Unravelling the stratigraphy and sedimentation history of the of Uppermost Cretaceous to Eocene sediments of the Kuching Zone in West Sarawak (Malaysia), Borneo

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Abstract

1. Introduction

Thick, predominantly Cenozoic, terrestrial sedimentary successions in West Sarawak and NW Kalimantan are exposed in the Kuching Zone (Haile, 1974) of Borneo where they form large basins. The Kuching Zone is bounded by the Lupar Line to the north, which separates it from the Sibu Zone (Haile, 1974). In contrast to the terrestrial sediments of the Kuching Zone, the Sibu Zone consists of deep marine sediments of the Belaga Formation which is part of the Rajang Group (Liechti et al., 1960; Pieters et al., 1987; Tate, 1991; Hutchison, 1996). To the south the Kuching Zone is bounded by the Schwaner Mountains which are dominated by Cretaceous igneous and metamorphic rocks (Haile et al., 1977; van Hattum et al., 2013; Davies et al., 2014; Hennig et al., 2017).

In the western part of the Kuching Zone, terrestrial sediments of the Kayan Sandstone (Tan, 1981; Heng, 1992; Morley, 1998) form several isolated outliers or sub-basins that were informally termed the Kayan 'Basin' by Doutch (1992) and extend into NW Kalimantan (Fig. 1). In the eastern part of West Sarawak, terrestrial sediments are exposed in the Ketungau Basin (Haile, 1957; Tan, 1979; Pieters et al., 1987). The Ketungau Basin extends from West Sarawak into Kalimantan and is separated by the Semitau Ridge from the Melawi Basin (Pieters et al., 1987; Doutch, 1992), which is the largest of the Cenozoic sedimentary basins of the Kuching Zone (Fig. 1). The Mandai Basin further east was suggested to be the eastern continuation of the Ketungau Basin (Doutch, 1992) and together with the West Kutai Basin form the eastern limit of the Kuching Zone.

The terrestrial sediments in West Sarawak south of the Lupar Line have been little studied and their ages and stratigraphy remain unclear. The few descriptions of rocks and field relations report fluvial to marginal marine facies (Liechti et al., 1960; Wolfenden & Haile, 1963; Wilford & Kho, 1965; Muller, 1968; Tan, 1979; Tan, 1993). The absence of fossils in most formations has hampered determination of stratigraphic relations. There is little knowledge of potential source regions. This study presents new field observations of successions of the Kayan Sandstone and the Ketungau Basin in West Sarawak. We present a revised stratigraphy based on field relations, lithological observations and facies discussed in this paper, supported by studies of detrital heavy minerals including zircons, and work by Breitfeld et al. (2014) and Breitfeld (2015), which provide new insights into ages, environment of deposition and sediment sources.

2. Kuching Supergroup – history and correlation of the Kayan and Ketungau Basins

All clastic terrestrial sedimentary successions of uppermost Cretaceous to Late Eocene age that form the large basins in the Kuching Zone are assigned here to a new Kuching Supergroup. In West Sarawak the Kuching Supergroup includes sedimentary rocks of the Kayan 'Basin' and Ketungau

Basin which are renamed here the Kayan Group and the Ketungau Group. Fig. 2 shows the distribution of these rocks south of the Lupar Line in West Sarawak.

These sedimentary rocks unconformably overlie a heterogeneous basement in the region of West Kalimantan and West Sarawak which Williams et al. (1988) named the NW Kalimantan domain and Hennig et al. (2017) termed West Borneo. The basement in this region includes sedimentary, metamorphic and igneous rocks with ages from Late Carboniferous to Late Cretaceous (e.g. Liechti et al., 1960; JICA, 1985; Tate, 1991; Rusmana et al., 1993; Hutchison, 2005; Breitfeld et al., 2017). Triassic to Cretaceous (older than c. 85 Ma) rocks, including the Cretaceous Lubok Antu Melange/Kapuas Complex and the Boyan Melange (Tan, 1979; Williams et al., 1986, 1988; Pieters et al., 1993) have been interpreted as representing an accretionary setting (Hutchison, 2005) formed at a Mesozoic Paleo-Pacific subduction margin (Breitfeld et al., 2017; Hennig et al., 2017).

