Sedimentology of the Jalan Salaiman and Bukit Melinsung outcrops, western Sabah: is the West Crocker Formation an analogue for Neogene turbidites offshore?

AMELIA G. WILLIAM[1], JOSEPH J. LAMBIASE, STEFAN BACK[2] AND MOHD. KHALID JAMIRAN[3]

Department of Petroleum Geoscience
Universiti Brunei Darussalam
Tungku Link BE 1410
Brunei Darussalam

[1]Present address: ExxonMobil Exploration and Production Malaysia Inc., Kuala Lumpur
[2]Present address: Department of Geology, Aachen University, Aachen, Germany
[3]Present address: Murphy Sarawak Oil Co. Ltd., Kuala Lumpur

Abstract: Outcrops of the West Crocker Formation in western Sabah are dominated by coarse-grained sandstones interbedded with shale, although numerous bedding-plane thrust faults that form preferentially in the shales and weathering that favours exposure of sandstone suggest that the actual sand-shale ratio may be significantly lower. The sandstones occur as amalgamated units with individual beds that are generally 1–6 m thick within 25–65 m thick parasequences. Most sandstones are massive and display partial Bouma sequences. The sands are texturally immature with a high proportion of rock fragments and poorly sorted. Their sedimentary structures and texture are consistent with a short transport path down a relatively steep slope and then rapid deposition from collapse fall-out in high density turbidity currents. In the outcrops studied in detail, comprising nearly 500 m of succession some of which is laterally continuous up to 500 m, most beds are sheet sands and a few are lobate and there is no evidence of channeling. The bed geometries, texture and depositional mechanism all suggest relatively small lobes that coalesced to form a sand-rich slope apron.

Palaeocurrent directions are consistently to the north, indicating a transport direction that is oblique to the northeast-southwest marginal basin. This suggests that the West Crocker strata were derived from nearby Rajang Group sediment, possibly in response to the initial phase of the uplift that formed the Deep Regional Unconformity. The tectonic setting, facies distribution, stratigraphic architecture, sand body orientation, texture and sorting of the West Crocker turbidites are all significantly different from those of the Neogene turbidites offshore and, therefore, they are a poor analogue for the younger sands.

INTRODUCTION

The depositional setting and stratigraphic architecture of the turbidites in the West Crocker Formation have the potential for contributing to an improved understanding of the complex geological history of Sabah and to more efficient exploitation of its deepwater petroleum reserves. As the youngest of the exposed rocks that were deposited in response to the Late Cretaceous to early Miocene opening of the South China Sea (Hutchison, 1996a), their depositional setting holds important clues to the configuration of the northwest Borneo margin as that tectonic phase drew to a close. The margin's configuration also is a central issue in a debate about their relevance as analogues for Neogene turbidites offshore. Whilst Crevello (2001, 2002) considers the West Crocker turbidites as direct analogues for the younger, deepwater sands, Back and Lambiase (2001) argue that the very different tectonic setting in the Oligocene and early Miocene generated a significantly different stratigraphic architecture.

The West Crocker outcrops in western Sabah are scattered over an area of approximately 3,000 sq km (Fig. 1) and represent the most extensively exposed turbidite system on the northwest Borneo margin; stratigraphic relationships in the Tenom Gorge indicate an Oligocene to early Miocene age (Fig. 2; Wilson, 1964). A few studies have addressed different aspects of the depositional system of the West Crocker Formation (Collenette, 1958; Stauffer, 1968; Tongkul, 1987; Tajul Anuar Jamaludin, 1989; Crevello, 2002). It is generally agreed that the turbidites were deposited in a foreland basin that developed in response to uplift of the Rajang accretionary prism during the Sabah Orogeny in the late Eocene (e.g. Tongkul, 1990; Hutchison,

Paper presented at GSM Petroleum Geology Conference & Exhibition 2002

1996a), although the palaeogeography of northwest Borneo and the exact timing of events during the early Tertiary are poorly constrained. The thickness of the West Crocker succession is uncertain; Wilson (1964) suggested that there is at least 6,000 m of section whilst Tongkul (1987) argues for approximately 1,000 m. The West Crocker Formation lies immediately below the Deep Regional Unconformity of Levell (1987) that marks the boundary with the overlying Neogene shallow marine clastics (Fig. 2) that were deposited in discrete peripheral basins by prograding deltas with growth fault systems (Hutchison, 1996a; Back and Lambiase, 2001).

Generally, the West Crocker outcrops are mostly sandstones with thinner interbedded shales; the sandstones form prominent ridges and outcrops occur where the ridges are breached. However, ridges account for only a relatively small percentage of the area encompassed by the West Crocker Formation, suggesting that shale comprises a much higher proportion of the formation than is apparent in outcrop. The sandstone-shale distribution is further complicated by post-depositional thrust-faulting that makes stratigraphic reconstruction between outcrops nearly impossible. Also, numerous bedding-plane parallel thrust faults, preferentially within the shale units, render estimates of sand-shale ratios unreliable even within individual outcrops.

The present study investigated the sedimentology and stratigraphic development of the West Crocker turbidites in order to develop a depositional model that can constrain several factors that bear on the configuration of the margin and the relevance as analogues for Neogene turbidites. These include source of the sediment, distance and direction of transport, and size, orientation and architecture of the sandstone units. A preliminary evaluation of numerous outcrops indicated a similar sedimentological character throughout, but a variable amount of post-depositional deformation; two were selected for detailed study because they are much less deformed than most and because one has the thickest continuously exposed vertical succession whilst the other represents the most continuous lateral exposure. Approximately 350 m of vertical section is exposed continuously in the Bukit Melinsung outcrop (Fig. 1), although lateral continuity is limited to around 50 m. About 70% of the succession is very fine to granular sandstone and the remaining 30% is shale. Individual beds in the Jalan Salaiman outcrop near Kota Kinabalu (Fig. 1) can be traced laterally for approximately 500 m. They consist of very coarse to coarse grained, 1–6 m thick sandstones interbedded with thinner shales in a 130 m thick, continuously exposed vertical succession.

SEDIMENTOLOGY

The Jalan Salaiman and Bukit Melinsung outcrops were logged in detail to define grain size trends, sedimentary structures, the nature of bed contacts and trace fossil distribution and the logs were then used to identify stacking patterns and the lateral geometry of each sand body. Microfossil assemblages were determined from the interbedded shales and the sandstones were analyzed petrographically to evaluate gross composition.

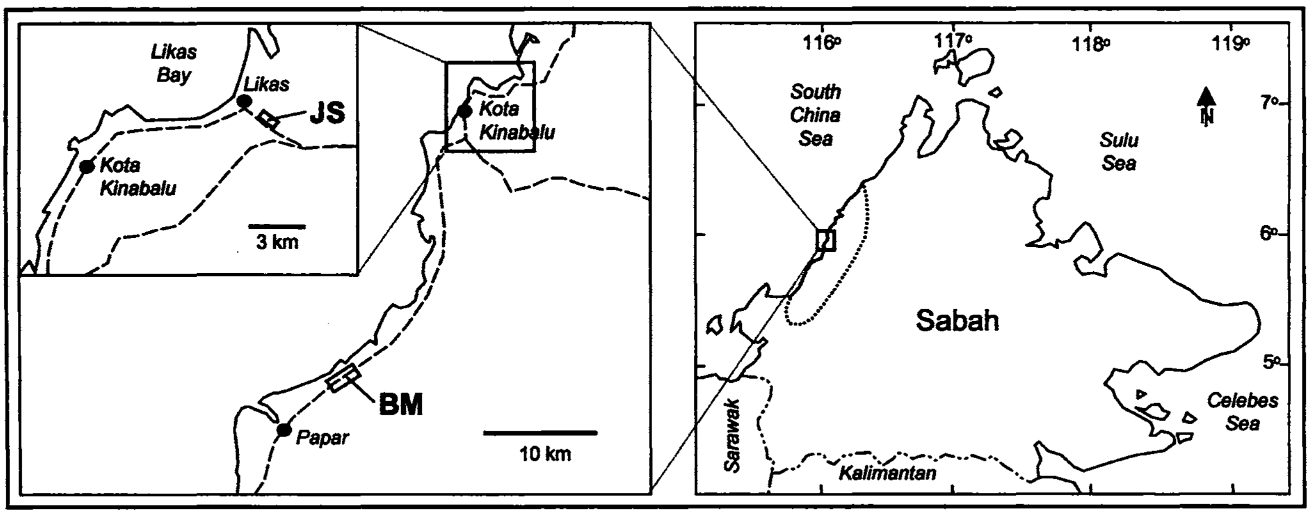

Figure 1. Distribution of the West Crocker Formation in southwestern Sabah and location of the Jalan Salaiman (JS) and Bukit Melinsung (BM) outcrops. Major roads are shown with dashed lines and the approximate areal extent of West Crocker Formation outcrops as a dotted line.

