ABSTRACT

Borneo, located in equatorial SE Asia, is the third largest island in the world, although it is topographically low. One of the unusual features of Borneo is the large amount of Cenozoic clastic sediments that have accumulated in several basins on and around the island. The ultimate source areas of the Cenozoic sequences have been suggested to be either mainland SE Asia/Indochina or Borneo itself. During the Paleogene until the earliest Miocene, deep marine turbidites were deposited in an accretionary wedge setting. Provenance studies on these Paleogene sediments based on detrital modes of sandstones and heavy mineral studies show that they have all been derived from a recycled orogenic source. Upper Cretaceous to Eocene sediments, the Sapulut and Trusmadi Formations, are compositionally mature (quartzose recycled), and may have been derived from mainland SE Asia/Indochina. During the Eocene there was an important change in sediment maturity and a provenance shift from quartzose to intermediate recycled sandstones. Heavy mineral studies show that the Eocene-Oligocene sediments of the Crocker Formation are mainly derived from granite, and that granite debris has been derived directly from its source or has been only slightly recycled/transported. The ultimate source area for these sediments was probably the Schwaner Mountains of southern Borneo, although a minor component of ophiolite debris suggests derivation from nearby basement of northern Borneo. The relative immaturity and heavy mineral suites of the Crocker Formation indicate it was derived from Borneo itself rather than SE Asia/Indochina, but primarily from basement sources rather than by recycling of older sediments.

INTRODUCTION

Borneo, the third largest island in the world with an area of almost 750,000 km², is located in equatorial SE Asia. It consists of the Indonesian state of Kalimantan, the Malaysian states Sabah and Sarawak, and the Sultanate of Brunei. Borneo has a low topography, and surface elevation rarely reaches more than 1000 m. Only in Sarawak and Sabah are there peaks of more than 2500 m, and the isolated granite of Mount Kinabalu (4095 m) in Sabah is the highest mountain in SE Asia. Borneo has a tropical wet climate, and until the mid 20th century most of Borneo was covered by thick lowland rainforest.

Sabah lies within the wide plate boundary zone between the Eurasian, Pacific, Philippine, and Australasian plates, and is bounded by three marginal basins, the South China Sea, Celebes Sea and Sulu Sea (Figure 1). The South China Sea is relatively shallow in the west, deepening towards the east, and formed as a result of extension, including the creation of new seafloor in the east, within a large continental region. Extension has been active since at least the Early Cenozoic, and ocean floor formation began in the Oligocene and ended in the Middle Miocene. Subduction of the proto-South China Sea occurred along the western Sabah margin from at least Eocene times, and ceased in the Early Miocene. The Celebes Sea is a marginal basin, located between the Sulu arc and the north arm of Sulawesi. Magnetic anomalies from the Celebes Sea have been identified as Eocene in age. The Sulu Sea is a small (about 400 kilometres wide), NE-SW elongated and deep basin, and formed in the Middle Miocene in a back-arc setting.

Borneo has a complex history of Cenozoic convergence, and is surrounded by several onshore and offshore sedimentary basins. Thicknesses of up to twelve kilometres of clastic sediments have been
reported in places for the Neogene sequences alone. The Cenozoic sediments of northern Borneo consist of two major sequences (Figure 2). During the Paleogene, deep marine turbidites were deposited in an accretionary wedge setting. After a major orogenic event in the Early Miocene subsidence resumed, and during the Neogene fluvio-deltaic and shallow marine sediments were deposited with a drainage pattern similar to the present-day configuration. The Cenozoic sediments of Borneo host a number of important hydrocarbon plays.

