STRATIGRAPHY AND SEDIMENT PROVENANCE, BARITO BASIN, SOUTHEAST KALIMANTAN

Duncan Witts*
Robert Hall*
Robert J. Morley**
Marcelle K. BouDagher-Fadel***

ABSTRACT

The Barito Basin is located in southeast Kalimantan. It contains a thick Cenozoic sedimentary succession that overlies basement rocks of Paleocene and older age. This paper presents a revised stratigraphy and depositional model for the basin and identifies sediment source areas, based on new lithostratigraphic, biostratigraphic, petrographic and paleocurrent data collected as part of a field-based study.

The oldest sedimentary rocks of the Barito Basin succession are assigned to the Tanjung Formation. They include conglomerates, sandstones, siltstones, mudstones, limestones and coal, deposited in a fluvio-tidal coastal plain to marginal marine setting. Palynomorph assemblages indicate deposition began in the late Middle Eocene and foraminifera show that it continued until latest Early Oligocene. During this time, sediment was being sourced from the west and southwest. The Tanjung Formation is overlain by the Montalat Formation in the north and the Berai Formation in the south. These are laterally equivalent in age and were deposited in marginal fluvio-deltaic to fully marine conditions respectively. Foraminiferal assemblages indicate this phase of deposition continued until the Early Miocene. The Warukin Formation overlies these formations, and includes limestones, mudstones, siltstones, sandstones and lignites deposited in a marginal marine to fluvio-deltaic setting. Palynomorph assemblages date the top of the formation as Late Miocene. Palaeocurrent data indicate sediment was being transported from the west for the oldest part of the formation, and partly from the east for the younger coal-bearing sequences. It is suggested that this reversal in palaeoflow records uplift of the Meratus Mountains.

INTRODUCTION

The Barito Basin is located in southeast Kalimantan, Borneo. The basin contains a thick succession of sedimentary rocks that are well exposed along the eastern margin of the basin (Fig. 1). The basin is bound to the west by the Schwaner Complex, comprising poorly dated regionally and contact metamorphosed rocks and Cretaceous granitic plutons and volcanic rocks. The northern margin is defined by the ‘Cross Barito High’ (Moss et al., 1997), an onshore continuation of the NW-SE-trending Adang fault zone. This separates the Barito Basin from the Kutai Basin to the north. Bounding the Barito Basin to the east is the Meratus Complex. This forms a NE-SW-trending belt of uplifted ophiolitic, subduction-related metamorphic and arc-type rocks ranging in age from Jurassic to Cretaceous (Wakita et al., 1998). The Meratus Complex is interpreted to record a phase of collision and accretion along the southern margin of Sundaland during the mid Cretaceous, and now separates the Barito Basin from the smaller Asem-Asem Basin and the Paternoster Platform to the east. The stratigraphic similarity between these areas suggests they were once connected, forming a single depocentre throughout much of the Paleogene and Early Neogene, prior to the uplift of the Meratus Complex.

A number of models have been proposed to explain the evolution of the Barito Basin, largely developed from hydrocarbon exploration. However, due to the limited number of biostratigraphic analyses and scarcity of age-diagnostic fossils, the sedimentary succession has, until this study been poorly dated. Also, there are no published studies investigating the provenance of the sandstones. Consequently, the sediment source areas have never been identified although the Schwaner Complex is often suggested as the sediment source during the Paleogene (e.g. Rose & Hartono, 1978; Hamilton, 1979; Siregar &
This paper presents results from an extensive field-based study conducted in the Barito Basin. A revised stratigraphy is presented, built on existing nomenclature, and better dated using palynology and foraminiferal assemblages. Sandstone petrography, U-Pb dating of zircons and palaeocurrent data suggest new interpretations of sandstone provenance. These new data have significance for hydrocarbon exploration in the basin and provide important information on the geological evolution of the surrounding region.