2.1. Kayan Group

The sediments assigned here to the Kayan Group were originally all mapped as, or included in, the Plateau Sandstone of the Klingkang Range (Liechti et al., 1960; Wolfenden & Haile, 1963; Wilford & Kho, 1965). Later, Haile (1968) introduced the term Kayan Sandstone for the sedimentary rocks exposed in the Kayan Syncline, at Gunung Serapi, at Gunung Santubong and in the northern Pueh area in order to distinguish them from the Plateau Sandstone which he considered to be younger. Haile (1968) also separated sedimentary rocks of the Bungo Range and Gunung Penrissen and named them Penrissen Sandstone. Tan (1981) subsequently abandoned the term Penrissen Sandstone and included it in the Kayan Sandstone. Fig. 3 shows the different early stratigraphic terms.

Muller (1968) proposed three zones for the Plateau Sandstone in West Sarawak (later renamed to Kayan Sandstone) based on palynomorphs and Morley (1998) later revised the ages of these zones.

Zone D – The *Rugubivesiculites* zone is the oldest part of the Kayan Sandstone and is exposed in the northern Pueh area, Lundu area (west of the Kayan Valley) and in the southeastern Bungo Range. Morley (1998) suggested a Late Maastrichtian to Paleocene age.

Zone E – The *Proxapertites* zone is exposed in the Pueh area and in the Kayan Syncline where it is the upper part of the Kayan Sandstone, and at the Bungo Range where it is overlain by Zone F. The age was reinterpreted by Morley (1998) to be probably Early Paleocene to Late Paleocene.

Zone F – The *Retitriporites variabilis* zone is the youngest part of the Kayan Sandstone. It is exposed only in the central parts of the Bungo Range at Gunung Penrissen. An Early Eocene age was given by Morley (1998).

In this study we introduce the term Kayan Group for all the sedimentary rocks in the western part of the research area, and which include the Kayan Sandstone (restricted to palynology zones D and E) and the Penrissen Sandstone (palynology zone F). Fig. 3 summarises the stratigraphic terms used previously, the palynological zones, and the proposed revised stratigraphy of this study.

2.2. Ketungau Group (Ketungau Basin)

The Ketungau Group is the name proposed here for the sedimentary rocks of the Ketungau Basin which crosses the border from Sarawak to Kalimantan and for sedimentary rocks close to, and north of, the Klingkang Range.

The oldest sedimentary rocks of the Ketungau Basin (Fig. 4) were originally termed Kantu Beds in Kalimantan and West Sarawak by Zeijlmans van Emmichoven and ter Bruggen (1935) and Zeijlmans van Emmichoven (1939). In Kalimantan the term Kantu Formation is now used (e.g. Pieters et al., 1987; Doutch, 1992; Heryanto and Jones, 1996). This is overlain by the Tutoop Sandstone which has its type locality in Kalimantan at Gunung Tutoop (Williams and Heryanto, 1985; Heryanto and Jones, 1996) where it is widely distributed. The youngest unit in Kalimantan is the Ketungau Formation (Pieters et al., 1987; Heryanto and Jones, 1996), which does not extend into West Sarawak. Williams and Heryanto (1985) and Heryanto and Jones (1996) used the term Merakai Group for the sediments of the Ketungau Basin in Kalimantan.

In Sarawak the term Silantek Beds was used for the oldest sedimentary rocks in the Sadong Valley (Haile, 1954), but those in the Undup Valley were named Kantu Beds (Haile, 1957). Haile (1957) recognised a number of sandstone and shale ‘zones’ in the Kantu Beds. Tan (1979) redefined the sandstone zones of Haile (1957) as the Basal Sandstone Member and Temudok Member and the Upper Kantu Beds shale as the Redbed Member (Fig. 4). Liechti et al. (1960) renamed the Silantek and Kantu Beds of Haile (1954, 1957) as the Silantek Formation. The Silantek Formation is overlain by the Plateau Sandstone which is the equivalent of the Tutoop Sandstone of Kalimantan.