Sedimentary facies

William (2001) and Mohd Khalid Jamiran (1999) identified three facies in the Jalan Salaiman and Bukit Melinsung outcrops, namely thick sandstones, thin interbedded sandstones and shale, and shale. The thick sandstones generally occur as amalgamated beds, although a few are isolated between thin shales. Amalgamated units generally consist of 4–25 sandstone beds with a total thickness of 6–33 m (Fig. 3A).

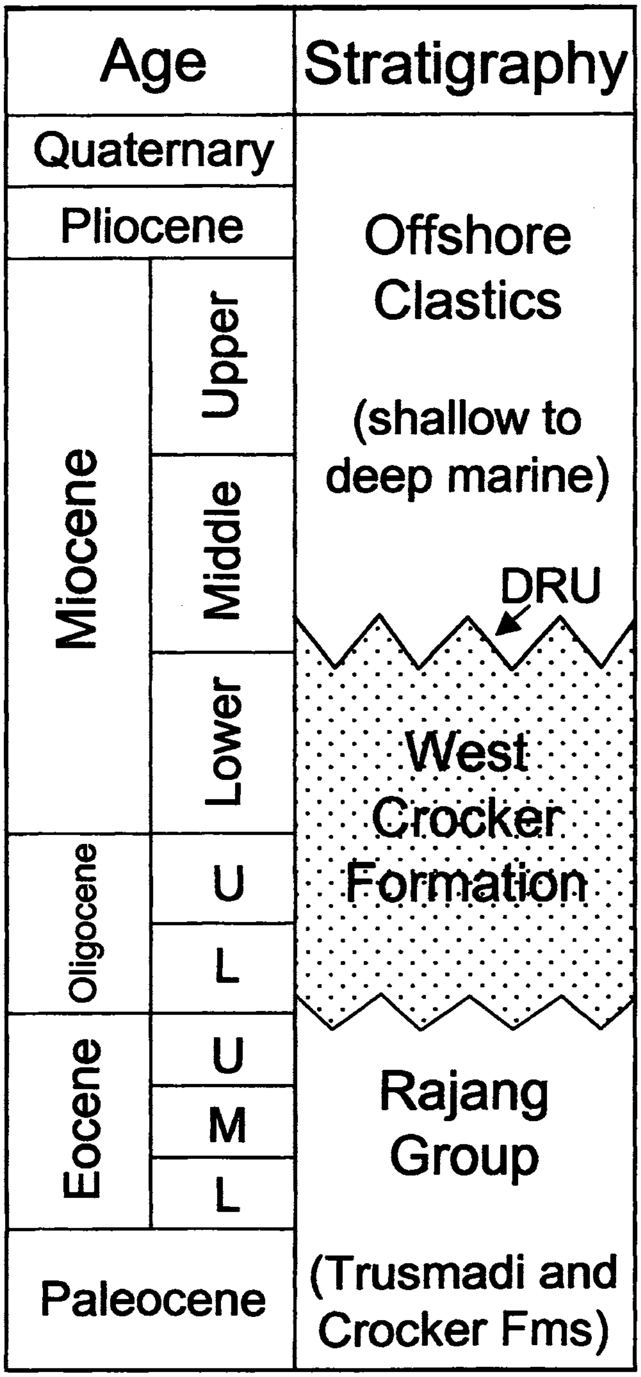

Figure 2. Stratigraphic setting of the West Crocker Formation; DRU indicates the Deep Regional Unconformity of Levell (1987) (Simplified from Hutchison *et al.*, 2000.)

Individual beds generally thicken and coarsen upward within the amalgamated units but bed thickness remains constant laterally for at least the exposed distance of 500 m in the Jalan Salaiman outcrop so that nearly all the sand bodies have a sheet-like geometry, although the thickness of some beds varies locally due to faulting. A few of the isolated sandstones are conclusively lobate; at least one end pinches out with a convex upward geometry, generally over a distance of 5–10 m from a maximum thickness of about 0.5 m (Fig. 3B). Basal contacts are straight and sharp and relatively few are scoured, although bedding-plane parallel faults cause some bed boundaries to be irregular and wavy. Load structures are moderately common and tool marks are rare; flute casts occur on the base of several sandstones bed and all indicate a northerly palaeoflow direction when corrected for structural dip (Fig. 3C).

Within each unit, the lower sandstone beds are relatively thin (0.3–1.0 m) and generally grade upward from coarse or very coarse sand to fine sand, laminated silt and finally shale. Most beds are massive at the base and pass upward into parallel lamination (Fig. 3D), although some have convoluted bedding that passes upward into parallel lamination. Sandstone beds 1–6 m thick, and rarely up to 10 m thick, occur near the top of the amalgamated units. They generally are coarse to very coarse sand, massive and structureless. Grain size distribution is uniform throughout, but grades into medium sand a few centimetres from the top of the bed. Parallel lamination and, less commonly, contorted lamination occurs locally. The uppermost part of the massive sand bodies locally contains thin laminations of carbonaceous material and is rippled or wavy-bedded.

The silts and shales that cap the sandstones are usually laminated and contain abundant carbonaceous material (Fig. 4A); isolated ripple cross-stratification and climbing ripples occur locally in thin sandy interbeds (Fig. 4B). Generally, the sandstones in the amalgamated units have flat, straight and sharp upper contacts; the few that appear to have gradational upper contacts and scoured basal contacts are those that are in the lower part of the units. One distinctive feature of the massive sandstones is that mudstone clasts are common at the top of the beds. Also, rounded sandstone boulders 0.2–0.3 m in diameter occur on the top of one massive sandstone bed; they are composed of silt and fine sand that is stratified with carbonaceous material.

The interbedded sandstone and shale facies is monotonous alternations of 4–8 cm thick sandstones and shale within a 0.5–1.5 m thick unit that extends laterally for a minimum of 500 m (Fig. 5A). These

Figure 3A. Amalgamated sandstone unit in the Jalan Salaiman outcrop. The succession youngs toward the right of the photo.

Figure 3B. Lobate sandstone geometry; the bed is convex upward (the younging direction is toward the right of the photo) and has a flat base.

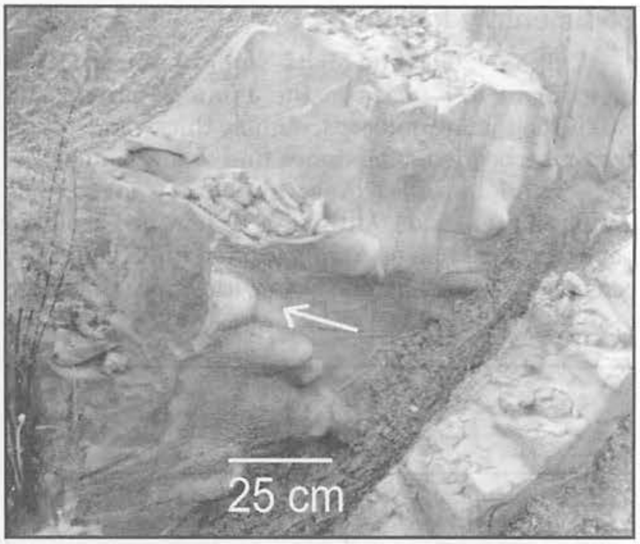

Figure 3C. Flute casts at the base of a sandstone bed. The arrow indicates the flow direction, which is northerly when corrected for structural dip.