**METHODS**

Palynomorphs and foraminifera have been used to date the sedimentary succession. Palynological analysis was conducted by Lemigas in Jakarta. No palynological zonation for the Eocene of the Sunda region has been published, and so this study has provided the basis for such a zonation, described in summary form below. For the Miocene, reference is made to the zonation of Morley (1978, 1991). Foraminifera were analysed at University College London by Dr. Marcelle BouDagher-Fadel and sediments have been dated using larger foraminifera by reference to the Letter Stage scheme of van der Vlerk & Umbgrove (1927) as modified by Adams (1970), BouDagher-Fadel & Banner (1999) and BouDagher-Fadel (2008) and planktonic foraminifera by reference to Tourmarkine & Luterbacher (1985) for the Eocene, and Bolli & Saunders (1985) for the post Eocene. Letter Stages and planktonic foraminiferal zones are correlated in BouDagher-Fadel (2008). Sandstone provenance was determined from detrital modes and U-Pb dating of detrital zircons. Detrital modes were determined from 80 sandstones. Zircons from 17 sandstone samples for which the stratigraphic age was known were dated at University College London, using LA-ICPMS. The New Wave 213 aperture-imaged, frequency-quintupled laser ablation system (213 nm) was used, coupled to an Agilent 750 quadrupole-based ICP-MS. Real time data were processed using GLITTER™. Repeated measurements of external zircon standard Plesovic (reference age determined by thermal ionization mass spectrometry (TIMS) of 337.13±0.37 Ma (Sláma et al., 2008)) and NIST 612 silicate glass (Pearce et al., 1997) were used to correct for instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U. Data were filtered using standard discordance tests with a 10% cut-off. The $^{206}\text{Pb}/^{238}\text{U}$ ratio was used to determine ages less than 1000 Ma and the $^{207}\text{Pb}/^{206}\text{Pb}$ ratio for grains older than 1000 Ma. Data were processed using Isoplot™. A total of 1539 concordant U-Pb ages were obtained. 766 palaeocurrent measurements were collected from dune cross-beds within channel sand bars and small-scale ripples. All measurements were corrected for structural dip. The Rayleigh’s Test for a Preferred Trend was applied to all datasets. Critical values are given by Mardia (1972). Stratigraphic logs, lithofacies analyses, trace fossils, palynomorphs and foraminifera have been used to determine depositional environments of the sedimentary succession.

**EOCENE PALYNOLOGICAL ZONATION**

Since no published palynological zonation is available to characterise the Middle-Late Eocene boundary, a reference section was compiled on which a zonation could be based. Due to limited exposures, several profiles from the same area were joined to form a single reference section containing 41 samples. The palynological zones are defined as follows:

**Zone E6 - Middle Eocene**
Characterised by the presence of the Middle Eocene markers *Beaupreadites matsuokae* and *Polygalacidites clarus* in an assemblage dominated by ‘Indian’ taxa such as *Palmaepollenites* spp, *Lanagiopollis* spp, *Lakiapollis ovatus* and *Retistephanocolpites williamsi*. All are common to abundant in the Middle Eocene Nanggulan Formation (Lelono, 2000).

**Zone E7 - Late Eocene**
Characterised by the first consistent occurrence of *Cicatricosisporites dorogensis*, and by the absence of *Meyeripollis nayarkotensis*, which ranges from the base of the overlying zone.

**Zone E8 - Late Eocene**
Based on the regular presence of *Meyeripollis nayarkotensis* and the absence of *Magnastriatites howardi*, which ranges from the base of the overlying zone.

**Zone E9 - Late Eocene**
Characterised by the overlap of *Magnastriatites howardi* and the Eocene marker *Proxapertites operculatus*, which has its top at topmost Eocene in Southeast Asia, India and Africa (Morley, 2000).