The sediments of the Ketungau Basin in West Sarawak are underlain by, or in faulted contact with, the calcareous Lower Eocene Engkilili Formation in the westernmost part of the Lupar Valley (Haile, 1996), at Tanjung Bako they are unconformably above the Sejingkat Formation (Tan, 1993) and they are in faulted contact with the Lubok Antu Melange/Kapuas Complex in the Lupar Valley (Tan, 1979; Pieters et al., 1993).

In Sarawak Haile (1957) and Tan (1979) described Middle to Upper Eocene foraminifera from the lowermost part of the Silantek Formation, although these are mostly referred to as Upper Eocene in the literature (e.g. Pieters et al., 1987; Doutch, 1992, Heryanto and Jones, 1996). Tan (1979) interpreted for one sample an age of Lutetian to early Priabonian. Table 1 displays the foraminifera assemblages reported by Haile (1957) and Tan (1979). Most of the foraminifera are long-ranging and not age indicative, but the assemblages 1, 5 and 7 suggest a Middle Eocene (Lutetian, Bartonian) age after BouDagher-Fadel (2013). Nannofossils (nanno-plankton) reported by Tan (1979) include *Coccolithus* sp., *Pemma* sp. and *Prinsiacea* sp., which indicate a Middle Eocene (Lutetian) age (Klumpp, 1953; Perch-Nielsen, 1985; Young and Bown, 1997; Bown, 2005; Young et al., 2014). Those new age interpretations suggest that the lowermost part of the Silantek Formation was deposited in the Middle Eocene (Lutetian).

A Late Eocene age was assumed for the Plateau Sandstone of Haile (1954, 1957) by Liechti et al. (1960) and for the Tutoop Sandstone (Pieters et al., 1987). Doutch (1992) suggested an Early Oligocene age. An extension into the Miocene was suggested by Tan (1979, 1981 and 1993). However, no age data is available for the succession. A conformable contact with the underlying Silantek Formation was reported by Haile (1957) and Tan (1979), which suggests that the formation could be of Middle to Late Eocene age.

Table 2 displays the previous subdivisions introduced for the western part of the Klingkang Range (Haile, 1954) and for the eastern part (Haile, 1957; Tan, 1979) that consists of the Silantek Formation and the Plateau Sandstone.

It is proposed to modify the established stratigraphy to incorporate new findings made in this paper and by Breitfeld (2015) to group the sediments of the Ketungau Basin under the term Ketungau Group. These consist of the established Silantek Formation and Tutoop Sandstone (Plateau Sandstone) as well as the newly termed Ngili Sandstone and Bako-Mintu Sandstone, which were previously included in the established units. The Upper Silantek Redbed Member/Upper Kantu Beds/Upper Silantek Beds is considered to be part of the Tutoop Sandstone. It is also proposed to use the Kalimantan term Tutoop Sandstone instead of the West Sarawak term Plateau Sandstone, because of the common use and misuse of the term Plateau Sandstone for various different formations in Sarawak at different times (see e.g. ter Bruggen, 1935; Zeijlmanns van Emmichoven, 1939; Milroy, 1953; Haile, 1954, 1957, Liechti et al., 1960; Tan, 1993; Hutchison, 2005). Fig. 4 shows the correlation of the different terms used in Kalimantan and West Sarawak and their interpreted ages.

3. Kuching Supergroup – new stratigraphy and field relations

Fig. 5 summarises the new stratigraphy for the uppermost Cretaceous to Eocene sedimentary rocks in West Sarawak shown in Fig. 2.

3.1. Pedawan Unconformity

The term Pedawan Unconformity is introduced in this paper for the major angular unconformity that separates the Upper Cretaceous turbidites of the Pedawan Formation from the uppermost Cretaceous to Paleocene Kayan Sandstone.

