the low-latitude upwelling zones. Spec. Publ. Grzybowski Foundation.

Keij, A.J.,1964, Late Cretaceous and Palaeogene arenaceous foraminifera from flysch deposits in northwestern Borneo. Malaysia Geol. Survey Ann. Report 1964, p. 155-158.

McMonagle, L.B., Lunt, P., Wilson, M.E.J., Johnson, K.G., Manning C. and Young, J., 2011, A re-assessment of age dating of fossiliferous limestones in eastern Sabah, Borneo: implications for understanding the origins of the Indo-Pacific marine biodiversity hotspot. Palaeogeogr., Palaeoclim., Palaeoecol. 305, p. 28-42.

Morley, R.J., 1991, Tertiary stratigraphic palynology in Southeast Asia: current status and new directions. Geol. Soc. Malaysia Bull.. 28, p. 1-36.

Noad, J.J., 1999, The Sedimentary Evolution of the Tertiary of eastern Sabah, Northern Borneo. Unpublished PhD. thesis, University of London.

Noad, J., 2001, The Gomantong Limestone of eastern Borneo: a sedimentological comparison with the near-contemporaneous Luconia Province. Palaeogeogr., Palaeoclim., Palaeoecol. 175, p. 273-302.

Noad, J., 2013, The power of palaeocurrents: reconstructing the palaeogeography and sediment flux patterns of the Miocene Sandakan Formation in eastern Sabah. Indonesian J. Sedimentary Geol. 28, p. 31-40.

Preece, R. C., 1999, The Physiological Response of Equatorial Neogene Bathyal Benthic Foraminifera to Low Oxygen Conditons. Unpublished Ph.D. thesis, University of London.

Preece, R. C., Kaminski, M. A. and Dignes, T. W., 1999, Miocene benthonic foraminiferal morphogroups in an oxygen minimum zone, offshore Cabinda. In: Cameron, N.R., Bate, R.H. and Clure, V.S. (eds.) The Oil and Gas Habitats of the South Atlantic, Geol. Soc., London, Spec. Publ. 153, p. 267-282.

Rangin, C., 1989, The Sulu Sea, a back-arc setting within a Neogene collision zone. Tectonophysics 161, p.119-141.

Rangin, C. and Silver, E., 1990, Geological setting of the Celebes and Sulu Seas. In: Rangin, C. et al. (eds.) Proc. Ocean Drilling Program, Initial Reports, 124, p. 35-42.

Rangin, C. and Silver, E. A., 1991, Neogene tectonic evolution of the Celebes-Sulu basins: new insights from Leg 124 drilling. In: Rangin, C. et al. (eds.) Proc. Ocean Drilling Program, Scient. Results 124, p. 51-63.

Simmons, M. D., Bidgood, M.D., Brenac, P., Crevello, P.D., Lambiase, J. J. and Morley, C.K., 1999, Microfossil assemblages as proxies for precise palaeoenvironmental determination- an example from Miocene sediments of northwest Borneo. In: R.W. Jones and M.D. Simmons (eds.) Biostratigraphy in Production and Development Geology, Geol. Soc., London, Spec. Publ. 152, p. 219-241.

Taylor, B. and Hayes, D. E., 1980, The tectonic evolution of the South China Sea Basin. In: Hayes, D. E. (ed.)*The tectonic and geologic evolution of South-east Asian Seas and Islands*, American Geoph. Union, Geoph. Mon. 23, p. 89-104.

Taylor, B. and Hayes, D. E., 1983, Origin and history of the South China Sea Basin. In: Hayes, D. E. (ed.) *The tectonic and geologic evolution of South-east Asian Seas and Islands* 2, American Geoph. Union, Geoph. Mon. 27, p. 23-56.

Ujiie, H. 1977, New species and subspecies of benthonic foraminifera from the Miocene Sandakan Formation, north Borneo. In: Contributions to the Geology and Palaeontology of S.E. Asia, University of Tokyo Press, 18, p. 87-102.

Yin, E.H., 1985, Geological Map of Sabah, 1:500,000 scale, Third edition. Geological Survey of Malaysia.