**STRATIGRAPHY**

The sedimentary succession of the Barito Basin unconformably overlies basement rocks of Sunaryo, 1980; Courteney et al.1991; van de Weerd & Armin, 1992; Satyana et al., 1999). This paper presents results from an extensive field-based study conducted in the Barito Basin. A revised stratigraphy is presented, built on existing nomenclature, and better dated using palynology and foraminiferal assemblages. Sandstone petrography, U-Pb dating of zircons and palaeocurrent data suggest new interpretations of sandstone provenance. These new data have significance for hydrocarbon exploration in the basin and provide important information on the geological evolution of the surrounding region.
Paleocene and older age (Sikumbang, 1986). The succession comprises five formations that record a full transgressive to regressive cycle (Fig. 2). The oldest sedimentary rocks are assigned to the Tanjung Formation and were deposited in a fluviotidal coastal plain to marginal marine environment. The formation becomes increasingly marine-influenced up section. Palynomorph assemblages date the base of the formation as late Middle Eocene by reference to palynological zone E6 (see Fig. 2). The assemblages contain common elements which relate to the Middle Eocene dispersal of plant taxa from India (Morley, 1998; Lelono, 2000). The major part of the Tanjung Formation is Late Eocene and Early Oligocene. The Late Eocene interval is dated by reference to the evolutionary appearances of Cicatricosisporites dorogensis, Meyeripollis nayarkotensis and Magnastratiattes howardi. The latter taxon is often thought to have first appeared in the basal Oligocene (Germeraad et al. 1968), but is recorded commonly in the Tanjung Formation stratigraphically below well dated Late Eocene marine sediments with common planktonics, which include Turborotalia pomeroli, Globigerinatheca spp and Hanfkenina alabamensis, indicating the Late Eocene planktonic zone P15-P16. The age of the top of the formation is referred to Letter Stage Td (late Early Oligocene) by reference to the overlap of the larger foraminifera Nummulites fichteli and Eulepidina spp.

The Tanjung Formation is overlain by the Berai Formation in the south and the Montalat Formation in the far north of the basin. They are laterally equivalent in age but are lithologically dissimilar. The Berai Formation records fully marine conditions, and is characterised by shallow water platform carbonate rocks. The Montalat Formation records marginal marine to braided delta deposition and extends across the Barito/Kutai divide. The base of the Berai Formation has been referred to Te1 to lower Te5 Letter Stages (planktonic zone P21-N4) based on the presence of Heterostegina borneensis and association with overlying samples (BouDagher-Fadel, 2008).

The Warukin Formation overlies the Berai and Montalat Formations. It records a return to shallow marine and then terrestrial, fluvio-deltaic conditions. The base of the formation shows distinct marine influence and can be referred to upper Te5 to middle Tf1 Letter Stages (planktonic zone N6-N8) based on the presence of Miogypsinodella sp., Miogypsinia spp., and L. (N) broweri and association with underlying samples (BouDagher-Fadel, 2008). The top of the formation is older than 7.4 Ma based on reference to the Florschuetzia meridionalis palynological zone.

The Dahor Formation was not investigated during this study. It is reported to overly the Warukin Formation and comprises a succession of polymict fluvialite and shallow marine sedimentary rocks (Satyana & Silitonga, 1994; Seeley & Senden, 1994; Satyana, 1995; Gander et al., 2008) derived from the Meratus Complex during the Plio-Pleistocene.

**SANDSTONE COMPOSITION**

**Tanjung Formation**

Sandstones of the Tanjung Formation are quartz arenites and sub-litharenites (Folk, 1968) and plot within the ‘craton interior’ and ‘quartzose recycled’ fields of Dickinson & Suczek (1979), see Fig. 3. They contain mainly angular monocrystalline and rounded polycrystalline quartz grains with minor anhedral feldspars, sub-angular radiolaria-bearing chert, and lithic fragments. Monocrystalline quartz has either simple or slightly undulose extinction pattern and typically contains strings or bands of fluid inclusions, indicating a plutonic origin. Polycrystalline quartz has high angles of undulose extinction, more than three crystals per grain (often showing alignment), bimodal crystal size within a single grain, and strings of fluid inclusions. These features indicate a metamorphic parentage (Smyth et al., 2008a). Feldspars comprise <1% of the total composition, and are mainly strained plagioclase (undulose extinction) suggesting a metamorphic origin or a post-depositional deformation (Passchier & Trouw, 2005). Most of the lithic fragments are schistose.