Even though the Cenozoic sediments of Borneo contain major hydrocarbon resources, only a few published studies have investigated the provenance of the sediments on and around Borneo (Kim Kiat, 1994; Tanean et al., 1996). There are two principal views on the Cenozoic sediments; those who have suggested the sediments to have been derived from far away in SE Asia/Indochina as a result of the collision of India with Eurasia (e.g. Hall, 1996; Hutchison, 1996; Métivier et al., 1999), and those who suggested the sediments to have been derived from a more local source on Borneo itself (e.g. Hall and Nichols, 2002; Hutchison et al., 2000). Hall and Nichols (2002) have calculated that if all the Cenozoic clastic sediments on and around Borneo had been derived from Borneo itself, this would imply a removal of an average of 6 kilometres of crust from Borneo. However, there are no extensive outcrops of deeply exhumed metamorphic rocks on Borneo that indicate areas of deep erosion, which raises the question of whether sediments were derived by rapid recycling of older sediments without deep burial for long periods.

Recent studies have raised interesting new ideas and questions. Hutchison et al. (2000) reported detrital zircon fission track ages from a variety of types and ages of Tertiary clastic strata of Sabah, and found that all of the zircon fission track ages are Cretaceous. They stated that these ages indicate that the ultimate source area remained above the zone of thermal annealing of zircon, because none of the Tertiary sediments in which they are found have been buried deep enough to ‘reset’ the zircons. Crevello (2002) studied the sedimentary characteristics of the Eocene-Oligocene deep-marine turbiditic Crocker Formation, and suggested that the textural and compositional immaturity of the sands indicate a proximal source. He also noted the abundance of chert lithic fragments in some of the sands, which he suggested may have been derived from an ultramafic ophiolite source.

This study is dealing with the question of whether the large volumes of Cenozoic sediments were derived from SE Asia or from a more local source in Borneo, and this paper presents the first results of work aimed to collect direct evidence on the provenance of the Borneo sediments. The part of the study that is presented here concentrates on the provenance of the Paleogene deep-marine turbiditic sediments of the NW Borneo margin, the Upper Cretaceous-Eocene Sapulut and Trusmadi Formations and the Eocene-Oligocene Crocker Formation of Sabah (Malaysia).

**METHODS**

The samples used in this study were collected in Sabah during previous field studies by members of the SE Asia Research Group, and during recent field studies when samples were collected specifically for the purpose of provenance studies. The Cenozoic sediments were the main target of sampling. Sandstones were the main lithology that was sampled, and are generally of a medium to coarse grain size, from which the best preserved and most reliable heavy mineral suites can be separated. Samples were collected at intervals of several meters. Other lithologies that were sampled include siltstones and mudstones, and rocks from the ophiolite basement of Sabah. A total of nearly 300 samples was collected.

Detrital modes of sandstones (Dickinson et al., 1983) were used in thin section to determine the main provenance categories to which they belong. Heavy minerals were separated from the same sandstone samples. Samples were separated by the partial freezing method and by the funnel separation method (Mange and Maurer, 1992). Assemblages of detrital heavy minerals are used to interpret the provenance of the sandstones in further detail (Morton and Hallsworth, 1994). Heavy mineral samples were studied with a binocular microscope and with a Hitachi S3000 scanning electron microscope (SEM) fitted with a Link Isis series 100 microanalysis system to perform elemental analyses of single minerals.

Detrital zircons were isolated from the heavy mineral separates for varietal studies; the zircons are studied for rounding and abrasion features that indicate transport and sedimentary recycling, and the euhedral zircon varieties are further classified by the typology method of Pupin (1980). In the near future, U-Pb ages of the detrital zircons will be obtained by SHRIMP-
analysis (Sensitive High Resolution Ion Microprobe). The method of High Resolution Heavy Mineral Analysis (HRHMA), that has been successfully applied in the hydrocarbon industry to date and correlate barren sequences (Mange-Rajetzky, 1995), will be used on a number of continuous exposed sections that were sampled systematically with a spatial resolution of several metres. This method allows the subdivision and correlation of biostratigraphically barren sequences on the basis of their heavy mineral content.

