Provenance and geochronology of Cenozoic sandstones of northern Borneo

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Abstract

The Crocker Fan of Sabah was deposited during subduction of the Proto-South China Sea between the Eocene and Early Miocene. Collision of South China microcontinental blocks with Borneo in the Early Miocene terminated deep water sedimentation and resulted in the major regional Top Crocker Unconformity (TCU). Sedimentation of fluvio-deltaic and shallow marine character resumed in the late Early Miocene. The Crocker Fan sandstones were derived from nearby sources in Borneo and nearby SE Asia, rather than distant Asian and Himalayan sources. The Crocker Fan sandstones have a mature composition, but their textures and heavy mineralogy indicate they are first-cycle sandstones, mostly derived from nearby granitic source rocks, with some input of metamorphic, sedimentary and ophiolitic material. The discrepancy between compositional maturity and textural immaturity is attributed to the effects of tropical weathering. U–Pb ages of detrital zircons are predominantly Mesozoic. In the Eocene sandstones Cretaceous zircons dominate and suggest derivation from granites of the Schwaner Mountains of southern Borneo. In Oligocene sandstones Permian–Triassic and Palaeoproterozoic zircons become more important, and are interpreted to be derived from Permian–Triassic granites and Proterozoic basement of the Malay Tin Belt. Miocene fluvio-deltaic and shallow marine sandstones above the TCU were mostly recycled from the deformed Crocker Fan in the rising central mountain range of Borneo. The provenance of the Tajau Sandstone Member of the Lower Miocene Kudat Formation in north Sabah is strikingly different from other Miocene and older sandstones. Sediment was derived mainly from granitic and high-grade metamorphic source rocks. No such rocks existed in Borneo during the Early Miocene, but potential sources are present on Palawan, to the north of Borneo. They represent continental crust from South China and subduction-related metamorphic rocks which formed an elevated region in the Early Miocene which briefly supplied sediment to north Sabah.

1. Introduction

The Eocene–Lower Miocene Crocker Fan of northern Borneo (Fig. 1) represents one of the largest Paleogene sedimentary deposits of SE Asia. Despite preservation of several kilometres of siliciclastic turbidite sandstones and shales, their provenance is largely unknown. Sedimentation of Crocker Fan in the Eocene began at about the same time as collision of India and Asia. Previous studies of SE Asia have suggested material may have been derived from distant sources which could have included the eastern Himalayas (Hamilton, 1979; Hall, 1996; Hutchison, 1996; Métivier et al., 1999), whereas other studies have suggested that nearby source areas, possibly Borneo itself, may have been important (Hutchison et al., 2000; William et al., 2003; Hall and Morley, 2004; van Hattum et al., 2006). The Early Miocene was a period of collision of micro-continental fragments with the western edge of Borneo, and cessation of deep marine sedimentation. Shortly after, and throughout the Neogene, vast amounts of siliciclastic sediments, estimated to be up to 12 km in thickness, were deposited in marginal basins on and around Borneo (Hamilton, 1979; Hall and Nichols, 2002). These sedimentary basins host important hydrocarbon occurrences. The provenance of these sediments is also poorly understood.

Although there has been work on the sedimentology of the Crocker Fan sediments, these have been concerned mainly with depositional environment, and there have been few studies of composition and textures. The provenance characteristics of the northern Borneo sandstones are discussed here based on analysis of detrital modes, heavy minerals, as well as determination of detrital zircon U–Pb ages. Neogene formations including the Meligan and Setup Shale Formations of SW Sabah and the Kudat Formation (Fig. 2) of northern Sabah were also studied. Although
these formations were deposited at the same time (Early Miocene) in a similar depositional environment and climate, their sandstone characteristics are very different, and reflect important differences in provenance.

The identification of source areas for the Crocker Fan and Neogene sandstones helps to constrain sediment availability and pathways, and provides new insights in the tectonic setting of northern Borneo between the Eocene and Miocene. A unique feature of Borneo is that it experienced a humid tropical climate throughout the Cenozoic. Tropical weathering during source erosion and sediment transport was found to have a more profound influence on the characteristics of sandstones than is often assumed. This study has identified some of the limitations of provenance studies on sandstones that have experienced tropical weathering.

2. Geological background

Northern Borneo (Fig. 1) lies in an area of complex Cenozoic convergence at the Eurasian margin influenced by relative motions of the Indian–Australian, Pacific and Philippine Sea plates (Hamilton, 1979; Hutchison, 1989; Hall, 1996, 2002, 2012). Sundaland was an extensive continent during the Cenozoic and was largely emergent land during eustatic lowstands and glacial intervals. Despite the present flat surface and shallow seas covering the Sunda Shelf it has been a tectonically active area, and includes many deep sedimentary basins containing large volumes of clastic sediment (Hall and Morley, 2004).

The Indochina Block forms much of Indochina and extends from the continental shelf of Vietnam westwards across Cambodia to the western uplifted margin of the Khorat Basin of Thailand (Hutchison, 1989). Granites and granodiorites occur throughout the Indochina block (Metcalfe, 1996), and span a wide age range. Palaeozoic granites in NE Indochina have ages which are predominantly Silurian, but other batholiths are younger, at 250–190 Ma. In the southern part of the Indochina block there are Jurassic and Cretaceous plutons (Hutchison, 1989).

Lower Palaeozoic sediments are generally absent from Indochina. The Indochina Block was emergent during the Devonian and Carboniferous, and locally continental sediments were deposited. Carboniferous–Permian limestones were deposited to the north and west of the Kontum Massif, and Permian shallow marine clastic sediments were deposited at the peripheries of the Indochina landmass. Mesozoic sediments are widespread in Indochina, often within fault-bounded grabens, where they include sandstones, mudstones and volcaniclastics. Cenozoic sediments are typically continental and coal-bearing, and are developed in local depressions. Widely distributed Cenozoic basalts indicate episodes of rifting (Hutchison, 1989).

The eastern Himalayas contain continental blocks that were once part of Gondwana, prior to Carboniferous–Permian separa-
These terranes are characterised by platform Palaeozoic successions, in places covering Precambrian basement, which is usually not exposed (Hutchison, 1989). The eastern Himalayas, like some areas in Indochina, have a high concentration of rift-, subduction- and collision-related granite batholiths (Mitchell, 1979). The major magmatic arc of the Himalayas is the Gandise or Transhimalayan batholith system. It contains a variety of granites with ages from Cretaceous to Eocene (Maluski et al., 1983).

The India–Asia collision is widely considered to have initiated in the Eocene although the exact timing remains controversial (e.g. Tapponnier et al., 1986; Besse and Courtillot, 1991; Rowley, 1996; Aitchison et al., 2007; Najman et al., 2010; van Hinsbergen et al., 2011; Ali and Aitchison, 2012; White and Lister, 2012) and large volumes of sediment must have been transported from the collision zone to the south or east. It has been suggested that the large SE Asian rivers draining from eastern Tibet to the Indochina coast had different routes prior to the onset of the India–Eurasia collision, and that before the late Miocene drainage in Asia was significantly different from the present day (Clark et al., 2004). Prior to the uplift of the Tibetan plateau (Clark et al., 2005) the Mekong and Salween may have been less important rivers than they are today, and much of the sediment from eastern Tibet was shed into the Gulf of Tonkin by the palaeo-Red River.