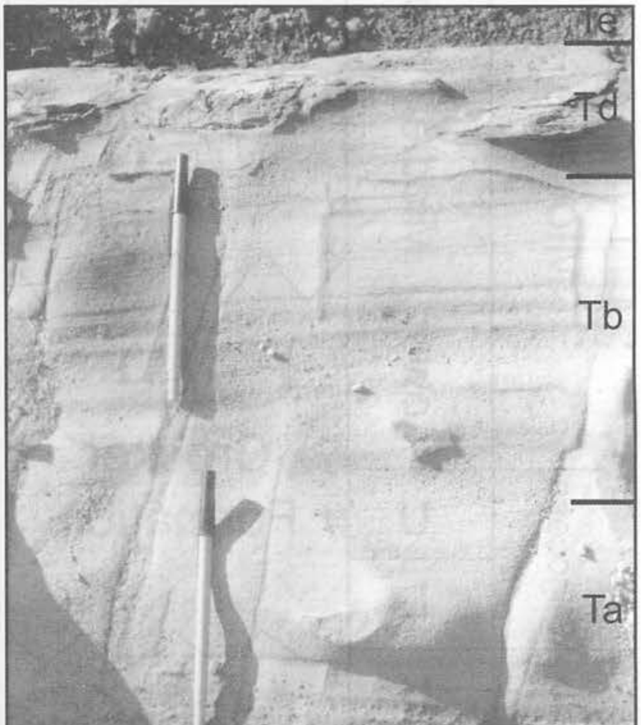

Figure 3D. Turbidite bed with a scoured base and a sharp upper contact with an overlying shale. The sandstone is massive with very coarse sand and granules near the base and grades into parallel laminated, medium sand. The unit comprises Bouma divisions Ta, Tb, Td and Te.

occur stratigraphically above thick amalgamated sandstone units and underlie thick shale beds. The sandstone layers generally are fine to medium-grained sand. However, some beds grade upward from coarse to medium-grained sand to parallel laminated sand and silt and some layers have discrete and climbing ripples or parallel lamination, often a with high content of carbonaceous material. A majority of the sandstones have sharp basal and top contacts and are capped by thin homogeneous and laminated shale layers, although a few have gradational contacts.

Shale units are homogeneous and range from 0.5–5.0 m in thickness. They are very continuous laterally and can be traced for at least 500 m along with the other facies. The lower part of the shale units usually have thin interbeds of fine to silty sand that exhibit straight, sharp contacts and ripple cross-lamination (Fig. 5B).

Figure 4A. Thin laminated shale with abundant carbonaceous material.

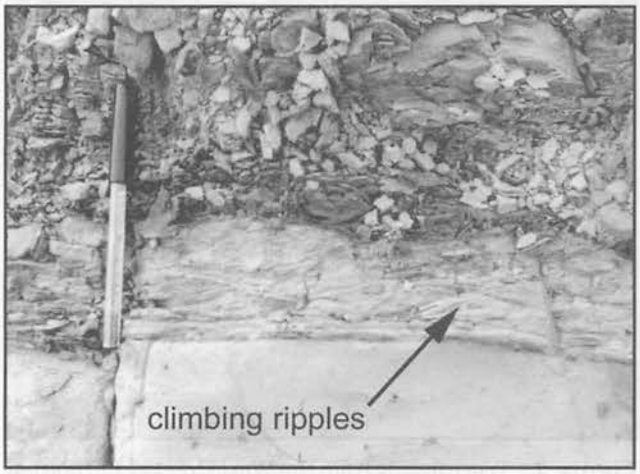

Figure 4B. Climbing ripples in the siltstone cap at the top of a sandstone.

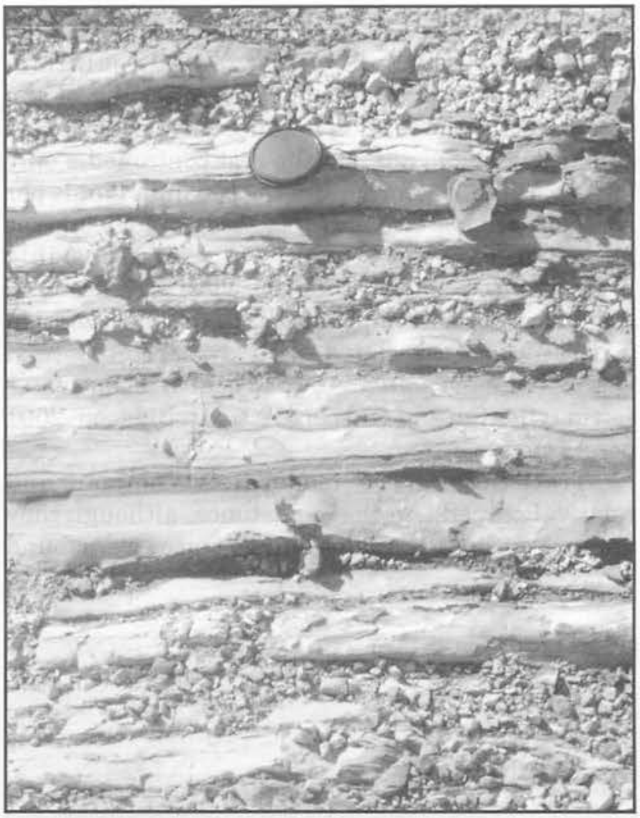

Figure 5A. Thin interbedded sandstone and shale. The sands have a variety of sedimentary structures including ripple cross-stratification, climbing ripples, parallel lamination and graded bedding.

Figure 5B. Shale with thin siltstone layers.

Trace fossils and microfossils

Microfossil analysis yielded minimal information about the depositional setting of the West Crocker Formation because most of the shale samples were barren and the rest contained a only few agglutinating foraminifera (1–6 individuals per sample); all are either *Haplophragmoides* spp. or *Recurvoides* spp. except for one possible *Trochammina* sp. (M. Bidgood, 2001 pers. comm.) Agglutinating foraminifera that occur in isolation generally are associated with dysaerobic bottom waters and normally indicative of a deep water setting (Benton and Harper, 1997; M. Bidgood, 2001 pers. comm.).

Trace fossils are moderately common and relatively diverse in the sandstones, although they are rare within the shales and no traces were found in the interbedded sandstone and shale. Those in the shales are *Helminthoida* and *Megagrapton(?)* of the deepwater *Nereites* ichnofacies (Fig. 6; Pemberton *et al*., 1992), although *Planolites (?)* that are 0.3–0.5 cm in diameter are equally common.

Generally, trace fossils are not abundant in the sandstone facies. They are most common in the finer grained intervals near the bed tops but occur on relatively few beds. However, many of the beds in a recently excavated section of the Bukit Melinsung outcrop are highly bioturbated, although individual burrows are not identifiable; this suggests that weathering has partially obscured the effects of bioturbation in the older outcrops and that there may be significantly more bioturbation than can be observed. A variety of trace fossils occur in the sandstones, including *Ophiomorpha*, *Thalassinoides*, *Terebellina*, *Planolites* and *Paleophycus* that are 0.3–0.5 cm in diameter, *Asterosoma* and *Rhizocorallium* (Fig. 7). *Ophiomorpha* range from 1.0–2.5 cm in diameter and are up to 0.3 m long (Fig. 8). However, each locality tends to have a low diversity and some are even monospecific. Tajul Anuar Jamaluddin (1989) identified a similar trace fossil assemblage, as well as *Crossopodia*.