The unconformity can be seen in the western and northwestern part of the Kayan syncline (Fig. 6a and b), at the southern tip of Tanjung Santubong (Fig. 6c) and in the Sungai Chupin area (Fig. 6d). The Kayan Sandstone usually overlies the Pedawan Formation with a conglomerate at the base (Fig. 6e and f), marking a major change from deep marine to terrestrial sedimentation in the Kuching Zone in the Late Cretaceous.

Muller (1968) and Morley (1998) described Santonian palynomorphs from the youngest section of the Pedawan Formation (Fig. 3) and Breitfeld et al. (2017) reported Turonian foraminifera and zircon ages of 86 to 88.5 Ma (Santonian to Coniacian) from the Pedawan Formation. The oldest sections of the Kayan Sandstone contain palynomorphs of Late Maastrichtian to Paleocene age (Morley, 1998), indicating a hiatus of c. 15 Ma (Fig. 3).

3.2. Kayan Group

3.2.1. Kayan Sandstone

The Kayan Sandstone forms the lower part of the Kayan Group. It comprises sedimentary rocks in the Kayan Syncline, at Gunung Serapi, at Tanjung Santubong, in the Pueh area and the lower sandstones of the Bungo Range. It includes the *Rugubivesiculites* and *Proxapertites* zones of Muller (1968) and is therefore of Late Maastrichtian to Late Paleocene age (Morley, 1998). Based on differences in lithology and environment of deposition, the Kayan Sandstone shows slight variations which are described below from different locations. It is not possible to subdivide the Kayan Sandstone into members as outcrops are isolated, and it is not possible to correlate between them. They could represent different stratigraphic levels.

Kayan Sandstone within the Kayan Syncline

The lower contact with the Pedawan Formation is an angular unconformity which can be seen in both the westernmost part of the synclinal basin and in the Sungai Chupin area. The Kayan Sandstone is composed of pebbly sandstones, thin conglomerate layers, sandstone, siltstone, reddish and greyish mudstone and coals. The most complete sections were observed at the 'Buffer Wall' road (Fig. 7a) and around Bukit Snibong. A total thickness of approximately 350 m is exposed in the Kayan Syncline. An erosional surface marks the top of the Kayan Sandstone in the Kayan syncline.

Kayan Sandstone of Gunung Serapi

The contact of the Kayan Sandstone with the underlying Pedawan Formation is either faulted or unconformable. West of Gunung Serapi the Serapi massif is separated by a N-S trending fault zone from the Kayan Syncline (Fig. 2). Gunung Singai is the southern continuation of the Serapi range from which it is separated by a NE-SW trending fault (Fig. 2 and Fig. 7b).

The Kayan Sandstone at Gunung Serapi is composed of thick sandstones interbedded with thin carbonaceous dark mudstone layers, thin conglomerates and alternations of sandstone and mudstone. Large scale trough cross-bedding is often observed within the sandstone beds. The thickness at Gunung Serapi is about 900 m and the top is an erosional surface.

Kayan Sandstone of the Bungo Range

In the Bungo area the Kayan Sandstone forms the spectacular Bungo Range ridge and the lowermost part of the Bungo Syncline. The contact of the Kayan Sandstone with the Pedawan Formation is either an angular unconformity or faulted. The Kayan Sandstone is approximately 800 m thick and composed predominantly of conglomerate, pebbly sandstone, and sandstone which is often cross-bedded, minor siltstone, dark to purple coloured mudstone, volcaniclastic sandstone and tuffaceous mudstone. It is overlain by the Penrissen Sandstone in the Bungo Syncline. The contact was not observed.