Peninsular Malaysia includes rocks typical of a Palaeozoic continental margin, which are intruded by abundant tin-bearing Permian–Triassic and minor Cretaceous granites (Cobbing et al., 1992). The granites are part of what is known as the SE Asian Tin Belt (Garson et al., 1992; Beckinsale, 1979; Cobbing et al., 1992) which extends from Myanmar southwards to the Thai-Malaya Peninsula and further south into the Indonesian Tin Islands (Fig. 1). Liew and Page (1985) showed that the granites were derived from, and intrude, Proterozoic continental crust. Thermochronological studies show exhumation of Tin Belt granites in the Cretaceous and Cenozoic (Krähenbuhl, 1991; Kwan et al., 1992; Cottam et al., in press).

Borneo is suggested to be the product of Mesozoic and Cenozoic accretion of ophiolitic, island arc and microcontinental fragments onto Sundaland (Hamilton, 1979; Hutchison, 1989; Metcalfe, 1996; Hall et al., 2008; Hall, 2012; Hall and Sevastjanova, 2012). Extensive granitoid plutons and associated volcanics form the Schwager Mountains in southern Borneo. They intrude metamorphic rocks of the Pinoh Group. The igneous rocks yield radiometric ages ranging throughout the Cretaceous (Williams et al., 1988). In western Sarawak smaller Cretaceous granitoids form relatively small, isolated intrusions in an arcuate belt from the Indonesian border in the west to the Nieuwenhuis Mountains in the east (Tate, 2001). A thick succession of Upper Cretaceous–Lower Miocene deep marine sediments of the Rajang Group and the Crocker Formation form much of the main mountain range of western, central and northern Borneo. There was southward subduction of the Proto-South China Sea beneath the north Borneo margin from the Eocene to the Early Miocene. The Crocker Fan sediments were deposited at an active subduction margin on the south side of the Proto-South China Sea. Subduction ceased in the Early Miocene when there was collision of extended continental crust (Palawan, Reed Bank and Dangerous Grounds blocks) and the NW Borneo margin (e.g. Hamilton, 1979; Holloway, 1982; Taylor and Hayes, 1983; Tan and Lamy, 1990; Hazebroek and Tan, 1993; Hall, 1996, 2002; Hutchison et al., 2000). This episode is referred to as the Sabah Orogeny (Hutchison, 1996). Deep marine sedimentation stopped, but sedimentation resumed in the Early Miocene in a fluvio-deltaic to shallow marine setting. During the Miocene the central mountains of Borneo became elevated and rapid removal of material by erosion in a humid tropical setting generated great volumes of sediment (Hall and Nichols, 2002).

Fig. 2. Onshore stratigraphy of NW Borneo and interpreted equivalent major unconformities offshore.
Sediment provenance studies from Borneo are few and have concentrated on the Neogene strata (Tanean et al., 1996). There are two main lines of thought regarding the provenance of the Paleogene Crocker Fan: (1) sediments were derived from distant source areas, probably exposed by the India–Eurasia collision, and were either transported over the Sunda Shelf by major rivers such as the proto-Mekong (Hutchison, 1989, 1996; Hall, 1996; Métivier et al., 1999) and/or from mainland SE Asia longitudinally along the Borneo deep water margins into a subduction complex (Hamilton, 1979) or alternatively (2) the characteristics of the sediment, and traps and obstructions on the Sunda Shelf, are interpreted to indicate that material was derived from nearby sources, possibly Borneo itself, exposed by local tectonics and quickly eroded in a tropical setting (Hall, 2002; Morley, 2002; William et al., 2003). These two scenarios do not necessarily contradict each other, and a combination of the two is possible.

3. Stratigraphy

The onshore stratigraphy of northern Borneo is shown in Fig. 2, based on published literature, new field studies (van Hattum, 2005), and interpretation of the provenance and geochronological results of this study. Cenozoic sedimentary deposits in northern Borneo can be divided into two parts: (1) Deep marine rocks of the Upper Cretaceous to Eocene Rajang Group (Sapulut Formation) and the Eocene to Lower Miocene Crocker Fan (Trusmadi, Crocker and Temburong Formations). The thickness of the Crocker Formation in Sabah may locally exceed 10 km (Collenette, 1958; Hutchison, 1996) and the main palaeocurrent direction is NNE (Stauffer, 1967) suggesting a source area in the SSW. (2) Fluvio-deltaic to shallow marine sedimentation resumed in the Early Miocene and continued until at least the end of the Miocene. The Top Crocker Unconformity (TCU) separates deep marine deposits from younger sedimentary rocks (van Hattum, 2005; Hall et al., 2008). Drainage patterns became similar to the present day from the late Early Miocene.

The age and stratigraphy of the Crocker Fan are still relatively poorly known. Dating of the Crocker Fan based on biostratigraphy is difficult due to the paucity of age-determining fossil assemblages (Liechti et al., 1960) and the internal stratigraphy is often not clear. All available biostratigraphic ages from western Sabah (Rutten, 1915, 1925; van der Vlerk, 1951; Stephens, 1956; Collenette, 1958, 1965; Liechti et al., 1960; Wilson, 1961; Wilson and Wong, 1964; Jasim, 1991; Jasim et al., 1995) were compiled and were used to produce a contoured age map of the Upper Cretaceous–Lower Miocene sedimentary rocks of western Sabah (Fig. 3). There is a distinct trend of westward younging within the Crocker Fan, away from land at the time.

The TCU has previously been correlated in different ways with unconformities offshore, typically in sequences deposited above...
the Crocker Fan. On land it marks the termination of deep marine sedimentation and a change from deep water sediments and melanges to fluvial and shallow marine sediments. Offshore, this unconformity was identified by earlier workers (e.g. Bol and van

Fig. 4. Onshore traces of the Middle Miocene Deep Regional Unconformity (DRU) and the Lower Miocene Top Crocker Unconformity (TCU) in Sabah interpreted from SRTM image and field mapping of the Meligan Formation by Wong (1962).
Hoorn, 1980; Levell, 1987; Hazebroek and Tan, 1993) as an unconformity below the Miocene hydrocarbon-producing strata of NW Borneo, but was left unnamed. Most studies of the offshore region have paid little attention to this important unconformity although younger unconformities are widely discussed, for example, the well-known Middle Miocene Deep Regional Unconformity (DRU) which has commonly been correlated (e.g. Levell, 1987) with Early or Middle Miocene collision, we believe incorrectly (Hall et al., 2008; Hall, in press). Younger regional unconformities, such as the Intermediate and Shallow Regional Unconformity (IRU and SRU) are best known offshore (Hazebroek and Tan, 1993). Although difficult to observe in the field, because of the difficulties of penetrating into the rainforest interior of Sabah and Sarawak in deep river valleys, both the TCU and DRU can be clearly separated on SRTM (Shuttle Radar Topography Mission) images (Fig. 4).

Neogene fluvio-deltaic to shallow marine sediments overlie the TCU. The Setap Shale Formation of SW Sabah (Fig. 2) is a monotonous marine succession of dark clay and shale with minor intercalations of thin-bedded sandstone and siltstone (Wilson and Wong, 1964). Towards the east the proportion of sand increases, and the Setap Shale Formation occasionally interfingers with the sandy Meligan Formation. Their age is Early Miocene. The lithology of the Setap Shale Formation resembles that of the older Temburong Formation of SW Sabah (Fig. 2), which is the upper part of the Crocker Fan. The Setap Shale and the Temburong Formations are often difficult to tell apart in the field. However, the Temburong Formation is deformed together with the Crocker Formation and has experienced low-grade metamorphism. The Setap Shale Formation is non-metamorphic and generally less deformed. In the Temburong Formation Bouma sequences can be observed indicating deep marine turbiditic deposition, but the Setap Shale Formation contains shallow-marine Skolithos burrows.