**Montalat Formation**

Sandstones from the Montalat Formation are quartz arenites, sub-arkoses and minor sub-litharenites (Folk, 1968). The Dickinson & Suczek (1979) ternary plots suggest a ‘craton interior’ provenance (Fig. 3). The sandstones are composed of angular monocrystalline and rounded polycrystalline quartz grains with minor anhedral feldspars and lithic fragments. Monocrystalline quartz grains have simple or slightly undulose extinction pattern and contain characteristics of a plutonic origin, or are inclusion-free, exceptionally bright in thin section and have sharp extinction, suggesting a volcanic parentage (Smyth et al., 2008a). Polycrystalline quartz has features indicative of a metamorphic origin. Feldspars comprise 2.4% of the total composition. These are mainly strained and
unstrained plagioclase with minor K-feldspar indicating a predominately metamorphic parentage with minor input from an acid plutonic source. Lithic grains include schist and igneous rock fragments.

**Warukin Formation**

Sandstones of the Warukin Formation are quartz arenites, and rare sub-arkoses (Folk, 1968) and plot mainly within the ‘quartzose recycled’ field of Dickinson & Suczek (1979), see Fig. 3. They contain a mixture of angular and rounded monocrystalline quartz and rounded polycrystalline quartz grains with minor amounts of anhedral and rounded feldspar, rounded clasts of radiolaria-bearing chert and lithic fragments. Monocrystalline quartz grains contain features suggestive of plutonic and volcanic origin. A number of rounded grains with diagenetic quartz overgrowths were identified, implying multiple recycling. Most of the polycrystalline quartz grains are of probable metamorphic origin. Feldspars comprise 1% of the total composition and are mainly strained plagioclase and K-feldspar, suggesting metamorphic and plutonic provenance. Lithic fragments are mainly composed of schistose material.

All the sandstones of the three formations are compositionally mature, yet texturally immature which is relatively unusual. Tropical alteration can significantly alter the composition of sandstone by the systematic destruction of unstable lithic fragments and feldspars during transport, deposition and storage. Borneo has been situated within tropical latitudes and climate since the Mesozoic and we believe the apparent discordance between compositional and textural maturity has been produced by intense tropical processes. The standard plots of detrital modes may therefore mislead in identifying provenance because they were developed in mainly non-tropical settings.

**PALAEOCURRENT ANALYSIS**

Palaeocurrent data for the Tanjung, Montalat and Warukin Formations are shown in Figs 4 to 6. The data indicate that during the deposition of the Tambak Member of the Tanjung Formation (which accounts for approximately 80% of the formation), sediment was transported by rivers towards the north. Orientations of small-scale ripples within the tidal facies indicate a SW-directed tidal flood. This implies the coastline was located towards the northeast. Palaeocurrent measurements from the Kiwa Member of the Montalat Formation indicate sediment was being transported towards the northwest. Palaeocurrent data from the Barabai Member of the Warukin Formation indicate sediment was transported towards the east-southeast. This continued into the lower part of the Tapin Member. A change is recorded from the top of the Tapin Member where palaeocurrent data indicate sediment was being transported towards the west.

**GEOCHRONOLOGY OF DETRITAL ZIRCONS**

**Tanjung Formation**

Detrital zircons were analysed from seven samples collected from the Mangkook and Tambak Members of the formation. A total of 656 concordant U-Pb ages were obtained. Ages range from Neoarchean to Cretaceous (Fig. 7). The most prominent populations are Cretaceous, of which 32% are Early Cretaceous (140±5.7 Ma to 99.8±6.1 Ma) and 62% Late Cretaceous (99.3±4.8 Ma to 70.7±5 Ma), and Devonian- Carboniferous (415.8±12.6 Ma to 300.5±5.1 Ma) with smaller Permo-Triassic (295.2±10.5 Ma to 205.7±7.6 Ma), Ordovician - Silurian (484.1±15.7 Ma to 417.6±13.2 Ma) and Proterozoic (2496.7±22 Ma to 544.8±16 Ma) populations. Jurassic and Archean grains are rare.