Kayan Sandstone in the Pueh area

In the Pueh area the Kayan Sandstone unconformably overlies the Serabang Formation and non-conformably the Pueh batholith (Wolfenden and Haile, 1963; Rusmana et al., 1993). About 50 m of Kayan Sandstone are exposed. The succession is composed mainly of medium grained sandstone, cross-bedded sandstone and dark coloured mudstone intercalations. Thin coal layers and abundant plant fragments are common. The lithologies are similar to the lower parts of the Kayan Sandstone in the Gunung Serapi area or the Kayan Syncline. The top of the Kayan Sandstone is marked by an erosional surface. In places, there is an undated conglomerate unconformably above this surface which may be Neogene to Quaternary.

Kayan Sandstone at Tanjung Santubong

The Pedawan Unconformity is exposed in the southern part of the Santubong peninsula. The Kayan Sandstone at Tanjung Santubong is about 800 m thick and forms Gunung Santubong (Fig. 7c). Above the unconformity the sediments are mainly composed of cross-bedded sandstone, pebbly sandstone, conglomerates and thin intercalated mud layers. Lithologies resemble those in the Kayan

Syncline and at Gunung Serapi. The sediments are intruded by various sills, possible of Neogene age. The top is marked by an erosional surface.

Hornfels at Tanjung Santubong

The northern tip of Tanjung Santubong is separated by a NW-SE trending fault from the rest of Santubong. It is composed of thinly bedded reddish mudstone interbedded with thin hornfelsed sandstone (Fig. 7d) and thicker hornfelsed sandstone packages. These lithologies have been intruded by a granitic sill, which baked the sediment into hornfels. It is uncertain to which formation the hornfels belongs. Thin mudstone-sandstone intercalations are typical of the Bako-Mintu Sandstone or the Silantek Formation (see below), but similar intercalations were also observed locally in the Kayan Sandstone.

3.2.2. Penrissen Sandstone

The Penrissen Sandstone is exposed in the Bungo mountain range in the centre of the Bungo syncline around Gunung Penrissen at the border with Kalimantan. The lower part of the Bungo syncline is assigned to the Kayan Sandstone as explained above. The upper part is assigned to the Penrissen Sandstone (modified from Haile, 1968).

At Gunung Penrissen about 1200 m of Penrissen Sandstone is exposed. Differences in age, lithology, facies and composition (Wilford, 1965; Muller, 1968; Morley, 1998; Breitfeld, 2015; this study) are the basis for separating it from the underlying Kayan Sandstone. The Penrissen Sandstone is composed mainly of conglomerate, pebbly sandstone and thickly bedded sandstone often with a reddish colour. Intercalations of mudstone and siltstone were observed.

No contacts of the Penrissen Sandstone could be observed in the field but at the centre of the Bungo syncline where it overlies the Kayan Sandstone there is a difference in dips suggesting an unconformity. The Kayan Sandstone dips gently to moderately south to southeast, whereas the Penrissen Sandstone is horizontal. However, this could also be explained by the synclinal structure of the Bungo-Penrissen area. The top is marked by an erosional surface and it is possible that the total thickness exceeds 2000 m.

The Penrissen Sandstone correlates with the *Retitriporites variabilis* zone of Muller (1968) and is therefore interpreted to be of Early Eocene age (Morley, 1998). The Penrissen Sandstone forms the upper unit of the Kayan Group.

3.3. Ketungau Group

3.3.1. Ngili Sandstone

The Ngili Sandstone marks the lowermost unit of the Ketungau Group. It is exposed along a fault strand with a similar direction as the Lupar Line (Fig. 2) and forms the lower part of the Gunung Ngili range (Fig. 7e). Previously it was mapped as Silantek Formation (Haile, 1954; Heng, 1992). However, the sediments differ lithologically and compositionally from the Silantek Formation. It is uncertain what underlies the Ngili Sandstone. A road section south of Gunung Ngili exposes deeply weathered almost vertically-dipping shale-silt alternations, which could represent the Cretaceous Pedawan Formation or even older Mesozoic sediments (Liechti et al., 1960; Wilford & Kho, 1965; Heng, 1992).