AGES OF CENOZOIC NW SABAH SEDIMENTS

The Cenozoic sediments of NW Borneo consist of two major sequences. From the Late Cretaceous to the Early Miocene sediments were deposited in a deep marine forearc setting. These sediments, of the Upper Cretaceous-Eocene Sapulut, Trusmadi and East Crocker Formations, the Eocene-Oligocene (West) Crocker Formation and the Oligocene-Lower Miocene Temburong Formation, are mainly sandstones and mudstones deposited by turbidity currents, and are exposed over most of NW Borneo in the Crocker Ranges, the main mountain range of northern Borneo. After a major orogenic event in the Early Miocene, producing the DRU (Deep Regional Unconformity), deep marine sedimentation ceased and local melanges were formed. Renewed subsidence resumed quickly; during the Neogene fluvio-deltaic and shallow marine sediments were deposited, but only limited outcrops are found onshore.

The Paleogene sediments of northern Borneo contain very few fossils, and fossils that are found are typically long ranging, so they are difficult to subdivide. The Sapulut Formation of southwestern Sabah is a non-metamorphic unit fairly well defined as Upper Cretaceous-Middle Eocene. The low-grade metamorphic Trusmadi and East Crocker Formations are distinguished mainly by their metamorphic grade, degree of deformation and very slight lithological variations. The Trusmadi Formation is mostly argillaceous, barren of any fossils and metamorphosed up to lower greenschist facies. The East Crocker Formation is distinguished from the West Crocker Formation by biostratigraphically barren marls that only occur in the East Crocker Formation (Liechti et al., 1960), but no biostratigraphical evidence for this distinction was ever reported. In this paper, the term Crocker Formation refers to the unmetamorphosed Eocene-Oligocene deep marine deposits of western Sabah. The poor definition of onshore Paleogene strata has led to a wide variation of conflicting stratigraphic interpretations, and there appears to be little or no current work that attempts to refine the ages of the onshore sediments of northern Borneo. The samples from the most recent field studies that were intended for nanofossil dating turned out to be mostly barren.

Because of the importance of dating, as a part of this study original reports of onshore fossil occurrences with narrow age ranges have been compiled to get a clear understanding of the age and distribution of the Paleogene sediments of NW Borneo. The ages have been derived from published literature and theses, and from new nanofossil finds. The ages and their locations were mapped, and approximate age contours were plotted (Figure 3). The Upper Cretaceous ages are all found in a limited area in southern Sabah and they all belong to the Sapulut Formation. A striking feature is the younging of Paleocene to Upper Oligocene sediments in a direction towards the WNW, a direction perpendicular to the general strike of the Paleogene sediments in the area. Major anomalies within the age contours (Figure 3) show a remarkable similarity with major structures in the area (Figure 2). It must be noted that the age contours appear more precise than they actually may be because of the relative small number of fossil dates. More fossil age data are needed to improve this.

The sediments of the far north of Sabah, in the Kudat Peninsula area, have been the subject of misinterpretations in a number of studies. Numerous Eocene fossil localities were reported in the Kudat Formation, the main body of sediment in this area, by Stephens (1956), and many later studies have used this as an argument to group the Kudat Formation together with the Eocene-Oligocene deep marine Crocker Formation. However, the data of Stephens (1956) were re-evaluated by Liechti et al. (1960), based on a survey by Clement and Keij (1958). They stated that the Kudat Formation is entirely Miocene, and that the determinations of Eocene age were either based on benthonic microfaunas which were originally thought to be age determining, or on Eocene larger foraminifera that are believed to be reworked. Based on these results the Kudat Formation is interpreted here to be time-equivalent to the Meligan Formation of Brunei and SW Sabah.
In addition, a database of paleocurrents was constructed from field observations and literature (Stauffer, 1967; Tongkul, 1987). The newly collected paleocurrent data on the turbidites of the Eocene-Oligocene Crocker Formation are compiled in Figure 4. The main set of directions is parallel to the main strike of the Crocker Mountains and to the NW Borneo Trench, and is towards the NNE. A minor set towards the NNW is also present.