The Meligan Formation (Fig. 2) is a relatively uniform sandstone succession and resembles the Oligo-Miocene Nyalau Formation of Sarawak (Liechti et al., 1960). Lower Miocene pelagic foraminifera were found in dark grey shales within the Meligan Formation (Wilson and Wong, 1962). The arenaceous microfauna, significant changes of thickness and presence of large foresets, in combination with widespread carbonaceous matter, ripple marks and cross bedding, indicate a littoral environment and very shallow marine conditions. Towards the top of the formation, paralic conditions are indicated by brackish-water faunas and an increase in lignites. The base of the Meligan Formation is generally conformable with the partly older Setap Shale Formation, and locally the two formations interfinger. The maximum thickness is reported to reach 4500–5500 m, but these are composite figures and in any vertical column the thickness does not exceed 3000 m (Liechti et al., 1960).

The Lower Miocene Kudat Formation (Fig. 2) also overlies the TCU and is a thick succession of predominantly sandy paralic to shallow marine sediments covering almost the entire Kudat Peninsula and parts of the Bongaya Peninsula in northern Sabah (Fig. 5). The Kudat Formation is the only formation in Sabah which can be subdivided into members (Stephens, 1956). The lowest Tajau Sandstone Member consists of very proximal sandy debris flows that have occasionally been reworked as storm beds with hummocky cross stratification. The overlying Sikuati Member contains paralic sandstones with layers of lignite. The formation was originally dated as Eocene–Miocene (Stephens, 1956) but Clement and Keij (1958) later showed that the Eocene and Oligocene ages were based either on benthic microfauna that are not age-determining, or reworked
larger foraminifera. They used numerous larger pelagic foraminifera to determine an Early Miocene age. The Kudat Formation is a time-equivalent of the Meligan and Setap Shale Formations of SW Sabah but unfortunately the unrevised ages of Stephens (1956) are often quoted as depositional ages (e.g. Lim and Heng, 1985; Tongkul, 1995; Petronas, 1999), leading to confusion over the origin and age of the Kudat Formation.

4. Methods

Analysis of detrital constituents is routinely used to interpret the provenance and palaeotectonic setting of sandstones (e.g. Dickinson et al., 1983). Heavy mineral analysis is useful for making provenance interpretations, as long as the provenance signal is successfully distinguished from the effects of hydraulic sorting and chemical destruction. Heavy mineral fractions in sandstones can also be used to identify sediment pathways, sediment dispersal patterns, sedimentary environments and for correlation of barren strata (Mange and Maurer, 1992).

Provenance analysis requires the freshest possible samples but exposure in Sabah can be poor because a humid tropical climate and lush vegetation cause outcrops to be eliminated or completely overgrown within a matter of years. Fresh samples of Cenozoic sandstones were collected from river sections and coastal outcrops, and new outcrops were discovered at sites of road construction and urban development during fieldwork in 2001 and 2002.
The Gazzi-Dickinson method of point counting was used for light mineral modal analysis in order to reduce grain size influence (Tucker, 1988) and 300 grains were counted per sample. Grains larger than 30 μm were counted as mineral constituents, and smaller grains were counted as matrix. Heavy mineral fractions were separated by methods similar to the funnel separation method of Mange and Maurer (1992). The heavy mineral grains were counted in permanent grain mounts using the ribbon count method yielding number frequencies of minerals.

Zircons were separated from the heavy mineral fractions for varietal studies and SHRIMP (sensitive high-resolution ion microprobe) U–Pb dating was carried out at the SHRIMP II facility at Curtin University of Technology, Australia where we attempted to analyse sufficient grains characterise the principal age populations. SHRIMP experimental techniques are discussed in detail by Smith et al. (1998).

5. Mineralogy

5.1. Light mineral detrital modes

The sandstones of the Crocker Fan have a mature quartzose composition (Fig. 6), and the most abundant clasts are plutonic quartz. Metamorphic and volcanic quartz are much less common, and volcanic quartz occurs only in the oldest samples of the Crocker Fan. When feldspar is present, K-feldspar is the most abundant type. It is most likely that the Crocker Fan sandstones have a mostly acidic plutonic source. Of the lithic fragments, radiolarian chert is never abundant but always present, forming up to 5% of the modal volume. This suggests that rocks of the ophiolitic basement were available for erosion. Other recognizable lithic fragments include schistose fragments, rare acid volcanic fragments and granite fragments in the coarser sandstones, and polycrystalline quartzose grains that could have an igneous or metasedimentary origin. Carbonate clasts are rare. Other detrital constituents include opaque grains, chlorite, muscovite and biotite.

During the Early Miocene quartzose sandstones of the Lower Miocene Setap Shale and Meligan Formations were deposited in SW Sabah above the Top Crocker Unconformity (TCU). These sandstones are similar to the Upper Cretaceous–Lower Miocene Rajang and Crocker sandstones, but are more mature in composition and texture (sorting and clast rounding). Their most important component is monocrystalline plutonic quartz and they appear to be recycled from the Crocker and Rajang sandstones.

The compositions of some sandstones of the Lower Miocene Kudat Formation of northern Sabah are quite different. Sandstones of the Tajau Sandstone Member are compositionally and texturally immature, with a mixed magmatic arc character (Fig. 6). They contain abundant K-feldspar and lithic clasts that suggest derivation from a nearby acid (meta)plutonic source. No potential source rocks are found in Sabah and the nearest potential source rocks are further north on Palawan. Limited palaeocurrent data from the Kudat Formation suggest that a source area to the north is likely. More mature sandstones of the Sikuati Member of the Kudat Formation, like the Setap Shale and Meligan Formation sandstones, resemble recycled Crocker sandstones.

5.2. Textures

The textures of the Crocker sandstones are strikingly immature, resembling first-cycle sandstones. The shape of the grains is angular to subangular, and there are few clasts with signs of sedimentary recycling. The sandstones tend to be poorly sorted, have a muddy matrix and very low porosity, making them of little interest as hydrocarbon reservoir sands. This is in contrast to their quartzose, compositionally mature character, which suggests a more advanced degree of sedimentary recycling. The low-grade metamorphic quartzites of the Trusmadi Formation are dense and quartz-cemented.

The QFL and QmFLt plots (Dickinson et al., 1983; Dickinson and Suczek, 1979) suggest that most of the Crocker sandstones have a recycled orogeny source (Fig. 6) but an important limitation of these plots is that they mostly disregard climatic influence on sandstone composition; throughout the Neogene there has been a humid tropical climate on Borneo leading to high weathering and erosion rates (Hall and Nichols, 2002). The interpretation of standard modal plots can be misleading for tropical sandstones because light mineral compositions can be strongly altered by humid tropical weathering during erosion, transport and alluvial storage of sand (Suttner et al., 1981; Johnsson et al., 1988). This occurs by the preferential destruction of feldspar and unstable lithic fragments relative to chemically stable quartz, therefore altering or destroying the tectonic modal character. Tropical weathering can account for the discrepancy between textural and compositional data of the Crocker Fan sandstones. The textural immaturity will be further highlighted by varietal zircon studies.

The Lower Miocene sandstones have a higher degree of grain rounding than the Crocker sandstones, consistent with sedimentary recycling. The Miocene sandstones are better sorted and have higher porosities than those of the Crocker Fan.