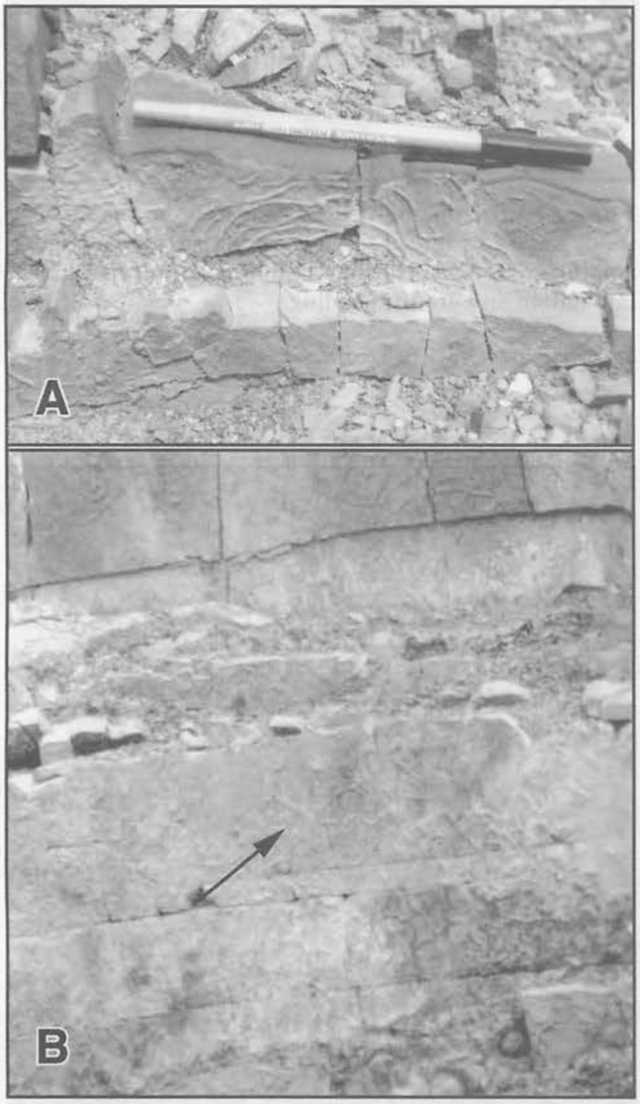

Figure 6. Trace fossils from the *Nereites* ichnofacies in shale beds. (A) *Helminthoida* (B) and a *Megagrapton(?)* (at the tip of the arrow) that is approximately 15 cm across.

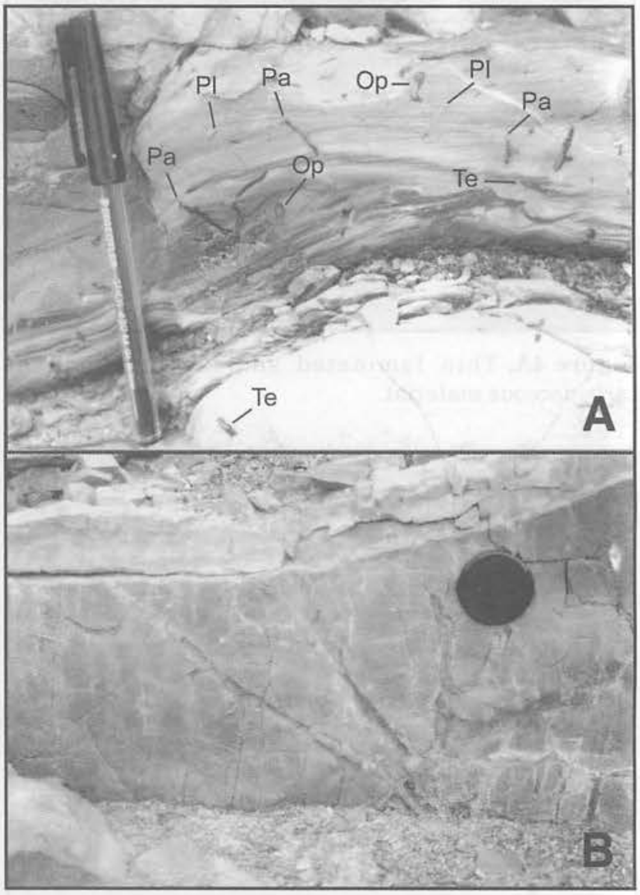

Figure 7. Trace fossils from the West Crocker Formation sandstones. (A) *Ophiomorpha* (Op), *Paleophycus* (Pa), *Planolites* (Pl) and *Terebellina* (Te). (B) *Thalassinoides*.

Petrography

The gross rock composition of 36 sandstones beds was analyzed in thin section and they generally contain 40–60% quartz, 15–25% feldspar, which is mostly microcline and orthoclase with a few occurrences of plagioclase, and 10–15% matrix. Lithic rock fragments account for 5–20 % of most samples and reach nearly 30% in a few so that the sandstones are mostly subarkoses with a few sublitharenites and litharenites (Fig. 9; Pettijohn *et al.* 1987). Twenty of the samples plot within the field that defines a continental block as the source of sediment, whilst the other 16 appear to have been derived from a recycled orogen (Fig. 9; Dickinson and Suczek, 1979). The overall distribution is consistent with a sandstone derived from an older sediment that was the first-cycle product of an eroded orogenic belt, in this case almost certainly the Rajang Group.

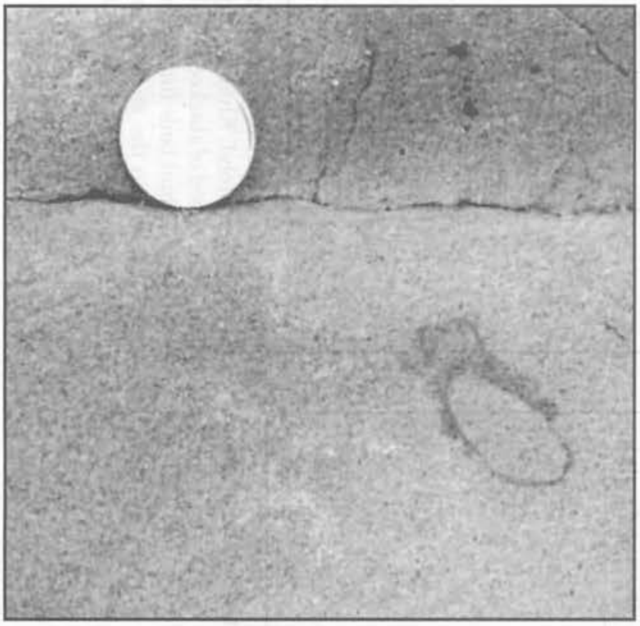

Figure 8. *Ophiomorpha* in a massive sandstone bed.

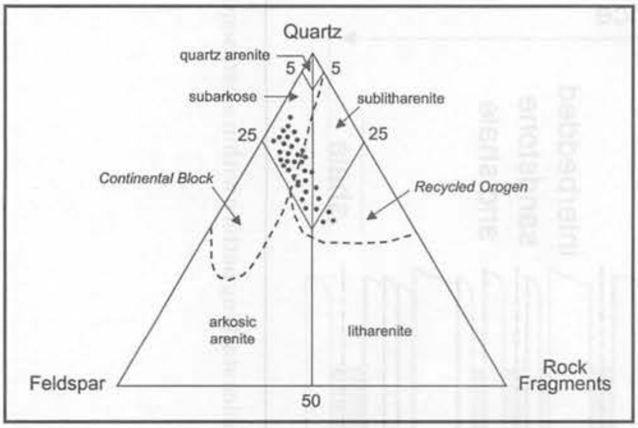

Figure 9. Gross composition of the West Crocker Formation sandstones based on the classification scheme of Pettijohn *et al.* (1987). The provenance fields for recycled orogens and continental blocks are from Dickinson and Suczek (1979).

The sandstones are texturally immature as all samples are poorly sorted and most grains are very angular to sub-angular, although sub-rounded grains are moderately common. The matrix is made of very fine grains and clay minerals; much of the clay fraction comprises authigenic clays formed during diagenesis or surface weathering. Similarly, a majority of the feldspars in the framework constituents have been replaced by sericite, kaolinite, muscovite and a few unidentifiable authigenic clay minerals. The petrographic analysis indicates that the sandstones were originally very immature and contained a considerable amount of feldspar and depositional matrix before diagenesis and surface weathering.

Stratigraphy

Generally, in both outcrops, the three sedimentary facies are stacked into coarsening-upward parasequences. The basal unit in each parasequence is a shale that is overlain by interbedded sand and shale, followed by an amalgamated sandstone unit that forms the uppermost unit (Fig. 10). The sandstone beds within the amalgamated units thicken and coarsen upward, which is a typical progradational stacking pattern (Normark, 1978; Ricci-Lucchi and Valmori, 1980; Macdonald, 1986; Walker, 1992).