RESULTS

Point counts were made for the sandstone samples, and the results were analysed by the method outlined by Dickinson et al. (1983) to identify the main provenance category to which they belong (continental, arc or recycled orogenic). The Paleogene deep marine sediments of the Crocker, Trusmadi and Sapulut Formations that outcrop in NW Borneo show a clear recycled orogenic signature when their sandstone compositions are plotted on a QFL diagram (Figure 5). Although there is some variation in QFL composition, no clear pattern emerges.

When the sandstone compositions are plotted on a QmFLt diagram (Figure 6), a distinct pattern within the recycled orogenic field emerges. The sediments that are reported to be the oldest in the region (the Sapulut Formation is regarded as Upper Cretaceous-Middle Eocene, the Trusmadi Formation is suggested to be Eocene) show the greatest compositional maturity. The Sapulut Formation sandstones are sublitharenites to subarkoses, and consist mainly of monocrystalline quartz grains, up to 15% of feldspar (mostly K-feldspar) and a relatively low percentage of lithic fragments. The Trusmadi Formation sandstones are sublitharenites, and consist of monocrystalline quartz grains, a considerable amount of chert and other lithic grains (both quartzose and unstable), and very low amounts of feldspar.

Although the sediments of the Crocker Fan are of an orogenic recycled origin, they are not as mature as would be expected if they had come from a distal source in mainland SE Asia/Indochina. The sandstones of the Eocene-Oligocene Crocker Formation are sublitharenites and lithic arenites, and are less mature in both composition and texture. Thin-section analysis shows that the sand grains of the Crocker Formation are fairly angular. Feldspar contents are very variable from 0 to 13%, but the feldspar grains are mostly K-feldspar. In addition, the sandstones are much richer in lithic fragments. Among the lithic fragments in the Crocker Formation there is a significant amount of chert. Other lithic fragments include sedimentary fragments other than chert, and minor amounts of metamorphic fragments, basalt and rare non-basaltic volcanics. This implies that a fresh sediment source must have become available to the Crocker Formation, and that extensive recycling from the older Sapulut and Trusmadi Formations is very unlikely. This decrease in sediment maturity and shift in provenance is estimated to have occurred in the Middle Eocene, around the same time as an orogenic event to the south in Sarawak, the so-called Sarawak Orogeny (Hutchison, 1996).

More detailed information is obtained from heavy mineral data. Two approaches have been used. The heavy minerals are studied as an assemblage, as the combination and abundance of several heavy mineral species is provenance-specific (Morton and Hallsworth, 1994). In addition, varietal studies were performed on the detrital zircons (typology of euhedral grains (Pupin, 1980) and zircon rounding), which allows further interpretation of provenance and transport conditions. Heavy mineral data are available for the Crocker Formation only at this stage; heavy mineral data of the older sediments of the Sapulut and Trusmadi Formations are not available yet.

The sandstones of the Crocker Formation usually contain only the stable and ultrastable heavy minerals. The most abundant heavy mineral component in all samples is zircon (Figure 7), often accompanied by significant numbers of tourmaline grains (Figure 8.1). Other accessory heavy minerals that occur in smaller numbers include rutile (Figure 8.2), almandine garnet, muscovite, biotite (Figure 8.3), staurolite (Figure 8.4), chloritoid and monazite (Figure 8.5). Framboidal pyrite (Figure 8.6) was observed in some of the samples; this mineral probably formed in situ. The dominance of zircon and tourmaline is an indication that the ultimate main source for the sediments of the Crocker Formation was granite, with a minor input of low-grade to medium-grade metamorphic rocks. The less stable heavy minerals that would have been provided by the source rocks have probably been eliminated during erosion and transport and by tropical weathering, but could possibly also have been destroyed by burial diagenesis or during later uplift, because meteoric water infiltration can be quite deep in tropical settings.
Another detrital heavy mineral that is present in the younger (Oligocene) parts of the Crocker Formation, and is sometimes relatively abundant, is chromian spinel. Chromian spinel is a very provenance-specific mineral, and it is a common accessory mineral in ultramafic rocks. The detrital chromian spinel grains are found as freshly fractured (Figure 9.1) or euhedral grains (Figure 9.2), but do not show much abrasion or other signs of any significant transport. The presence of these detrital chromian spinel grains together with significant amounts of chert in the light fraction of the sandstones is a strong indication that during the Oligocene the ophiolitic basement of northern Borneo was already present at the surface and available for erosion nearby.