The Ngili Sandstone is composed of carbonaceous mudstone interbedded with fine sandstone, siltstone, coarse-grained sandstone and conglomerate. Occasionally, thin coal seams are present. The coarser sandstone and conglomerate is characterised by abundant volcanic lithic fragments and white rip-up mud clasts. About 100 m of the Ngili Sandstone are exposed, but it could exceed this thickness as the lower contact is not exposed. The Ngili Sandstone is conformably overlain by the Bako-Mintu Sandstone which marks the top of the Gunung Ngili mountain range. So far no age data is available for the Ngili Sandstone, but it is assumed in this study that the Ngili Sandstone is of Middle Eocene age.

3.3.2. Silantek Formation

Based on the subdivisions of Haile (1957) and Tan (1979) and new observations, we propose a modified subdivision. The overall mud-dominated exposures of the Silantek Formation (Lower and Upper Shale zone of Haile, 1957) are referred as Shale Member in this study. Additionally, there are two thick sand-dominated successions that are described as the Marup Sandstone Member (corresponds to the Basal Sandstone of Haile, 1957; Tan, 1979) and the Temudok Sandstone Member (similar to Haile, 1957; and Tan, 1979). The Upper Silantek/Kantu Redbed unit is excluded from the Silantek Formation and is considered to be part of the Tutoop Sandstone as discussed later. This was already suggested by Tan (1979) but the established classification was still retained. A total thickness of approximately 2600 to 3000 m for the Silantek Formation is assumed by this study, while the maximum estimate by Haile (1957) was 6400 m. It is notable that fault strands similar to the Lupar Line cross-cut the Silantek Formation throughout, indicating that the fault trend is actually younger than the deposition of the Silantek Formation.

Marup Sandstone Member

The Marup Sandstone Member forms the lowermost part of the Silantek Formation. It is exposed at the eponymous Marup Ridge, the northern boundary of the Ketungau Basin. The Marup Sandstone Member may be correlative with the Haloq Sandstone of the Mandai Basin (Pieters et al., 1987) and with the Bako-Mintu Sandstone (see above).

Close to the Lupar Line the succession is steeply dipping to vertical (Fig. 7f) where it overlies the Lubok Antu Melange with an angular unconformity or faulted contact. The contact to the underlying Engkilili Formation is poorly studied and is suggested to be either faulted or conformable (Haile, 1996). Other interpretations (e.g. Tan, 1979) assumed a faulted contact.

The Marup Sandstone Member is mainly a quartzose to slightly polymict medium grained sandstone interbedded with thin layers of mudstone and siltstone. The lowermost part is composed of conglomerate and pebbly sandstone. Bioturbation is frequently observed. Field evidence indicates a thickness of approximately 800 m which is only half of the previously estimated maximum of 1600 m by Tan (1979). The Marup Sandstone Member grades into the Shale Member.

Temudok Sandstone Member

The Temudok Sandstone forms the Temudok Ridge south of Sri Aman. Towards the west the ridge disappears and towards the east the ridge becomes thinner and probably continues south of the Marup Ridge, where the Silantek Formation is intruded by Miocene acid volcanics (Sintang Suite) and therefore cannot be traced further. No ages have previously been reported, but the member is stratigraphically slightly higher than the Marup Sandstone Member.

The Temudok Sandstone comprises sequences of thick sandstone beds interbedded with organic-rich shale-siltstone alternations (Fig. 7g). The exposures can be strongly indurated. Weathered outcrops are yellowish while fresher exposures tend to be reddish to white. In close proximity to the Temudok Ridge there are several intrusions shown on the survey map (Heng, 1992) which could account for the indurated character. The intrusions were not observed during this study. The sandstone member forms a lenticular sand-dominated body of approximately 130 m thickness within the Silantek Formation surrounded by the Shale Member.

Shale Member

The Shale Member is conformably above the Marup Sandstone Member. It is composed of rare conglomerate, sandstone, siltstone, carbonaceous mudstone, shale and commonly siltstone-mudstone intercalations with thin layers of fine sandstone. The mudstone is commonly carbonaceous and fine coal seams occur within. These are often mined in small open pit mines. Field observations suggest a total thickness of the Shale Member of possible 1000 to 2000 m. It extends to the Klingkang Range, where it is conformably overlain by the Tutoop Sandstone.