There are a total of fourteen parasequences exposed in the Jalan Salaiman and Bukit Melinsung outcrops that range in thickness from 25 to 65 m (Mohd. Khalid Jamiran, 1999; William, 2001). Generally, the lower four Bukit Melinsung parasequences thicken upward with a corresponding increase in the proportion of sand, indicating that they comprise a single progradational parasequence set (Fig. 11). The parasequence set is incomplete because a relatively large fault forms its upper boundary. The upper four parasequences are much sandier than the lower four. However, they also thicken and coarsen upward and comprise part of another progradational parasequence set (Fig. 11).

DEPOSITIONAL MODEL

The sedimentary structures in the West Crocker Formation indicate that the sandstones were deposited by gravity-driven density currents, generally turbidity currents. Most beds contain partial Bouma sequences with divisions Ta, Tb and Td; Ta and Td; Ta and Tc, Ta and Te or just Ta. Partial Bouma sequences (Td and Te missing) and

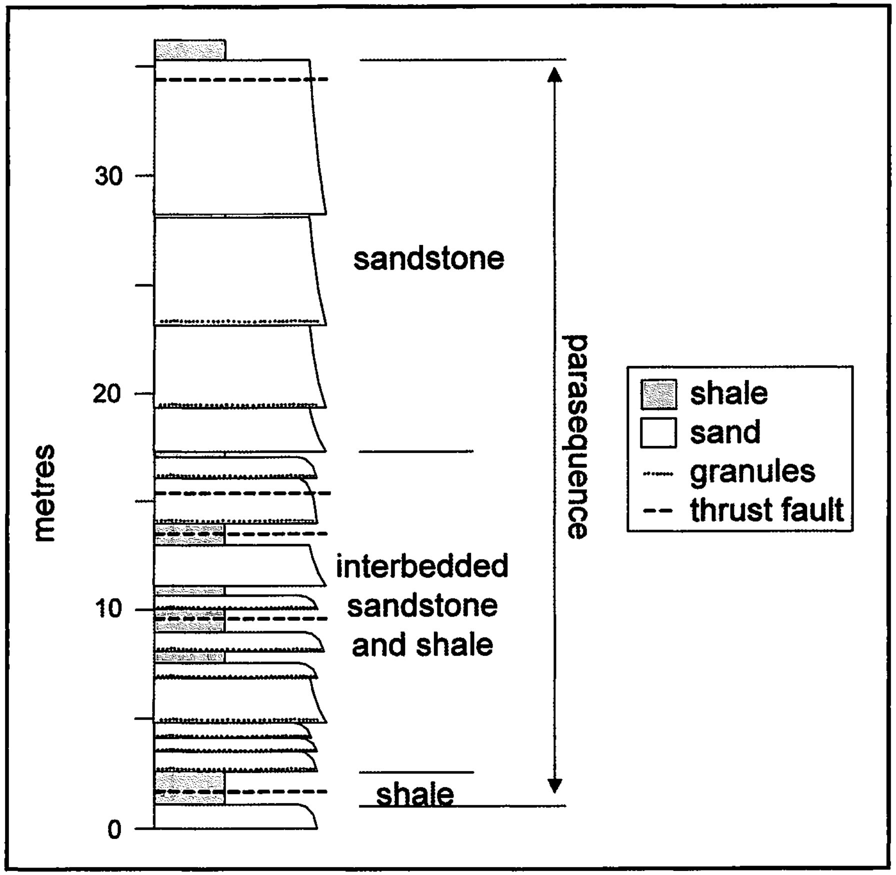

Figure 10. Facies stacking pattern within a parasequence in the Jalan Salaiman outcrop.

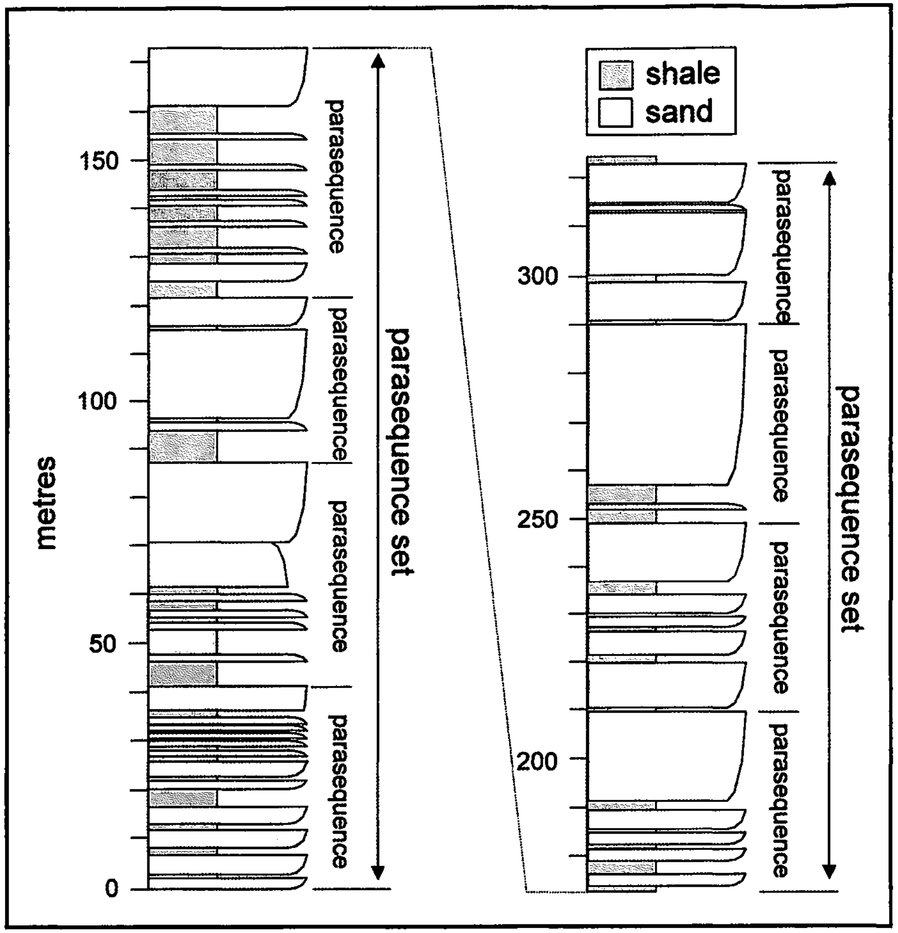

Figure 11. Generalised sequence stratigraphy of the Bukit Melinsung outcrop, revised from Mohd. Khalid Jamiran (1999). Note that the thicker sandstones are units comprised of stacked beds that thicken and coarsen upward within the unit, whilst individual beds fine upward. Also, there are several relatively large faults and folds within the succession that are not shown; the upper boundary of the lower parasequence set is one of the faults.

massive, structureless but graded amalgamated sandstone beds with sharp and straight upper and lower contacts are typical of high-density turbidites (e.g. Lowe, 1982; Walker, 1992; Stow *et al.*, 1996; Stow and Johansson, 2000).

Although the large amount of sand relative to shale would seem to suggest a sand rich system, the bedding-plane faults within the shales and the over-representation of sandstone relative to shale in outcrop make it impossible to accurately assess the local sand-shale ratio, although the overall amount of sandstone relative to shale clearly increases upward within the formation (Tongkul, 1987). Indeed, the outcrop pattern suggests a mud rich system. Alternating amalgamated sandstone beds and shales probably indicate relatively long periods of relative quiescence and limited sediment supply that were punctuated by episodes of rapid deposition that introduced large amounts of sand into the basin via successive, discrete density currents. The laterally continuous sheet-like beds with occasional lobate beds and no apparent channelisation, signify broad, low relief depositional lobes that are unconfined. As deposition occurred in a foreland basin setting, the progradational stacking pattern probably was generated by renewed uplift and erosion in the hinterland and/or eustatic sea level changes (Cant and Stockmal, 1993).

The very immature texture, angularity and poor sorting of the sandstones suggest a nearby sediment source and a short transport distance, as does the presence of angular to sub-angular feldspars that are easily destroyed by extensive transport (Carozzi, 1993; Harwood, 1988). The northerly sediment transport direction measured from flute casts corresponds with palaeocurrent measurements recorded by Stauffer (1968), Tongkul (1987), Hutchison (1996a, b) and Hutchison *et al.* (2000).