Zircon is one of the most stable heavy minerals. It is resistant to transport and tropical weathering and is not destroyed by burial diagenesis. The mechanical rounding of zircons is a qualitative but reliable proxy for sedimentary transport. Euhedral zircons (Figure 7.1) are indicative of a first cycle granite provenance, whereas subhedral zircons (Figure 7.2) can be first cycle, but have possibly undergone some sedimentary recycling and/or transport. Well-rounded zircons (Figure 7.3) have undergone multiple cycles of sedimentary recycling and/or transport. The zircon populations in the Crocker Formation show a dominance of euhedral to subhedral grains; these make up about 90% of all zircons. Very fresh euhedral zircons alone can make up as much as 40% of the zircon population. Well-rounded zircon grains are relatively rare, and make up only about 10% of the zircon population. Preliminary results based on the classification of the euhedral detrital zircons according to typology (Pupin, 1980) suggest that the fresh granites are mostly mantle-derived granites. Some different euhedral zircon types are shown in Figure 10. It is clear that the detrital zircons in the Crocker Formation are predominantly first- and second cycle granite-derived zircons. Material that has experienced a long path of transport and/or multiple cycles of sedimentary recycling is of low importance.

DISCUSSION

The older Upper Cretaceous-Eocene formations that are exposed in the Crocker Ranges, the Sapulut and poorly defined Trusmadi and East Crocker Formations, show a higher compositional maturity than the Upper Eocene-Oligocene (West) CrockerFormation. A more distal and recycled source for these sediments is possible, and they could possibly have been derived from mainland SE Asia/Indochina. However, they also predate the Asia-India collision that is proposed as the main mechanism that could have brought sediments from mainland SE Asia/Indochina to the Borneo basins.

One of the most interesting finds in the Eocene-Oligocene Crocker Formation is the abundance of relatively fresh detritus. The overall compositional immaturity of the Upper Eocene-Oligocene Crocker sandstones, together with the abundance of fresh, first cycle granitic zircons, and fresh ophiolitic chromian spinels contradicts the idea that the sediments of northern Borneo have a distant source. Although the sedimentation of the Crocker Formation occurred at the same time as the collision of the Indian plate with the Eurasian plate, there is no indication that any significant amount of sediment has been fed from the collision zone into the basins on and around northern Borneo.

The minor component of ophiolite-derived material (indicated by chert and chromian spinel) is most likely derived from exposure of the basement of northern Borneo; this basement is a Jurassic-Cretaceous ophiolite sequence. The new data suggest that the basement was exposed and available for erosion since at least the Oligocene.

The bulk of the sediment of the Crocker Formation is granite-derived, and was most likely deposited after a short or insignificant history of sediment transport and recycling. There are no granites older than Middle Eocene in northern Borneo, but there are three other regions with abundant granite that could have provided sufficient amounts of detritus to the Crocker Formation: (1) granites of Cretaceous age currently known from offshore drilling of shallow seas of the western South China Sea and Sunda Shelf; (2) the Permo-Triassic granites of the Tin Belt of Peninsular Malaysia, Thailand and the Indonesian Tin Islands and (3) the Schwanger Mountains of southern Borneo, mainly consisting of Lower Cretaceous monzogranites.