**Montalat Formation**

Detrital zircons were analysed from two samples, one from each member of the formation. A total of 177 concordant U-Pb ages were obtained. Ages from the Bentot Member are bimodally distributed, comprising Cretaceous (122.9±9.3 Ma to 66.9±19.9 Ma) and Proterozoic (2426.2±26.6 Ma to 906.4±44 Ma) populations. The Cretaceous population is dominated by Early Cretaceous zircons (122.9±9.3 Ma to 99.7±21.7 Ma), and the Proterozoic population is dominated by Paleoproterozoic grains (2426.2±26.6 Ma to 1600.8±26.3 Ma). Ages obtained from the Kiwa Member range from Cretaceous to Proterozoic. The most prominent population is Cretaceous (122.6±21.8 Ma to 76.6±19.5 Ma). 79% of which are Late Cretaceous. There is a small Devonian- Carboniferous population (398.6±30.5 Ma to 313.2±26.7 Ma), but zircons of other ages are rare.

**Warukin Formation**

Detrital zircons from seven samples collected from the Warukin Formation were analysed. Both members were represented. A total of 492 concordant U-Pb ages were obtained, ranging from
Mesoarchean to Paleogene. The largest populations are Cretaceous (143.9±9.3 Ma to 68.6±5.1 Ma), Permo-Triassic (295.7±18.5 Ma to 204.1±14.5 Ma) and Proterozoic (2493.0±45.1 Ma to 546.8±20.4 Ma). Jurassic ages form a small population (190.9±18.1 Ma to 145.8±25.6 Ma). Grains of other ages are rare.

**ZIRCON MORPHOLOGY**

Zircon morphology (expressed in terms of width-to-length ratio and prismatic character) is considered to reflect the physical and chemical conditions present during crystal growth (Schafer & Dorr, 1997). For example, elongate or needle-like crystals are commonly associated with rapidly ascending magmas, high-level granites and volcanic eruptive deposits (Corfu et al., 2003), whilst crystals with a low width-to-length ratio are produced during slow-cooling of plutonic intrusions. Representative images showing zircon morphology are presented in Fig. 8. Zircon types and their associated ages are described below.

The **Tanjung Formation** contains euhedral, elongate grains (Cretaceous age); euhedral, non-elongate grains (Cretaceous and Jurassic ages); euhedral, stubby grains (Cretaceous and Permo-Triassic ages) and well-rounded and angular grains (all ages from Neoarchean to Cretaceous). Zircons from the **Montalat Formation** include euhedral, elongate grains (Cretaceous and Proterozoic ages); euhedral, stubby grains (Cretaceous age); non-elongate, mostly rounded grains (Cretaceous and Triassic-Devonian ages); angular grain fragments (Cretaceous and Proterozoic ages) and rounded grain fragments (all ages from Cretaceous to Proterozoic). Zircons from the **Warukin Formation** include elongate grains (Cretaceous, Permo-Triassic and Archean ages); euhedral, non-elongate grains (Paleogene); euhedral, stubby grains (Cretaceous, Permian and Proterozoic ages); rounded, non-elongate grains and rounded and angular fragments (all ages from Cretaceous to Mesoarchean). Many of the older, rounded zircons from each formation have etched and pitted surfaces, interpreted as features of multiple recycling.

**POSSIBLE SOURCE AREAS**

It is commonly believed that the Schwanger Complex was providing sediment to the Barito Basin area during much of the Cenozoic, and the Meratus Complex provided additional sediment into the basin during the Neogene. Therefore, radiometric ages from these areas have been compiled. The Lower Cretaceous Schwanger granites range in age from 130 Ma to 100 Ma (Williams et al., 1988) and form the main pluton in the Schwanger Complex, based on K-Ar analysis of hornblende and biotite. Zircons from a smaller Upper Cretaceous pluton yield ages of 87 Ma and 80 Ma (van Hattum et al., 2006). The Pinoh Metamorphic rocks form an E-W-trending belt in the north of the Schwanger Complex. Their exact age is unknown. All that is known for certain is they are older than the Cretaceous granites that intrude them. In the Meratus Complex a Lower Cretaceous granite has a K-Ar age of 115 Ma (Heryanto et al., 1994) and most metamorphic rocks have Cretaceous K-Ar ages that range from 140 to 105 Ma (Parkinson et al., 1998). Wakita et al. (1998) reported 2 Jurassic K-Ar ages of 165 and 180 Ma from metamorphic rocks.