The generally structureless and massive turbidite sandstones indicate rapid deposition, probably by collapse fall-out from high-density turbidity currents (Stow and Johansson, 2000) caused by an abrupt decrease in slope angle along the transport path. The parallel lamination and climbing ripples near the top of the sandstones and in the shale caps are the consequence of the rapid and continuous fall out of finer grains during the final stages of deposition. The sharp bed contacts are the product of sediment bypassing and sequential sedimentation of different particle populations from turbulent high density flows comprised of suspended very coarse to fine grains (Lowe, 1982; Stow *et al.*, 1996).

Nearly all the trace fossils belong to the *Cruziana* ichnofacies that is indicative of a shelfal environment (Frey and Pemberton, 1984; Pemberton *et al.*, 1992). However, those in the shale, *Helminthoida* and *Megagrapton(?)*, are deep water traces of the *Neirites* ichnofacies (Pemberton *et al.*, 1992). A similar segregation of deep and shallow water trace fossils has been documented in deep water settings (e.g. Kern and Warme, 1974; Crimes *et al.*, 1981) as a function of substrate control (G. Pemberton, 2002 pers. comm.), suggesting that the West Crocker turbidites are deep water deposits.

All the sedimentary characteristics are most consistent with deposition on a slope apron (Fig. 12; Macdonald, 1993; Reading and Richards, 1994). The sediments were supplied episodically from uplifted Rajang Group strata in the active orogen and transported down a relatively steep slope through lateral conduits oblique to the long axis of the adjacent proximal basin. Sands were deposited

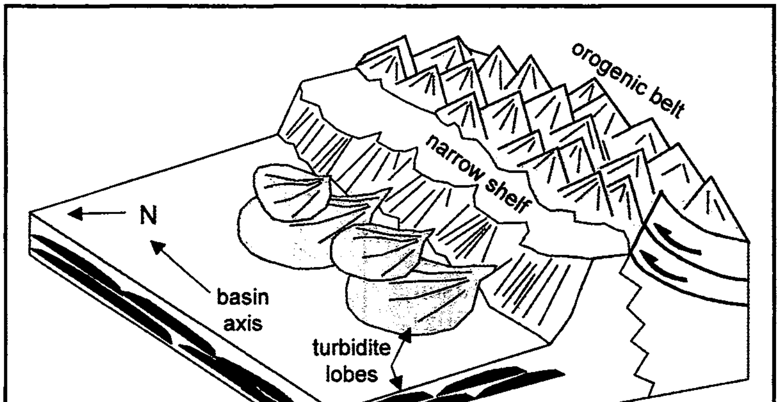

Figure 12. Slope apron depositional model for the West Crocker Formation turbidites. See the text for an explanation.

rapidly at the toe of the slope where they formed small-scale lobes; the relatively thin sandstone beds (nearly all are < 6 m and most are < 2 m thick) suggest that the depositional lobes were not large but had radiuses in the range of 1–5 km or less (Stow and Johansson, 2000). This results in a surface slope on the lobes of less than 1° even for the thickest parasequence of 65 m, which corresponds well with other sand-rich slope aprons, e.g. the middle Tonkawa Sandstone (Kumar and Slatt, 1984). The lobes coalesced to form a complex, margin-parallel linear sheet of sandstone that did not extend far into the basin (Reading and Richards, 1994; Stow *et al.*, 1996). This geometry gave rise to the present-day topography where the sandstones form relatively continuous, margin-parallel ridges separated by valleys underlain by shale (Tongkul, 1987). Thus, the slope apron model satisfies the requirements of 1) an episodic sediment supply, 2) a short transport distance down a steep slope, and 3) the abrupt slope change that causes the rapid deposition that is necessary to generate the immature texture and composition, sedimentary structures, trace fossil assemblage, unconfined lobate geometry and stratigraphic architecture of the West Crocker Formation turbidites.

DISCUSSION

The slope apron depositional model for the West Crocker Formation turbidites is significantly different from previous interpretations and appears to conflict with some aspects of the established Oligocene-early Miocene tectonic history and palaeogeography of NW Borneo, as well as questioning the relevance of the turbidites as analogues for Neogene deep water sands. The key issues that bear on the regional questions are the source of the sediment and the distance and direction of transport; for their relevance as analogues, stratigraphic architecture is the prime consideration.

Depositional setting

Previous investigators have interpreted the West Crocker Formation as a large submarine fan, analogous to the present day Bengal Fan, that was fed from a major point source to the southwest (Stauffer, 1968; Tongkul, 1987,1994; Hutchison, 1996a; Tan and Lamy, 1990; Crevello, 2002). According to Hutchison (1996a), the West Crocker Formation originated as a submarine fan fed by turbidity currents flowing northeast, parallel to the continental margin. He speculated that the largest river in the region, the Mekong, supplied sands to the turbidite fan during the opening of the South China Sea, with the fluvio-deltaic Meligan Formation representing the delta of the great river system. Similarly, Tongkul (1994) suggested that the West Crocker Formation sediments were derived from the southwest and transported axially, as well as laterally from the northwest and southeast, into an elongate, northeast-southwest trending basin.

Both interpretations imply that the main sediment source was to the southwest, far away from the West Crocker depocentre. This argument is partially based on palaeogeographic reconstructions that indicate marine waters covered present-day Sabah prior to the uplift that produced the Deep Regional Unconformity, thereby precluding a sediment source to the south and east. However, the immature texture and composition necessitate a short transport distance and a large component of orogenic rocks; this is more consistent with a nearby, uplifted Rajang Group source.

The measured palaeocurrent directions also are not conclusive evidence of sediment supply from the southwest. Deep water deposits in foreland basins very commonly exhibit axial, or near axial, palaeoflow indicators when sediment initially enters the basin laterally because the depositional systems turn parallel to the basin axis (Cant and Stockmal, 1993). Also, there is an important distinction between northeasterly, margin-parallel transport and the northerly palaeocurrents noted above; the latter are margin-oblique and therefore constitute oblique, lateral transport into the basin (Fig. 13).

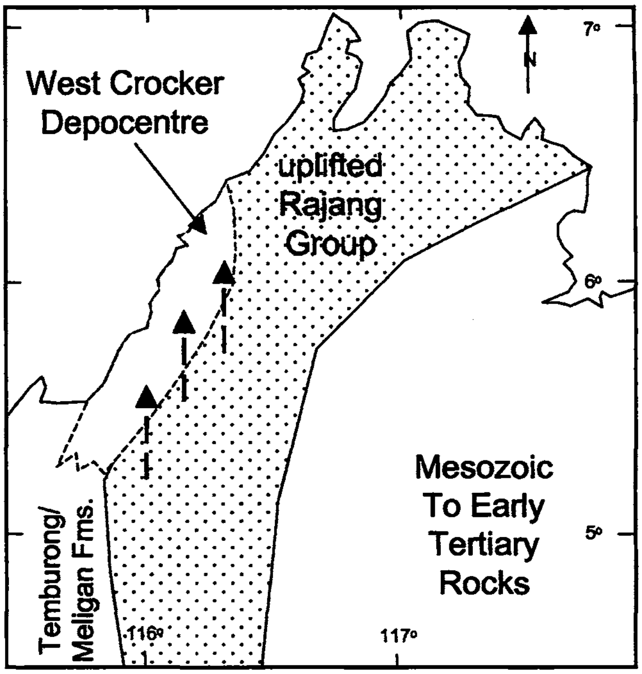

Figure 13. Schematic map of provenance area and transport paths (dashed arrows) during deposition of the West Crocker Formation.

Moreover, recent work on drainage patterns associated with the Himalayan Uplift indicates that the Mekong River could not have been the source of the West Crocker sediment. Prior to the late Miocene, nearly all the drainage from the Tibetan Plateau apparently was through present-day Pakistan, India, Bangladesh and Myanmar (C. Morley, 2002 pers. comm.). The Mekong River originated somewhat later but flowed eastward into the Red River (Clark *et al.*, 2002) until is assumed its present course only 5 to 6 million years ago (Dorobek and Olson, 2001). Similarly, the Meligan Formation probably was not deposited by a river originating to the southwest. Tate (1974) interpreted the sandstones in the Meligan Formation as fluvio-deltaic but Koopman (1996) indicates progradation of the Meligan Delta from the east-southeast rather than from the southwest. Moreover, the Meligan Formation unconformably overlies the West Crocker Formation in Sabah (Liechti *et al.*, 1960); it is therefore unlikely that they are different, time-transgressive facies of the same progradational system despite a partial overlap in age (Wilson, 1964).