Very little is known of the Cretaceous granites submerged in the shallow parts of the western South China Sea; they are known to form hydrocarbon reservoir rocks in the offshore strata of Vietnam (Lac
et al., 1997). It is not very likely that they have supplied great volumes of sediment to the Borneo basins, as this would require substantial bypass of sediment over a region of the Sunda Shelf/shallow South China Sea where there are many extensional basins that would have acted as sediment traps (Morley, 2002), as well as carbonate build-ups on the Dangerous Grounds and Luconia microcontinents, that would have acted as a barrier to the bypass of clastic sediments. The area offshore of Vietnam was an area of active sedimentation since at least the Oligocene (Lac et al., 1997).

It is unlikely that the granites of the Tin Belt have supplied much material to the Crocker Formation. If material from these granites had ended up in great quantities in the Crocker Formation, one of the abundant heavy minerals would have been cassiterite, which is highly resistant to weathering. SEM studies so far have shown that cassiterite, or any other Sn-bearing mineral, is absent from the Crocker Formation. The ages of the Tin Belt granites are predominantly Permo-Triassic; it is unlikely that they have supplied the zircons in the Tertiary strata of northern Borneo, as it has been shown they all yield Cretaceous fission track provenance ages (Hutchison et al., 2000).

On the other hand, the zircon ages are consistent with the Lower Cretaceous ages reported for the bulk of the granites of the Schwaner Mountains (Williams et al., 1988). The best interpretation of the current data set is that the bulk of the sediments of the Eocene-Oligocene turbiditic Crocker Formation has been derived from the granites of the Schwaner Mountains. It has been shown that exhumation of the Schwaner Mountains granites to above the zone of thermal annealing of zircons may have occurred as early as the Cretaceous (Hutchison et al., 2000). It is possible that the sediments have undergone one cycle of sediment recycling within the Cretaceous-Eocene sediments of the Rajang Fold Belt of Sarawak (Malaysia). The initial results of classification of euhedral detrital zircons on their typology are consistent with monzogranites, and these results therefore are consistent with possible derivation of granitic detritus from the Schwaner Mountains. A sketch map (Figure 11) shows some of the major provenance elements of (western) Borneo at the time of deposition of the younger parts of the Crocker Formation.

The distinct decrease in compositional maturity in the Oligocene Crocker sediments (Figure 6) is estimated to occur in the Middle Eocene, at the same time that a major unconformity is found in the sediments of Sarawak, further to the south. The event that caused this unconformity is referred to as the Sarawak Orogeny (Hutchison, 1996). Although this unconformity has not been identified in any outcrops in Sabah, it is likely that the Sarawak Orogeny uplifted new source areas that supplied material to the Crocker Formation. These source areas were either Cretaceous-Eocene sediments of the Rajang Fold Belt, and/or freshly exposed granites of the Schwaner Mountains. This is also consistent with the measured paleocurrent directions in the Crocker Formation (Figure 4).

The classification of the pre-Oligocene deep marine sediments of northern Borneo is still a problem. The new provenance results provide further constraints on the poorly defined onshore Paleogene stratigraphy of northern Borneo. The large-scale stratigraphic divisions of northern Borneo have been re-evaluated along a transect from Brunei through the Crocker Range up to the Kudat and Bongaya peninsulas of northernmost Borneo, and have been compiled in Figure 12. This update includes the results of literature review, notably on the Kudat area, and the Kudat Formation is interpreted here as a coherent Miocene sedimentary unit overlying local melanges, in agreement with field observations and the reevaluation of Liechti et al. (1960). The onshore stratigraphy of southwestern Sabah is very similar to the nearby sedimentary sequences of onshore Brunei (Sandal, 1996). The bulk of the Crocker Formation in western Sabah is shown in Figure 11 as the West Crocker Formation, and is regarded as mainly Oligocene.