5.3. Heavy minerals

The heavy minerals of all Crocker Fan sandstones are predominantly those that are chemically stable. A summary of the contents of detrital heavy minerals in the Crocker Fan sandstones is shown in Table 1. The heavy minerals are dominated by zircon and

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Average heavy mineral contents (%)</th>
<th>Trusmadi Fm Eocene</th>
<th>Crocker Fm Eocene–L. Miocene</th>
<th>Setap-Meligam Fm Lower Miocene</th>
<th>Kudat Fm (Tajau) Lower Miocene</th>
<th>Kudat Fm (other) Lower Miocene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zircon</td>
<td>27.2</td>
<td>36.9</td>
<td>46.9</td>
<td>24.4</td>
<td>42.8</td>
<td></td>
</tr>
<tr>
<td>Tourmaline</td>
<td>46.7</td>
<td>38.5</td>
<td>33.2</td>
<td>7.8</td>
<td>25.9</td>
<td></td>
</tr>
<tr>
<td>Rutile</td>
<td>6.7</td>
<td>6.0</td>
<td>7.0</td>
<td>2.3</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>Cr-Spinel</td>
<td>2.2</td>
<td>1.1</td>
<td>4.4</td>
<td>0.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Garnet</td>
<td>2.8</td>
<td>7.0</td>
<td>3.2</td>
<td>34.0</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Apatite</td>
<td>5.2</td>
<td>3.9</td>
<td>1.0</td>
<td>9.8</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>Pyroxene</td>
<td>0.7</td>
<td>0.8</td>
<td>0.6</td>
<td>7.6</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Amphibole</td>
<td>0.4</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Monazite</td>
<td>0.1</td>
<td>0.3</td>
<td>0.2</td>
<td>1.1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>8.0</td>
<td>5.2</td>
<td>3.5</td>
<td>12.9</td>
<td>4.6</td>
<td></td>
</tr>
</tbody>
</table>
tourmaline. Other common minerals are rutile, garnet, chromian spinel and apatite. There are also minor quantities of pyroxene, amphibole and monazite. Authigenic heavy minerals include brookite and anatase. It is striking that detrital zircon and tourmaline usually show few signs of abrasion.

Apatite, a common mineral in acid igneous rocks, is not always present, and many apatite grains that do occur are often pitted or partially dissolved, even in the freshest sandstone samples. Apatite is unstable under conditions of acidic weathering (Morton, 1984), especially humid tropical conditions, and apatite dissolution may have occurred at any stage of source erosion, transport and deposition. Some samples of the Trusmadi Formation that contain no apatite do contain relatively fresh pyroxene, suggesting that the ophiolitic material was less weathered than acid igneous material.

Chromian spinel is nearly always present, but never exceeds 4% of the total heavy mineral fraction. It shows very little abrasion, indicating that a local ophiolitic source must have been important. This was most likely the basement of northern Borneo, which consists mostly of Mesozoic ophiolites (Hutchison, 1978; Hall and Wilson, 2000). Less stable ferromagnesian minerals are absent although clinopyroxenes and amphiboles are sometimes preserved.

The abundance of garnet is very variable but is usually subordinate to zircon and tourmaline. The garnets rarely show signs of chemical destruction. The provenance of the garnet is not certain. Potential source rocks are the Pinoh Metamorphics of southern Borneo, intruded by the granites of the Schwaner Mountains (Pieters and Sanyoto, 1993), or the basement of the Tin Belt (Krähenbuhl, 1991).

The presence of detrital cassiterite, although rare, indicates that the Tin Belt probably supplied material to the Crocker Fan. Despite being chemically stable, cassiterite is a very brittle and dense mineral. It is hydraulically separated from lower density sediment at an early stage of transport (Hosking, 1971), and does not get re-entrained.

It is notable that volcanic material is absent in most of the Crocker Fan sandstones. The poorly dated Oligocene Labang Formation contains relatively large amounts of pyroxene and hornblende, which suggest a greater input from intermediate and basic source rocks than to other sediments of western Sabah. It contains some of the least mature sandstones of Sabah, with a possible magmatic arc provenance based on their modal compositions, and was probably deposited in a forearc position but closer to the arc than the Crocker Fan.

Despite the compositional maturity of the heavy mineral assemblages of the Crocker Fan sandstones, their grain shapes indicate a low textural maturity, with a high proportion of unabraded, probably first cycle, zircons. Tourmalines have a similar character. A small proportion of strongly coloured zircons, mostly purple varieties, are usually well rounded and probably have a polycyclic history. The dominance of unabraded zircon and tourmaline suggests a proximal acid plutonic source. There are no Paleogene or older granites in northern Borneo itself. The nearest potential source areas are the Cretaceous granites of the Schwaner Mountains (southern Borneo) and the mainly Permain–Triassic granites of the Malay-Thai Tin Belt.

The heavy mineral assemblages of the Lower Miocene Setap Shale and Meligan Formations are also compositionally very mature and dominated by zircon and tourmaline (Table 1). Other minerals include rutile, chrome spinel, garnet, apatite and pyroxene.

Fig. 7. Chrome spinel-zircon (CZi) vs garnet-zircon (GZi) index value diagram of western Sabah sandstones. CZi indicates the amount of ophiolitic material relative to acid igneous material, GZi indicates the amount of metamorphic material relative to acid igneous material. Throughout the Crocker Formation a small but steady input of ophiolitic material, but a rather variable input of metamorphic material.

5.4. Heavy mineral indices

Indices of mineral pairs with similar hydraulic and diagenetic behaviour may reflect provenance, provided that they are stable within the diagenetic and weathering context of the study, and that they have similar densities and grain sizes, which are the main controls on hydrodynamic behaviour. Morton and Hallsworth (1994) proposed a number of mineral indices that largely reflect provenance characteristics. Of these indices, the apatite-tourmaline index (ATi) is likely to be affected by tropical weathering during erosion, transport and sedimentation, and may therefore be unsuitable for provenance interpretations in this study. The index values of GZi (garnet-zircon) and CZi (chromian spinel-zircon) are the most useful for provenance interpretations of the western Sabah sandstones. The CZi index provides an indication of the amount of ophiolitic material relative to acid igneous material, and the GZi index gives an indication of the amount of metamorphic material relative to acid igneous material.
CZi values of the Crocker and Trusmadi Formations are typically 2–7 (Fig. 7), indicating a minor but consistent input of ophiolitic material. The CZi values vary from 0 to 61. The large variation in garnet contents in the Crocker Formation, suggests changing input from metamorphic sources. CZi and CZi indices are not correlated implying ophiolitic and metamorphic source rocks in different areas.

CZi values of the Setap Shale and Meligan Formations, which were interpreted above to be largely recycled from the Crocker Formation, are generally higher than those of the Crocker sandstones, suggesting that they had an additional supply from a ophiolitic source. The Setap Shale and Meligan Formations show relatively low CZi-values which can be accounted for simply by recycling of Crocker sandstones (Fig. 7).

CZi values of the Kudat Formation sandstones are variable but tend to be low, especially in the Tajau Sandstone Member, suggesting a limited input of ophiolitic material. However, CZi values of the Kudat Formation sandstones show a large variation with the highest values in the Tajau Sandstone Member (CZi = 73), confirming an important metamorphic source. In contrast, there is little garnet in the mature quartzose and younger Sikuati Member of the Kudat Formation, which is interpreted to have been recycled from the Crocker Fan.