The tectonic setting, size and geometry of the West Crocker turbidites are much different than those of modern deep water submarine fan systems associated with major rivers like the Bengal, Amazon, Indus or Mississippi. These large, extensive fans most commonly form on passive continental margins where their geometry, architecture and facies distribution are largely controlled by autocyclic factors (Reading and Richards, 1994). In contrast to the thin sandstone beds and small lobes of the West Crocker Formation, fans associated with large rivers are 500–3,000 km long 500–1100 km wide and 500–3,000 m thick; they deposit sands that generally are finer and texturally more mature than the West Crocker sands in relatively thick lobes tens of kilometres wide (Reading and Richards, 1994).

It may be possible to reconcile the apparent difference between previous studies (e.g. Tongkul, 1994; Hutchison, 1996a) and the depositional setting for the West Crocker Formation presented here by re-evaluating the timing of its deposition relative to regional tectonic events and, possibly, the significance of some of those events. There is general agreement that the thick succession of Late Cretaceous and Palaeogene deep marine sediments that underlie the West Crocker Formation was sourced from the southwest whilst the overlying Neogene strata were derived from the east (Tongkul, 1994; Hutchison, 1996a); most authors accept that the change in source direction occurred during development of the Deep Regional Unconformity, thereby grouping the West Crocker Formation with the other pre-unconformity units.

However, the unconformable relationship between the West Crocker Formation and the underlying Rajang Group, with its accompanying change in metamorphic grade (Hutchison, 1996a), clearly defines the West Crocker as a distinct system. Also, recent work suggests that the Deep Regional Unconformity is diachronous in Sabah and that it is slightly older in central Sabah than to the west (R. Hall, 2002 pers. comm.). Coupled with the high rates of post-Cretaceous uplift that have been recorded from the Telupid area (Hutchison *et al.*, 2000), this provides a mechanism whereby sediment could be supplied to western Sabah from the east before the Deep Regional Unconformity developed in that area. Thus, the change in source area could have pre-dated the Deep Regional Unconformity, allowing Rajang Group sediments to be uplifted, eroded and re-deposited further west as the West Crocker Formation (Fig. 13). An easterly source is supported by the presence of clastic sedimentary rocks and high grade metamorphic rocks (from the Telupid area?) in the rock fragment component of the West Crocker Formation sandstones (Stauffer, 1968). If so, then the unconformity at the base of the West Crocker Formation, rather than the Deep Regional Unconformity, marks the regional change in sediment source direction. Also, the progressive east to west uplift associated with the Deep Regional Unconformity accounts for the upward increase in sandstone relative to shale within the West Crocker Formation.

Relevance as analogues

The present study suggests that the West Crocker Formation turbidites are poor analogues for the Neogene turbidites offshore northwest Borneo. The Neogene turbidites were deposited into discrete, peripheral basins beyond the shelf edge of a growth-faulted margin (Hutchison, 1996a; Back and Lambiase, 2001) where they form basin floor fan systems that are normal to the margin and up to 120 km long and 30 km wide (Salahuddin *et al.*, 1996; Marzuki Mohamad and Lobao, 1997; Grant, 2002). The fans are constructed from individual lobes that are three or more times as large as those interpreted from the West Crocker Formation and they have well-defined channel and levee systems (Salahuddin *et al.*, 1996; Marzuki Mohamad and Lobao, 1997; Grant, 2002). The relatively large fans, with larger lobes and well-developed channel and levee systems, result in a significantly different facies distribution, bed geometry and stratigraphic architecture when compared to the small, slope apron fans of the West Crocker Formation. Also, the sand bodies deposited by the elongate Neogene fans have a margin-normal orientation, in contrast to the margin-parallel orientation of the West Crocker sandstones.

Additionally, the younger turbidites are almost certainly finer grained, texturally and compositionally more mature and better sorted than the sandstones of the West Crocker Formation because the Neogene sands were derived from uplifted West Crocker sediments (Hutchison, 1996b; Hutchison *et al.*, 2000) and then transported 150 km or more offshore during an additional sedimentary cycle. Most sands on the Neogene fans were deposited in response to eustatic sea level falls (Marzuki Mohamad and Lobao, 1997), suggesting that this last transport cycle involved shallow marine reworking on a delta as well as fluvial transport. Also, the sands often reached their deep water destination only after first filling and then spilling over one or more proximal basins on the slope (Marzuki and Lobao, 1997). It is highly unlikely that the grain size, texture and sorting of the West Crocker Formation sediments could remain unaffected by transport along the complex pathway that brought them to the deep sea. As the West Crocker Formation is significantly different from the Neogene turbidites with respect to sand body orientation, facies distributions, bed geometries, stratigraphic architecture, textural maturity and sorting, it is clear that they are not suitable analogues for the offshore sands.

CONCLUSIONS

The sedimentology of the West Crocker Formation leads to the following conclusions:

1. The massive sandstone beds generally comprise partial Bouma sequences, indicating rapid deposition by high-density turbidity currents and their immature composition and texture and poor sorting necessitates a short transport distance.
2. Amalgamated sandstones were deposited during episodic events as small, prograding lobes on a slope apron. The lobes coalesced at the toe of the slope to produce linear sand bodies.
3. All aspects of the sedimentology indicate that oblique, short distance transport of uplifted Rajang Group sediment into a marginal basin is the most likely scenario for the deposition of the West Crocker strata.
4. The West Crocker Formation has a significantly different tectonic setting, sand body orientation, facies distribution, stratigraphic architecture, texture and sorting than the Neogene turbidites offshore and is therefore a poor analogue for the younger sands.

ACKNOWLEDGEMENTS

The authors wish to thank Mike Simmons for assisting with the trace fossil identifications and George Pemberton for valuable discussion about their significance, Mike Bidgood for the microfossil analysis. We thank our colleagues Abdul Razak Damit, John Warren, Angus Ferguson and Chris Morley for many fruitful discussions and Charles Hutchison and Robert Tate for their constructive comments on an earlier version of the manuscript. Amelia William wishes to thank Brunei Shell Petroleum, Universiti Brunei Darussalam and Shell International for financial support and Mohd. Khalid Jamiran thanks ExxonMobil Malaysia for sponsoring his research.

REFERENCES

BACK, S. AND LAMBIASE, J.J., 2001. Deep-water reservoirs of Northwest Borneo: evaluating potential outcrop analogs. *Deep-water Sedimentation of South East Asia.* FOSI (Indon. Sediment. Forum), 2nd Regional Seminar, 94–95.

BENTON, M.D. AND HARPER, D., 1997. *Basic Paleontology.* Longman, 342p.

CANT, D.J. AND STOCKMAL, G.S, 1993. Some controls on sedimentary sequences in foreland basins: examples from the Alberta Basin. *Intl. Assoc. Sediment. Spec. Publ. 20*, 49–65.

CAROZZI, A.V., 1993. *Sedimentary Petrography.* Prentice Hall, 263p.

CLARK, M.K., ROYDEN, L. AND BURCHFIEL, B.C., 2002. Surface uplift, tectonics and erosion of eastern Tibet as inferred from major river incision and large-scale drainage patterns. *Chapman Conference on Continent-Ocean Interactions within East Asian Marginal Seas Abstracts.*

COLLENETTE, P., 1958. The geology and mineral resources of the Jesselton-Kinabalu area, North Borneo. *Br. Borneo Geol. Surv. Mem. 6.*

CREVELLO, P.D., 2001. Turbidite and deep water depositional systems of Borneo: reservoir models of basin floor and slope reservoir fan systems. *Deep-water Sedimentation of South East Asia.* FOSI (Indon. Sediment. Forum), 2nd Regional Seminar, 86–87.

CREVELLO, P.D., 2002. The great Crocker submarine fan: a world class foredeep turbidite system. *28th Indon. Petrol. Assoc. Proc. 1*, 377–407.