CONCLUSIONS

It is shown from provenance studies that the Upper Cretaceous-Eocene Sapulut and Trusmadi Formations, the oldest sediments in northern Borneo, are compositionally relatively mature, and could have had a significant history of transport and/or recycling. The bulk of the Eocene-Oligocene sediments of the Crocker Formation of northern Borneo are ultimately derived from a relatively fresh granitic source. It is also shown that a minor amount of ophiolite-derived material is present in the younger parts of the Crocker Formation. Their source area is suggested to be the
local ophiolitic basement of northern Borneo. Only minor amounts of metamorphic material have been found in the Crocker Formation.

The granitic material has been derived either directly from the granite, or via one episode of sedimentary recycling. The area with sufficient volumes of granite to provide the material for the Crocker Formation that best fits our data set is that of the Schwaner Mountains in southern Kalimantan where there are Lower Cretaceous monzogranites. On the basis of the results so far it is likely that the bulk of the sediment of the Crocker Formation is derived from Borneo rather than mainland SE Asia/Indochina. Although these sediments postdate the India-Asia collision, they are compositionally less mature than would be expected if they were derived from Asia.

With regard to hydrocarbon exploration in Borneo and offshore, provenance studies, and heavy mineral studies in particular, offer a new insight into the history of the clastic sediments on and around Borneo. Although in mature areas of hydrocarbon exploration the information obtained from provenance studies is regarded as important, very few such studies have been performed for the basins in and around Borneo. Provenance studies can provide understanding of the source area evolution of the region, and the timing of sediment availability and dispersal patterns. These studies also offer potential for stratigraphic correlation in regions where conventional biostratigraphically-based correlation may be poor. The character of the source regions may also be of importance in predicting properties of potential reservoirs, particularly as exploration moves into undrilled areas in the deepwater areas offshore.

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REFERENCES


Figure 1 – The present day plate configuration of the SE Asian region. Sabah, the main area of study, is located on the north of the island of Borneo, in the centre of the region (Hall, 2002).
Figure 2 – Simplified geological map of Sabah (northern Borneo), modified from Balaguru (2001) and sources therein. The main target of this study is the voluminous Paleogene sediment sequence of western Sabah coloured in green.
Figure 3 – Compilation map showing the approximate age distribution of the onshore Paleogene sediments of NW Borneo, based on published and newly discovered age–specific fossil occurrences in outcrops.
Figure 4 – Paleocurrent directions from flutes at the bottom of turbidite beds in the Crocker Formation, and an example of bi-directional flutes at the bottom of one turbidite bed in the Sapulut Formation of southern Sabah. Vertical scale of outcrop approximately 2.5 m.

Figure 5 – Triangular QFL plot showing the detrital modes of the sandstones of the Paleogene NW Borneo onshore sediments. Based on Dickinson et al. (1983).
Figure 6 – Triangular QmFLt plot showing the detrital modes of the sandstones of the Paleogene NW Borneo onshore sediments. Based on Dickinson et al. (1983).

Figure 7 – Examples of different detrital zircon morphologies in the Crocker Formation: (1) euhedral; (2) subhedral; (3) rounded.

Figure 8 – Heavy minerals from the Crocker Formation: (1) tourmaline; (2) rutile; (3) biotite; (4) staurolite; (5) monazite; (6) frambooidal pyrite.
Figure 9 – Example of (1) fractured and (2) euhedral detrital chrome spinel in the Crocker Formation.

Figure 10 – Examples of some different zircon crystal types.
Figure 11 – Sketch map showing the major provenance elements and pathways during deposition of younger parts of the Crocker Formation of Sabah (Northern Borneo). No structural displacement, rotation, shortening or extension has been included in this sketch. Tr–Jr = Triassic–Jurassic metamorphic rocks, Cret. = Cretaceous ophiolite complex of the Meratus Mountains.
Figure 12 – Revised stratigraphy of the onshore sediments of NW Borneo between Brunei Darussalam (south, left in diagram) and Kudat Peninsula (north, right in diagram).