5.5. Zircon varietal studies

Zircon morphology is widely used in provenance studies to determine the nature and genesis of the source rocks. Variolet studies are helpful in low-diversity, ultramature heavy mineral assemblages, where conventional species-level heavy mineral studies prove inconclusive because zircon is chemically ultrastable and is not affected by weathering or diagenesis. Zircons were studied for shape, colour and, if present, internal structure. SEM images of typical morphologies with proportions of morphological types in the Crocker, Meligan and Kudat Formations are shown in Supplementary Document 1.

The zircon varieties in different parts of the Crocker Fan are mostly similar. Sandstones contain a high proportion of euhedral and subhedral colourless zircons mixed with smaller amounts of rounded colourless and sometimes purple zircons. They probably all endured a comparable transport history. The high proportion of unabraded zircons makes it unlikely that they have travelled very far by fluvial transport, and it is likely they have been derived from relatively nearby source areas such as the Cretaceous granites of the Schwane Mountains and the Permian–Triassic granites of the Tin Belt rather than far away source areas such as the eastern Himalayas or Indochina.

The zircon varieties in the Neogene formations of western Sabah are also similar, except for the Kudat Formation. Although it seems likely from light and heavy mineral studies that the Meligan Formation has been recycled from the Crocker Formation, the zircons from the Meligan Formation are not significantly more rounded than those of the Crocker Formation, probably indicating a short transport path and/or rapid recycling.

The zircon varieties of the Tajau Sandstone Member of the Kudat Formation contain many more euhedral and subhedral zircons than other Lower Miocene sandstones, and very few subrounded and rounded zircons. This suggests a nearby acid plutonic or metamorphic source, rather than sedimentary recycling.

6. Example sections

Provenance characteristics of the Oligocene part of the Crocker Formation near the west coast of Sabah were studied at outcrop scale. Two outcrops had fresh continuous exposure of over 150 m of turbidite sandstones and mudstones, one at Lok Kawi Heights (17 km south of Kota Kinabalu) and one at Sepangar Bay (12 km NE of Kota Kinabalu). The sandstones all have a quartzose composition. The two outcrops are briefly described below and illustrated in Supplementary Document 1 with composite diagrams that show lithostratigraphy, palaeocurrent measurements, abundance of the most prominent heavy minerals (zircon, tourmaline, rutile, chromian spinel, apatite and garnet), provenance-sensitive heavy mineral indices, and zircon varieties.

Both sections are dominated by zircon and tourmaline, and contain relatively small amounts of rutile and chromian spinel. There are significant differences between the abundance of apatite and garnet in the two sections. The Sepangar Bay section is overall considerably richer in apatite than the Lok Kawi Heights section. Both sites were sampled below the modern-day weathering profile within months of excavation, so recent destruction of apatite is unlikely. The difference in apatite contents probably indicates different amounts of chemical weathering in the source areas of the two sections. In contrast, the difference in garnet contents is more likely to indicate differences in source rocks. The garnet contents in the Lok Kawi Heights section increase up section in sandstones of similar grain size, and this probably records an increasing influx of metamorphic detritus.

The sandstones of the Sepangar Bay section appear to be derived mostly from acid plutonic rocks, a smaller proportion of ophiolitic rocks, and a small and variable proportion of metamorphic rocks. The sandstones of the Lok Kawi Heights section have been derived primarily from acid igneous source rocks, but over time (the time span the sections represent is unclear) an increasing amount of metamorphic source rocks became available. Small amounts of ophiolitic material were available throughout.

The index values ATi (apatite-tourmaline), CZi (garnet-zircon), RuZi (rutile-zircon) and CZi (chrome spinel-zircon) show a large variation within the outcrops, especially CZi in the Lok Kawi section, suggesting a variable but increasing input of metamorphic detritus throughout the section. The ATi index may be influenced by weathering. Hurst and Morton (2001) point out that sediment homogenisation is more likely to occur on a shallow marine shelf, especially above the wave base, than in an alluvial basin, or in a deep marine basin. Deep-water sandstones with variable heavy mineral indices of pairs of minerals with similar hydraulic behaviour and chemical stability may have been derived directly from alluvial basins, bypassing any contemporaneous marine shelf, while deep-water sandstones with homogeneous heavy mineralogy are inferred to be fed by sediment that originally accumulated on shallow marine shelves where it was mixed. The variable heavy mineral indices of the deep-marine Oligocene Crocker Formation at Sepangar Bay and Lok Kawi suggest that the sediments of the Crocker Formation have been derived by shelf bypass directly from an alluvial basin. Before collisions between micro-continental blocks and western Borneo the shallow shelf area of northern Borneo may have been much more limited than at present.

The zircon varieties in the Sepangar Bay section show very little variation throughout the section. The zircon varieties suggest that the sediment has been derived from a mixed plutonic and sedimentary origin, indicated by the presence of both fresh euhedral and subhedral zircons as well as a relatively high proportion of subrounded and rounded zircons. The zircon varieties in the Lok Kawi Heights section are more varied than those of Sepangar Bay, and there are more euhedral and subhedral zircons. The highest proportions of unabraded zircons coincide with high proportions of garnet. It is possible that the peaks of garnet and unabraded zircons represent first-cycle provenance pulses from the Pinoch Metamorphics and Schwane Granites of southern Borneo.
7. Geochronology

Detrital zircon U–Pb ages aid identification of the source area and its age, and were determined for zircons from six Cenozoic sandstones. Samples were selected to represent a large area of western Sabah, and to represent the Eocene to Miocene age of strata. An important selection criterion was a reasonable constraint on the sample depositional age. Detrital zircon ages were obtained primarily from the Crocker Fan (Crocker and Trusmadi Formations), but ages were also obtained from one older Rajang Group sample from the Sapulut Formation and strata overlying the TCU from the Kudat Formation (Fig. 8). In addition, two samples from the Sukadana Granite of the Schwaner Mountains, considered to be a possible source area, were dated to compare their zircon ages with detrital zircons.

Zircon U–Pb ages can be obtained from both \( \frac{^{206}Pb}{^{238}U} \) and \( \frac{^{207}Pb}{^{206}Pb} \) ratios. The amount of \( ^{207}Pb \) in Phanerozoic zircons can be very small, and \( \frac{^{206}Pb}{^{238}U} \) ages are preferred to the \( \frac{^{207}Pb}{^{206}Pb} \) ages. In contrast, \( \frac{^{207}Pb}{^{206}Pb} \) ages are considered to be more accurate for Precambrian zircons (Pickard et al., 2000). Cathodoluminescence images were used to select grains. Few display internal zoning or later overgrowth. There were no differences between core and rim ages, and no indication of metamorphic resetting. Zircons appear to be igneous, and their ages can be compared to potential igneous source rocks.

**Fig. 8.** Probability plots of detrital zircon SHRIMP U–Pb ages from 6 Cenozoic western Sabah sandstone samples, with pie diagrams showing simplified source compositions of the Paleogene sandstones, based on heavy mineral characteristics and a principal component analysis of zircon age abundances. Provenance categories are Schwaner: Cretaceous granites of Schwaner Mountains; Tin Belt: Permian–Triassic granites of Malay-Thai Tin Belt; YB: Young basement; OB: Old Basement; Ophiolites: ophiolitic basement.
The Crocker Fan detrital zircon ages range from Eocene (50 Ma) to Archaean (2532 Ma). The different Paleogene samples display similar age populations (Fig. 9). The most prominent is Cretaceous (Group A: ca. 77–130 Ma), the second is Permian–Triassic (Group B: ca. 213–268 Ma) and there is a conspicuous Palaeoproterozoic (Group C: ca. 1750–1900 Ma). Smaller age groups include Jurassic and Silurian-Ordovician zircons. The Miocene Kudat sample was dominated by Jurassic-Cretaceous zircons, with a significant number of Palaeoproterozoic zircons. The individual samples are briefly described below and a complete listing of age data is in Supplementary Document 2, Tables 1–6.