CRIMES, T.P., GOLDRING, R., HOMEWOOD, P., VAN STUIJVENBERG, J. AND WINKLER, W., 1981. Trace fossil assemblages of deep-sea fan deposits, Gurnigel and Schlieren flysch (Cretaceous-Eocene, Switzerland). *Ecol. Geol. Helvet. 74*, 953–995.

DICKINSON, W.R. AND SUCZEK, C.A., 1979. Plate setting and sandstone composition. *Amer. Assoc. Petrol. Geol. Bull., 63*, 2164–2182.

DOROBEK, S.L. AND OLSON, C.C., 2001. Timing of major uplift in the eastern Tibetan Plateau as recorded by Neogene deposits of the paleo-Mekong Delta, offshore Vietnam. *Amer. Assoc. Petrol. Geol. Annual Mtg. Abstracts with Program*, A52.

FREY, R.W. AND PEMBERTON, S.G., 1984. Trace fossil facies models, *in* WALKER, R.G. (Ed.), *Facies Models*, 2nd Edition, Geol. Assoc. Canada, 189–207.

GRANT, C., 2002. The pink fan: a classic deep marine canyon-fill complex, Block G, NW Sabah. *Petroleum Geology Conference and Exhibition Abstracts, Bull. Geol. Soc. Malaysia, 78.*

HARWOOD, G., 1988. Microscopic techniques: II. Principles of sedimentary petrography. *In:* Tucker, M. (Ed.), *Techniques in Sedimentology*. Blackwell Scientific Publications, 108–173.

HUTCHISON, C.S., 1992. The Southeast Sulu Sea, a Neogene marginal basin with outcropping extensions in Sabah. *Bull. Geol. Soc. Malaysia, 32*, 89–108.

HUTCHISON, C.S., 1996a. *Geological evolution of South East Asia.* Geol. Soc. Malaysia, 350p.

HUTCHISON, C.S., 1996b. *South East Asian oil, gas, coal and mineral deposits.* Oxford University Press, 265p.

HUTCHISON, C.S., BERGMAN, S.C., SWAUGER D.A. AND GRAVES, J.E., 2000. A Miocene collisional belt in North Borneo: Uplift mechanism and isostatic adjustment quantified by thermochronology. *Jour. Geol. Soc. London, 157*, 783–793.

KERN, J.P. AND WARME, J.E., 1974. Trace fossils and bathymetry of the Upper Cretaceous Point Loma Formation, San Diego, California. *Geol. Soc. Amer. Bull., 85*, 893–900.

KOOPMAN, A., 1996. Regional geological setting. *In:* Sandal, S.T. (Ed.), *The Geology and Hydrocarbon Resources of Negara Brunei Darussalam.* Bandar Seri Begawan, Syabas, 49–63.

KUMAR, N. AND SLATT, R.M., 1984. Submarine-fan and slope facies of Tonkawa (Missourian-Virgilian) sandstone in deep Anadarko Basin. *Amer. Assoc. Petrol. Geol. Bull., 68*, 1839–1856.

LIECHTI, P., ROE, F.N., HAILE, N.S. AND KIRK, H.J.C., 1960. The geology of Sarawak, Brunei and the western part of North Borneo. *Br. Borneo Geol. Surv. Bull., 3*, 360p.

LEVELL, B.K., 1987. The nature and significance of regional unconformities in the hydrocarbon-bearing Neogene sequences offshore West Sabah. *Bull. Geol. Soc. Malaysia, 21*, 55–90.

LOWE, D.R., 1982. Sediment gravity flows II. Depositional models with special reference to the deposits of high-density turbidity currents. *Jour. Sed. Pet. 52*, 279–297.

MACDONALD, D.I.M., 1986. Proximal to distal sedimentological variation in a linear turbidite trough: implications for the fan model. *Sediment. 33*, 243–259.

MACDONALD, D.I.M., 1993. Controls on sedimentation at convergent plate margins. *Intl. Assoc. Sediment. Spec. Publ. 20*, 225–257.

MARZUKI MOHAMAD AND LABAO, J.J., 1997. The Lingan Fan: Late Miocene/Early Pliocene turbidite fan complex, NW Sabah. *In:* Howes, J.V.C. and Noble, R.A. (Eds.), *Proceedings of an International Conference on petroleum systems of SE Asia and Australasia.* Indon. Petrol. Assoc., 787–798.

MOHD. KHALID JAMIRAN, 1999. *Sedimentology and sequence stratigraphy of Bukit Melinsung, Papar, Sabah.* Unpubl. M.Sc. thesis, Universiti Brunei Darussalam, 50p.

NORMARK, W.R., 1978. Fan valleys, channels, and depositional lobes on modern submarine fans; characters for recognition of sandy turbidite environments. *Amer. Assoc. Petrol. Geol. Bull. 62*, 912–931.

PEMBERTON, S.G., MACEACHERN, J.A. AND FREY, R.W., 1992. Trace fossil facies models: environmental and allostratigraphic significance. *In:* Walker, R.G. and James, N.P. (Eds.), *Facies models: Response to sea level change.* Geotext 1, Geol. Assoc. Canada, 47–72.

PETTIJOHN, F.J., POTTER, P.E. AND SIEVER, R., 1987. *Sand and Sandstone.* 2nd ed, Springer-Verlag, New York, 571p.

READING, H.G. AND RICHARDS, M., 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. *Amer. Assoc. Petrol. Geol. Bull., 78*, 792–822.

RICCI LUCCHI AND VALMORI, E., 1980. Basin-wide turbidites in a Miocene, over-supplied deep-sea plain: a geometrical analysis. *Sediment. 27*, 241–270.

SALAHUDDIN, B., KARIMI, S., LOBAO, J.J. AND WANIER, M.M., 1996. Seismic identification of depositional processes in a turbidite fan environment, Deepwater Block SB-G, NW Sabah. *Bull. Geol. Soc. Malaysia, 41*, 13–29.

STAUFFER, P.H., 1968. Studies in the Crocker Formation, Sabah. *Malaysian Geol. Surv. Bull. 8*, 1–13.

STOW, D.A.V. AND JOHANSSON, M, 2000. Deep-water massive sands: Nature, origin and hydrocarbon implications. *Mar. Petrol. Geol. 17*, 145–174.

STOW, D.A.V., READING, H.G AND COLLINSON, J.D., 1996. Deep seas, *In:* Reading, H.G. (Ed.), *Sedimentary environments and facies.* Blackwell Scientific Publications, 395–453.

TAN, D.N.K. AND LAMY, J.M., 1990. Tectonic evolution of the NW Sabah continental margin since the Late Eocene. *Bull. Geol. Soc. Malaysia, 27*, 241–260.

TAJUL ANUAR JAMALUDDIN, 1989. Struktur sedimen dalam Formasi Crocker di kawasan Tamparuli, Sabah. *Bull. Geol. Soc. Malaysia, 24*, 135–157.

TATE, R.B., 1974. Palaeo-environmental studies in Brunei. *Brunei Mus. Jour. 3*, 285–305.

TONGKUL, F., 1987. The sedimentological and structure of the West Crocker Formation in the Kota Kinabalu area, Sabah. *In: GEOSEA IV Proceedings*, Jakarta 1987, Indon. Assoc. Geol., 135–156.

TONGKUL, F., 1990. Structural style and tectonics of Western and Northern Sabah. *Bull. Geol. Soc. Malaysia, 27*, 227–239.

TONGKUL, F., 1994. The Palaeogene basin of Sabah, East Malaysia. *Bull. Geol. Soc. Malaysia, 37*, 301–308.

WALKER, R.G., 1992. Turbidites and submarine fans. *In:* Walker, R.G. and James, N.P. (Eds.), *Facies models: Response to sea level change.* Geotext 1, Geol. Assoc. Canada, 239–263.

WILLIAM, A.G., 2001. *Sedimentology, stratigraphic architecture and reservoir characteristics of the West Crocker Formation turbidites.* Unpubl. M.Sc. Thesis, Universiti Brunei Darussalam, 69p.

WILSON, R.A.M., 1964. The geology and mineral resources of the Labuan and Padas Valley area, Sabah, Malaysia. *Borneo Reg. Malaysia Geol. Survey Mem. 17*, 150p.

Manuscript received 23 January 2003
Revised manuscript received 28 July 2003