Palaeocurrent data suggest a southern source for the Tanjung Formation. The Karimunjawa Arch located to the SW of the Barito Basin (Fig. 1, inset) is reported to have been elevated throughout the Late Eocene to Late Miocene (Bishop, 1980; Smyth et al., 2008b) and supplying sediment into the East and West Java Basins (Smyth et al., 2008b). It contains abundant exposures of quartz-rich sandstones, metasedimentary rocks, and quartz- and mica-rich phyllites and schists (Smyth, 2008). Zircons were analysed from Karimunjawa Island situated in the centre of the arch. A total of 186 concordant U-Pb ages were obtained (Fig. 9, top). These range from Proterozoic to Triassic. The dominant populations are Permo-Triassic (294.9±10.6 Ma to 218.5±5.4 Ma), Carboniferous-Devonian (401.8±9.3 Ma to 317.3±10.2 Ma) and Proterozoic (2439.7±14.8 Ma to 852.1±24.3 Ma). There is also a small population of Silurian and rare Ordovician ages.

**DISCUSSION**

The Barito Basin overlies basement rocks of distinctly different character. To the west is the Schwanger Complex, comprising plutonic, volcanic and metamorphic rocks that represent part of the pre-Cretaceous continental basement of Sundaland. To the east is the Meratus Complex. It records suturing along the Sundaland margin in the mid Cretaceous, but its subsequent history is poorly known due to limited exposures, most of which are located within the Meratus Mountains. The complex comprises Jurassic and Cretaceous metamorphic rocks, Cretaceous granitic, ophiolitic and arc rocks (Sikumbang, 1986; Wakita et al., 1998). Upper Cretaceous and Paleocene volcanic rocks and coarse-grained clastic sedimentary rocks of the
Manunggul Formation (Sikumbang, 1986) are also considered here as part of the basement.

The Tanjung Formation overlies these basement rocks unconformably. The oldest rocks above the unconformity are conglomerates and sandstones with palynomorph-bearing mudstone interbeds of the Mangkook Member. The mudstones are late Middle Eocene age. The member records the erosion and infilling of irregular basement topography and was deposited by debris flows and braided rivers. These are overlain by sandstones, siltstones, mudstones and coals (Tambak Member) deposited across a wide intertidal floodplain constructed by rivers flowing towards the north along the present western flank of the Meratus Complex. The floodplain extended from the Schwane Complex in the west, to the Petronoster Platform in the east, and from the area now submerged under the Java Sea to the northern margin of the present Barito Basin. Overlying the Tambak Member are fine grained sedimentary rocks of the Pagat Member, deposited in a marginal to shallow marine setting until the late Early Oligocene. Subsurface data and surface mapping show the Tanjung Formation thins to the west, east and south, with the greatest thicknesses north of Tanjung (Siregar & Sunaryo, 1980). These observations suggest a N-S orientation for the axis of a wide Eocene depocentre, with the thickest part of the sequence approximately in the position of the present-day Meratus Mountains. This configuration suggests that sediment could have been derived from the east, west or south.

An eastern source (SW Sulawesi) would have provided texturally immature sediment, rich in volcanic material. This is not supported by our data. In addition, there was mid-Eocene extension between the Petronoster Platform and SW Sulawesi, and by the Early Oligocene, much of the area, deposited to the east of the basin was below sea level and the site of carbonate deposition. A western source (Schwaner Complex) as previously suggested (e.g. Hamilton, 1979) would have supplied texturally immature, quartz-rich sediment with a significant plutonic component, and zircons of dominantly Cretaceous age. These characteristics are observed in all sandstones of the Tanjung Formation. However, a Schwaner source does not explain the zircons older than Cretaceous. Older zircons may have been derived from the Pino Metamorphic Group (in the Schwane Complex). However, this seems unlikely as the rocks are typically zircon-poor, and their position is inconsistent with palaeocurrent data. Extensive outcrops of Permo-Triassic granites are present in the Thai-Malay Peninsula, but transport from these distant areas would require a complicated and long drainage pattern in conflict with previous provenance studies (e.g. Clements, 2008). A plausible southern source area is the Karimunjawa Arch and basement areas beneath the East Java Sea. Hall et al. (2009) and Granath et al. (2011) suggest this region is underlain by Australian basement, over lain by a thick Permo-Triassic sequence. This could have produced the quartz and metamorphic debris observed in the sandstones, and would also account for the zircons of Permo-Triassic and older age. Furthermore, only a simple and relatively short (<300 km) drainage pattern would be needed to transport sediment northeast from the Karimunjawa Arch into the Barito Basin area where flow was then directed towards the north (Fig. 10). We suggest both the Schwane Complex and the Karimunjawa Arch were supplying sediment to the Barito area from the late Middle Eocene to late Early Oligocene.