7.1. MVH02-264, Sapulut Formation, Early Eocene

This sample is from the Eocene part of the Sapulut Formation, the youngest part of the Rajang Group. 55 U–Pb zircon ages were obtained and 45 zircons yielded concordant ages (Fig. 8). The most important age group is Cretaceous. Other Phanerozoic populations are Carboniferous, Devonian and Silurian. Jurassic and Silurian-Ordovician zircons are absent. There are few Precambrian zircons, but the most important age group is Palaeoproterozoic, with a significant number of Palaeoproterozoic zircons. The individual samples are briefly described below and a complete listing of age data is in Supplementary Document 2, Tables 1–6.

7.2. MVH02-142, Trusmadi Formation, Middle Eocene

This sample is from the Trusmadi Formation, the oldest part of the Crocker Fan. 66 ages were obtained from this sample, of which 48 were concordant (Fig. 8). The majority of the zircons yielding discordant ages are Proterozoic. The most prominent age group is Cretaceous. Other significant age groups are Triassic, Carboniferous–Early Permian and Ordovician. The most important group of concordant Precambrian zircons is Palaeoproterozoic. In this sample an Archaean zircon was encountered (2531.6 ± 11.2 Ma), which is the oldest radiometric age reported from Borneo. The oldest zircons tend to be coloured and/or rounded, and the younger Mesozoic zircons are mostly unabraded and colourless. The youngest age (49.9 ± 1.9 Ma) is very important in an area where biostratigraphical evidence is nearly absent and indicates the maximum depositional age to be Early Eocene.

7.3. MVH02-271, Crocker Formation, Late Eocene

This is the best-dated sample of the Crocker Formation based on Late Oligocene nannofossils (NP24-NP25) found nearby (E. Finch, 2013). The majority of the zircons yielded discordant ages are Proterozoic. The most prominent age group is Cretaceous. Other significant age groups are Triassic, Carboniferous–Early Permian and Ordovician. The most important group of concordant Precambrian zircons is Palaeoproterozoic. In this sample an Archaean zircon was encountered (2531.6 ± 11.2 Ma), which is the oldest radiometric age reported from Borneo. The oldest zircons tend to be coloured and/or rounded, and the younger Mesozoic zircons are mostly unabraded and colourless. The youngest age (49.9 ± 1.9 Ma) is very important in an area where biostratigraphical evidence is nearly absent and indicates the maximum depositional age to be Early Eocene.

7.4. MVH02-115, Crocker Formation, Oligocene

This sample was from one of the most northern outcrops of the Crocker Formation. Of the 72 ages from this sample, 59 are concordant (Fig. 8). The most important age group is Early Cretaceous, which account for 44% of the ages. There is also a significant number of Late Cretaceous zircons. Other age groups are Jurassic, Triassic and Palaeoproterozoic. Mesozoic zircons are mostly colourless and unabraded. Older Proterozoic zircons tend to be coloured and/or rounded.

7.5. MVH02-116, Crocker Formation, Late Oligocene

This sample is from the Trusmadi Formation, the oldest part of the Crocker Fan. 66 ages were obtained from this sample, of which 48 were concordant (Fig. 8). The majority of the zircons yielding discordant ages are Proterozoic. The most prominent age group is Cretaceous. Other significant age groups are Triassic, Carboniferous–Early Permian and Ordovician. The most important group of concordant Precambrian zircons is Palaeoproterozoic. In this sample an Archaean zircon was encountered (2531.6 ± 11.2 Ma), which is the oldest radiometric age reported from Borneo. The oldest zircons tend to be coloured and/or rounded, and the younger Mesozoic zircons are mostly unabraded and colourless. The youngest age (49.9 ± 1.9 Ma) is very important in an area where biostratigraphical evidence is nearly absent and indicates the maximum depositional age to be Early Eocene.
2002, pers. comm.) and represents the youngest part of the Crocker Fan. Of the 66 zircon ages 52 are concordant (Fig. 8). There is a relatively wide spread of ages compared to other samples, and there is also a high proportion of anhedral zircons. Cretaceous-Permian zircons form the main age group with a peak in the Late Permian. Other significant groups are Early Cretaceous, Carboniferous, Ordovician and Palaeoproterozoic.

7.6. MVH02-087, Kudat Formation, Tajau Sandstone Member, Early Miocene

The sample is a medium- to coarse-grained sandstone that contains 28% K-feldspar. The heavy mineral suite is relatively diverse, and is dominated by zircon, tourmaline, apatite and pyroxene, and contains minor amounts of rutile, garnet, monazite, kyanite, sillimanite, staurolite, chloritoid, sphene, serpentine, corundum and olivine. Of the 57 U–Pb zircon ages, 50 are concordant (Fig. 8). The majority of the zircons are Jurassic-Cretaceous. Major peaks are Early Cretaceous (ca. 121 Ma) and Early Jurassic (ca. 181 Ma). Jurassic zircons are relatively rare in other Sabah sandstones. A minor peak is Palaeoproterozoic (ca. 1867 Ma). The oldest zircon is dated at 2488 ± 16.3 Ma. The Mesozoic zircons are predominantly unabraded and colourless. Coloured and/or rounded zircons are mostly Precambrian, but occur throughout the age spectrum.

7.7. RT.C and RT.D, Sukadana Granite, Kalimantan, Cretaceous

Cretaceous granitoids and related volcanic rocks are widely distributed in the southern part of the Schwaner Mountains of Kalimantan. The main component of the Schwaner batholith in the Ketapang area is the Sukadana Granite which includes a range of rock types from monzonite to granite, with Cretaceous ages of 127–79 Ma based on K–Ar dating of hornblende and biotite and U–Pb dating of zircons (Haile et al., 1977; de Keyser and Rustandi, 1993). The results from the two samples analysed are summarised below and described with a complete listing of age data in Supplementary Document 3.

Samples RT.C and RT.D were collected about 16 km apart in the same medium- to coarse-grained monzogranite in the Ketapang area. 30 zircons were dated from sample RT.C. They are nearly all Late Cretaceous, with two age peaks at 87.0 ± 0.8 Ma and 83.8 ± 0.7 Ma, and a mean age of 84.7 ± 1.3 Ma. Most of the grains have a simple internal structure. There is one Jurassic grain (151.9 ± 1.5 Ma) which the SEM cathodoluminescence image suggests is a core; no other inherited ages were found. 13 zircons were dated from sample RT.D. They were all Late Cretaceous and slightly younger than those in sample RT.C with two age peaks at 84.0 ± 1.0 Ma and 79.7 ± 0.9 Ma, and a mean age of 81.7 ± 1.0 Ma, excluding one grain with a large error. SEM cathodoluminescence images of dated zircons from the sample show no older cores.

7.8. Age trends and provenance

There is a relationship between zircon ages, morphology and colour. Cretaceous colourless zircons are the least abraded, suggesting limited transport. Permian–Triassic zircons are more abraded than Cretaceous zircons, but colourless and unabraded zircons dominate, also suggesting a nearby source. The older, in particular Palaeoproterozoic, zircons are generally coloured and well-rounded, suggesting a long history of recycling.

In the Eocene sandstone samples unabraded Cretaceous zircons dominate (Fig. 8). Their ages are similar to those of Cretaceous granites of the Schwaner Mountains of southern Borneo (Fig. 1), which are the closest abundant granites. More distant Cretaceous granites are probably currently submerged in the Sunda Shelf (Pupilli, 1973) and are known from the Malay peninsula (Cobbing et al., 1992). Late Cretaceous zircons, which are more abundant than Early Cretaceous zircons in the oldest sandstones, are similar to zircon ages from the Schwaner Mountains Sukadana Granite. Early Cretaceous zircons become more abundant than Late Cretaceous zircons in the Upper Eocene–Oligocene sandstones, similar to the present-day distribution of Schwaner Mountains granites (Williams et al., 1988).

In the Oligocene sandstones Cretaceous zircons cease to dominate and Permian–Triassic ages become more common (Fig. 8). These zircons show slightly more rounding than Cretaceous zircons, probably reflecting a longer and/or higher energy transport path. Ages of Permian–Triassic zircons resemble those of voluminous granites in the Malay-Thai Tin Belt, suggesting the main source of the Crocker Fan sandstones shifted from the Schwaner Mountains to the Tin Belt during the Oligocene.

The proportion of usually well-rounded and coloured Palaeoproterozoic and Neoarchaean detrital zircons strongly correlates with the abundance of Permian–Triassic zircons, and they are interpreted to represent metasedimentary continental basement of the Permian–Triassic Tin Belt granites of the Malay Peninsula.

Ages of detrital zircons in the Crocker Fan do not match those of plutonic rocks in the eastern Himalayas or Indochina. Magmatic ages in the eastern Himalayas older than the Crocker Fan are 400–500 Ma, ca. 160 Ma, ca. 120 Ma and 40–70 Ma. The 400–500 Ma ages occur in zircon cores, and younger ages are thought to be related to Andean-style Gandise arc plutonism preceding India-Asia collision (e.g. Maluski et al., 1983; Ding et al., 2001; Booth et al., 2004). If Indochina had been an important source more abundant Precambrian and Palaeozoic zircons would be expected but it is possible that some of the Palaeozoic zircons were ultimately derived from Indochina.

Ages of detrital zircons from the Tajau Sandstone Member are mostly Jurassic and Cretaceous. Jurassic zircons are very uncommon in other Sabah sandstones. This supports the idea that the sandstones were derived from the Palawan block, which was originally part of South China, a region rich in Jurassic and Cretaceous granites. Provenance studies of Cretaceous–Eocene Palawan sandstone samples of similar composition to the Tajau Sandstone Member suggest that South China may have been the ultimate source (Suzuki et al., 2000). Although at present there are no exposures of Jurassic–Cretaceous granites on Palawan, they may well be submerged offshore of Palawan or in the area between Palawan and northern Borneo. Zircon cores from the Miocene Capeos granite in northern Palawan are Palaeoproterozoic, indicating melting of South China continental crust (Encarnación and Mukasa, 1997). The core ages are similar to the Palaeoproterozoic zircon ages in the Tajau Sandstone Member, supporting derivation from Palawan. There are no zircon ages younger than Cretaceous in the Tajau Sandstone Member. High-grade subduction-related metamorphic rocks of Palawan suggested above to have provided kyanite and garnet to the Kudat Formation sandstones are of Early Oligocene age, based on hornblende and muscovite Ar–Ar dating, and there are no zircon ages reported from the metamorphic rocks (Encarnación et al., 1995).

8. Principal component analysis

Hypotheses about sources of the zircons were tested with principal component analysis. The zircon ages of the Sapulut, Trusmadi and Crocker Formations were subdivided into age categories and a principal component analysis was performed. The sample from the Kudat Formation was excluded because of its potential Palawan source. A strong positive correlation between proportions of Permian–Triassic and Palaeoproterozoic zircons supports derivation of Palaeoproterozoic zircons from the Tin Belt. A strong negative correlation between the proportions of Cretaceous and
Permian–Triassic zircons supports the suggestion of two independent sources which were Cretaceous granites of the Schwanner Mountains and Permian–Triassic granites of the Tin Belt. The heavy mineral assemblages and correlations were used to construct a simple model of five provenance groups. The relative proportions as they appear in the individual samples are shown in Fig. 8.

1. Cretaceous zircons show a weak positive correlation with Cenozoic zircons, and they most likely represent Borneo sources. Cenozoic zircons were probably derived from nearby volcanic activity, and Cretaceous zircons from granites in the Schwanner Mountains.

2. Jurassic zircons show a strong positive correlation with Permian–Triassic zircons. The Permian–Triassic zircons represent the Tin Belt granites. Jurassic igneous rocks are not known from the Tin Belt, but it is possible that some acid volcanic activity continued into the Early Jurassic.

3. The proportions of Palaeozoic, Neoproterozoic and Mesoproterozoic zircons show strong positive correlations with each other. The source of this group is not clear. Although the metamorphic Pinoh Group of southern Borneo may have supplied some of these zircons, there is no strong correlation with Cretaceous zircons from the Schwanner Granites, which intrude the Pinoh Group.

4. The proportion of coloured and rounded Palaeoproterozoic and Archaean zircons strongly correlates with the proportion of Permian–Triassic zircons, and they probably represent metasedimentary continental basement rocks of the Tin Belt (Liew and Page, 1985).

5. Ophiolitic material is always present but its abundance can be estimated only from light and heavy mineral studies.

9. Discussion

Both the light and heavy mineral fractions of the Eocene–Lower Miocene deep marine Crocker Fan indicate the importance of first-cycle granitic source rocks. The light minerals are dominated by angular and poorly sorted igneous quartz and K-feldspar when feldspar is present. The heavy mineral fractions are dominated by unabraded zircon and tournamaline, suggesting limited sediment transport and a nearby source. The small but consistent presence of chert fragments and unabraded chromian spinel indicates a contribution from the ophiolitic basement of northern Borneo. The variable amounts of garnet indicates supply from metamorphic rocks, which fluctuated with time. Volcanism, indicated by volcanic quartz and zircons of ages similar to the depositional age of the sandstones, contributed small volumes of sediment in the Eocene. After the TCU sedimentation changed to shallow marine and fluvio-deltaic, and sediment recycling from the Crocker Fan became important.

There is a conspicuous discrepancy between the mature composition and the immature texture of the Crocker Fan sandstones. The textures and zircon ages strongly suggest that the sandstones were derived from nearby sources in Borneo and the Tin Belt. The mature composition can be explained by tropical weathering in a humid climate that prevailed in Borneo and nearby SE Asia throughout the Cenozoic (Morley, 1998). Thus, modal analysis of sandstone composition (Dickinson et al., 1983) may be of limited value for sandstones eroded and transported under humid tropical conditions, because of the rapid preferential destruction of feldspar and unstable lithic fragments (Suttner et al., 1981). More reliable provenance interpretations of tropical sandstones can be achieved by studies using combined petrographic (composition and texture), heavy mineral and zircon age analysis. The intensity of weathering in tropical climates can produce good quality hydrocarbon reservoir sandstones in a short time. Although the first-cycle sandstones of the Crocker Fan lack good reservoir properties due to the relatively large amounts of clay-sized material reducing porosity, the Miocene sandstones produced from recycling the Crocker Fan sandstones are highly quartzose sandstones with excellent reservoir properties.