During Late Oligocene to Early Miocene, extensive shallow water platform carbonates were deposited across much of the Barito Basin area, and deep water sediments were being deposited to the north, in the southern part of the Kutai Basin (Moss & Chambers, 1999). Across the northern margin of the Barito area, a large braid delta formed (Kiwa Member, Montalat Formation) in which deposition continued into the Early Miocene. Based on this palaeogeography, the sandstones of the Kiwa Member were likely sourced from the Schwane Complex and/or uplifted sedimentary successions of northwest Borneo (e.g. Rajang-Crocker Group). These would have produced a mixture of texturally immature and mature fragments, quartz and lithic-rich, including radiolaria-bearing chert and plutonic and metamorphic debris. The sandstone compositions and textural features suggest the Schwane Complex was the dominant source, which would also account for the large number of Cretaceous zircons. It is unlikely that significant numbers of zircons of older age were derived from the Pino Metamorphic Group as these rocks typically lack zircons. Alternatively, the small number of older grains reflects a less important source to the northwest. Palaeocurrent measurements conflict with this interpretation, but were collected from a relatively small area (<6 km²) and may record local flow.

By the Early Miocene, deposition of the Warukin Formation had begun, signifying the onset of a regression, probably driven by regional tectonic changes (e.g. Hutchison et al., 2000; Hall, 2002). Carbonate deposition was replaced by fluvio-deltaic
sedimentation. The Schwaner Complex and Karimunjawa Arch were emergent to the west and south respectively, and marine conditions existed to the east. This palaeogeography suggests sediment could have been transported from the northwest, west or south. A northwestern source would be expected to supply texturally mature quartz- and lithic-rich material and radiolaria-bearing chert fragments. Material of this character is present within the Warukin sandstones, and the age spectra of zircons are very similar to those of north Borneo (Fig. 9, bottom). The abundance of first cycle plutonic and volcanic quartz and a prominent Cretaceous zircon population strongly suggests Schwaner derivation, and is supported by palaeocurrent data. Sediment derived from the Karimunjawa Arch may be represented by schistose lithic fragments and polycrystalline quartz, but this could also have a Pinoh Metamorphic origin. There is no evidence that the Meratus Complex was emergent at this time.

By the Late Miocene, the upper part of the Tapin Member was being deposited in a brackish, fluvial environment. Emergent areas included the Rajang-Crocker Group, Schwaner Complex, and possibly the Meratus Complex and Karimunjawa Arch. The sandstones of the Tapin Member contain many features suggesting a Schwaner Complex and Rajang-Crocker Group provenance. These include their compositions, mixed textural maturities and zircon ages. If uplift of the Meratus Complex had begun, debris of Meratus basement rocks and Tanjung Formation would be expected in the sandstones. However, material of Meratus character is absent, and despite the abundance of recycled material, differentiating between recycled Rajang-Crocker Group and recycled Tanjung Formation material is difficult. Uplift of the Meratus Complex could explain the change to west-directed palaeocurrents at the top of the Tapin Member, and the absence of Meratus debris may be due to fact that the Meratus basement rocks were not yet exposed. We suggest that the sandstones of the Warukin Formation were mainly derived from the Schwaner Complex and to a lesser extent the Rajang-Crocker Group. Towards the top of the formation, it is probable that material was also sourced from the Tanjung Formation as a result of Meratus uplift. Palaeocurrent data suggest uplift may have begun in the Late Miocene.

CONCLUSIONS

From this study, the following conclusions have been made:

- The oldest sedimentary rocks of the Barito Basin are late Middle Eocene. This is considerably younger than some previous estimates (e.g. Campbell & Ardhana, 1988; Kusuma & Darin, 1989; Bon et al., 1996).
- The sandstones of the Tanjung Formation were probably derived mainly from the Schwaner Complex in the east, and the Karimunjawa Arch in the southwest.
- During the Late Oligocene, an extensive braid delta formed across the northern margin of the Barito Basin area, probably fed by material shed from the Schwaner Complex in the west and the Rajang-Crocker Group in the northwest.
- By the Early Miocene carbonate deposition was replaced by marginal marine to fluvo-deltaic deposition, represented by the Warukin Formation. The top of the formation is assigned to Late Miocene.
- The sandstones of the Warukin Formation were mainly derived from the Schwaner Complex and to a lesser extent the Rajang-Crocker Group. Towards the top of the formation, it is probable that material was also sourced from the Tanjung Formation as a result of Meratus uplift.
- Palaeocurrent data suggest uplift of the Meratus Complex may have begun in the Late Miocene.

ACKNOWLEDGEMENTS

We thank the following people for their assistance and contribution to this study: B. Sapiie from the Institut Teknologi Banding for his support and help in organising fieldwork; A. Rudyawan and Y. Sindhu for their valued assistance in the field; for discussions concerning the geology and evolution of Borneo and the Barito Basin we are grateful to J. Howes, D. Le Heron, G. Nichols, M. Cottam, I. Watkinson, J.T. Van Gorsel, I. Sevastjanova, B. Clements, Y. Kusnandar, S. Pollis and E. Deman. This research was funded by the SEARG.

REFERENCES


Morley, R.J., 1978, Palynology of Tertiary and Quaternary sediments in Southeast Asia, Indonesian


Figure 1 – Cenozoic geology of the Barito and Asem-Asem Basins (after Supriatna et al. (1994)).
Figure 2 – Generalised stratigraphy of the Barito Basin. Age diagnostic fauna and flora from this study are shown. East Indian (EI) Letter Stages correlated with planktonic zones by BouDagher-Fadel (2008). Numerical ages from GTS2004 (Gradstein et al., 2004).

Figure 3 – Ternary diagrams showing detrital modes of sandstones from the Tanjung, Montalat and Warukin Formations. (Left) Sandstone classification according to Folk (1968). (Right) Tectonic setting according to QmFLt ternary plot of Dickinson & Suczek (1979). Q: quartz, Qm: monocrystalline quartz, F: feldspar, L: lithics, Lt: total lithics (including polycrystalline quartz).
Figure 4 – Palaeocurrent data for the Tambak Member of the Tanjung Formation. Individual locations with fluvial data are shown on map. Total fluvial data are shown at top left. In addition, palaeocurrent data collected from small-scale ripples within tidal facies are shown in blue, centre left. Bin size is 10° on all plots.
Figure 5 – Palaeocurrent data for the Kiwa Member of the Montalat Formation. Total fluvial data is shown top left. Bin size is $10^\circ$ on all plots.
Figure 6 – Palaeocurrent data for Warukin Formation. Total fluvial data for the Barabai Member are shown bottom left. Total fluvial data for the lower part of the Tapin Member are shown centre left. Total fluvial data for the top of the Tapin Member are shown top left. Bin size is 10° on all plots.
Figure 7 – U-Pb ages of zircons analysed from sandstones of the Tanjung, Montalat and Warukin Formations.

Figure 8 – Examples of zircon morphologies present in the samples analysed. (A) euhedral, elongate, (B, C) euhedral, non-elongate, (D) rounded, non-elongate. Scale bar is 100µ in all images.
Figure 9 – (Top) U-Pb ages of zircons from Karimunjawa Arch samples. (Bottom) U-Pb ages of zircons from sandstones of the Rajang-Crocker Groups, northern Borneo (after van Hattum, 2005).
Figure 10 – Map showing suggested flow into the Barito Basin area during the Late Eocene based on data of this study. Flow into west Java from the Schwaner Complex, reported by Clements (2008) is also shown.