It is suggested here that most material of the Crocker Fan was derived from Borneo and nearby areas of SE Asia, rather than distant sources in mainland Asia exposed as a result of the India–Eurasia collision (van Hattum et al., 2006). Fluvial transport from distal Indochina and eastern Himalayan sources would have produced greater rounding of material, including zircons, rather than the abundant unabraded grains that are observed. Furthermore, detrital zircon ages of igneous origin do not match with igneous ages from these distant source areas. In contrast, the contrast, the most prominent detrital age groups do match well with Cretaceous granites of the Schwanner Mountains of southern Borneo and Permian–Triassic granites and Precambrian basement of the Malay–Thai Tin Belt.

During deposition of the lower part of the Crocker Fan in the Eocene Cretaceous granites (Schwanner Mountains and adjacent Sundra Shelf) contributed the majority of sediment. AFT data show that granites of the Schwanner Mountains were exhumed in the Late Cretaceous (Sumartadipura, 1976), and could have produced large amounts of sediment in the Eocene. Cretaceous AFT ages were also reported from Crocker Formation sandstones (Hutchison et al., 2000; Hall and Nichols (2002) suggested that northern Borneo sediments were mostly derived from Borneo itself throughout the Neogene, and this study suggests that Borneo may have supplied large amounts of sediment since at least the Eocene. A depositional and provenance model of the Crocker Fan at the end of the Eocene based on the results of this study is shown in Fig. 10.

In the upper part of the Crocker Fan (Oligocene) the proportion of Permian–Triassic zircons increases, with ages corresponding to those of the Tin Belt granites, as well as Palaeoproterozoic coloured and rounded zircons, probably from the Tin Belt basement. Zircons of similar ages are relatively common in modern river sediments from the Malay peninsula (Sevastjanova et al., 2011, 2012). The Tin Belt is further away from northern Borneo than the Schwanner Mountains, which may account for the slightly higher degree of zircon rounding. AFT ages from the Tin Belt granites indicate a major phase of exhumation in the Oligocene (ca. 24–33 Ma; Krähenbühl, 1991; Kwan et al., 1992), and it is at this time that the Tin Belt granites probably became available for erosion and material was transported to the Crocker Fan.

The heterogeneous character of indices of provenance-specific heavy mineral pairs (Morton and Hallsworth, 1999; Hurst and Morton, 2001) at outcrop scale suggests sediment supply into the deep marine basin directly from an alluvial/fluvial system, by-passing any shallow marine shelf, which was probably much more limited in width before Early Miocene closure of the Proto-South China Sea. Large volumes of sediment derived from the Schwanner Mountains of southern Borneo were being deposited in the Proto-South China Sea. The main drainage divide in southern Borneo was probably located considerably further south than its present position in the central Borneo mountains, which consist mainly of Rajang Group and Crocker Fan deep marine sedimentary rocks. The history of emergence of this mountain range is poorly known, but followed Early Miocene collision of continental fragments with Borneo. Deep marine sedimentation of the Crocker Fan terminated in the Early Miocene, during the final closure of the Proto-South China Sea and collision of micro-continental fragments with Borneo.

Collision produced a major unconformity, the Top Crocker Unconformity, incising sediments of the Crocker Fan. Subsidence and sedimentation resumed in the Early Miocene, with a drainage pattern similar to the present day. Fluvio-deltaic to shallow marine
Siliciclastic sediments were deposited in western and northern Sabah in a similar depositional and climatic setting, but with different compositions reflecting different sources. The sandstones of the Lower Miocene Meligan and Setap Shale of SW Sabah are primarily a product of sedimentary recycling. The characteristics of the quartzose sandstones are similar to those of the Upper Cretaceous–Eocene Rajang Group and the Eocene–Lower Miocene Crocker Fan, but are compositionally and texturally more mature. The Crocker Fan started to supply large amounts of sediment to the Lower Miocene basins. Local ophiolitic sources also continued to supply sediment. The local generation of large amounts of sediment is consistent with the ideas of Hall and Nichols (2002) that since the start of the Neogene Borneo itself supplied most of the material deposited in the basins on and around Borneo. The sandstones of the Meligan and Setap Shale Formation are potential excellent hydrocarbon reservoirs, and tropical weathering probably had a very important role in producing these highly quartzose sandstones.

In contrast, sandstones of the Tajau Member of the Kudat Formation are unlike any of the other Lower Miocene western Sabah sandstones. They are proximal debris flows and storm beds, and they are compositionally and texturally immature. The main sources were granitic and high-grade metamorphic rocks from a nearby area with smaller amounts of ophiolitic material. There were no fresh plutonic or metamorphic rocks exposed in northern Borneo during the Early Miocene. Potential metamorphic source rocks have been described by Encarnación et al. (1995) on Palawan, north of Kudat, where there are high-pressure subduction-related and high-temperature sub-ophiolitic metamorphic rocks. These rocks contain garnet, kyanite, apatite, epidote, and abundant K-feldspar, which fits well with the detrital mineral assemblages in the Tajau Sandstone Member. The metamorphic rocks on Palawan experienced peak metamorphic conditions in the earliest Oligocene in a subduction setting, followed by rapid cooling and exhumation in the Early Miocene related to collision of the Reed Bank and North Palawan continental fragments with northern Borneo and Palawan. In the Early Miocene Palawan started to supply sediment to northern Borneo in the Kudat area after the deep marine basin between the areas was eliminated. The mature character of the Sikuati Member of the Kudat Formation suggests that the Palawan source area was short-lived and recycling of the Crocker Fan became more important from later in the Early Miocene onwards.

10. Conclusions

The voluminous Eocene–Lower Miocene deep marine Crocker Fan sediments were mostly derived from nearby acid plutonic sources on Borneo, the Malay Peninsula and the Sunda Shelf, by a drainage system different from today. Distant source areas in mainland Asia did not play a significant role. During the Eocene mostly Cretaceous material was deposited, probably from the Schwaner Mountains and adjacent areas of the Sunda Shelf, and during the Oligocene an increasing amount of material was derived from the Permian–Triassic Tin Belt granites and its Proterozoic metasedimentary basement. Microcontinent collisions with Borneo in the Early Miocene terminated deep marine sedimentation, and changed the drainage pattern of Borneo and nearby SE Asia.

After closure of the Proto-South China Sea and cessation of deep marine deposition of the Crocker Fan fluvio-deltaic to shallow marine deposition occurred in basins on and around Borneo. Sandstones of the Lower Miocene Setup Shale and Meligan Formations of SW Sabah were mostly recycled from sediments of the Rajang Group and Crocker Fans on Borneo, now exposed in the main mountain range of Borneo. A smaller amount of material was supplied by local ophiolitic sources.
The lowest Tajau Sandstone Member of the Lower Miocene Ku- 
dat Formation was mostly derived from fresh granitic and high-
grade metamorphic rocks, from a nearby Palawan source. Palawan 
includes rocks that rifted from South China and collided in the 
Early Miocene; high-grade metamorphic rocks subducted in the 
Oligocene became available for erosion at this time. This Palawan 
source was short-lived and sandstones of the overlying Sikuatu 
Member of the Ku dat Formation are more similar to the Meligan 
Formation and they were probably recycled from the Crocker 
Formation.

Tropical weathering can strongly influence the composition of 
sandstones, and requires special attention when performing pro-
venance studies. A wide array of different methods should be used in 
order to achieve reliable provenance interpretations. Detrital 
geochronology and heavy mineral analysis (including varietal 
study) yield valuable results, but detrital modes should be used with 
care in tropical settings.

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