3.3.1. Bako-Mintu Sandstone

The Bako-Mintu Sandstone is a new term introduced in this study for the sedimentary succession at Tanjung Bako, on top of Gunung Ngili and in the headwater area of the Sebuyau and Sebangan rivers near Gunung Menuku (Mintu area) (Fig. 2). Previously the succession was mapped as Tutoop (Plateau) Sandstone by e.g. Haile (1957), Liechti et al. (1960), Wilford (1965), Heng (1992) and Tan (1993). However, no ages were reported and its correlation to/or mapping as Tutoop Sandstone was based on lithology and assumed ages (Tan, 1979; Tan, 1993). Johannson (1999) proposed to discuss the sandstones at Bako separately from the Tutoop Sandstone as it is potentially related to another sub-basin system, and introduced the name Bako Sandstone. This study follows the suggestion by Johannson (1999) and adds similar sediments on top of the Gunung Ngili range and in the Mintu area into the Bako-Mintu Sandstone.

However, the stratigraphic position of the formation is uncertain. The Bako-Mintu Sandstone unconformably overlies the Sejingkat Formation (Mesozoic melange) at Telok Wangkong at Tanjung Bako (Tan, 1993). Breitfeld et al. (2017) suggested the Sejingkat Formation could resemble similar lithologies as the Lubok Antu Melange and grouped them with various other formations into a Mesozoic accretionary complex. Thus, the Bako-Mintu Sandstone could be a lateral equivalent of the Marup Sandstone, which overlies the Lubok Antu Melange in the Lupar valley. At Gunung Ngili it overlies conformably the Ngili Sandstone, and in the Mintu area no contacts were observed.

The sequence comprises quartz-rich sandstones which are usually cross-bedded, dark mudstone interbeds, mud clast conglomerates, pebbly sandstone to conglomerate and mud-siltstone-sandstone intercalations. Charcoal seams or charcoal debris are observed throughout the succession. At Tanjung Bako, the formation forms spectacular sea cliffs, including the 'Sea stack' (Fig. 7h). In the Mintu area the sequence is approximately 140 m thick, at Gunung Ngili about 160 m and at Tanjung Bako it is approximately 240 m. The top of the unit marks an erosional surface in all locations.

3.3.2. Tutoop Sandstone (Plateau Sandstone)

The Tutoop Sandstone forms the Klingkang Range and is the youngest unit of the Ketungau Group in West Sarawak. The successions in the Mintu area, at Gunung Ngili and at Tanjung Bako previously mapped as Plateau (Tutoop) Sandstone are discussed as Bako-Mintu Sandstone (see above). The Upper Kantu Beds/Upper Silantek Redbed which was previously assigned to the Silantek Formation (Haile, 1957; Tan, 1979) is considered here to be part of the Tutoop Sandstone.

The contact with the underlying Silantek Formation was not observed in the field but it is reported to be conformable (Haile, 1957; Tan, 1979). The Tutoop Sandstone is composed of thick-bedded sandstone, massive sandstone, minor conglomerate intercalations and mudstone. The lower part of the unit is composed of red mudstone-sandstone intercalations (Fig. 7i) (previously the Silantek Redbed Member), while the upper part is composed of thick sandstone beds. The total thickness of the Tutoop Sandstone was assumed to be 1500 m (Heryanto and Jones, 1996), while approximately 800 m thickness were observed in this study in West Sarawak. The top is marked by an erosional surface in West Sarawak. In Kalimantan it is overlain by the Ketungau Formation (Pieters et al., 1987; Heryanto and Jones, 1996).

4. Field relations and environment of deposition

4.1. Kayan Sandstone

Literature interpretation

Muller (1968) and Wilford and Kho (1965) considered the Kayan Sandstone in the Kayan Syncline, Pueh area and the Bungo Range to represent a deltaic facies.

Description

The Kayan Sandstone is formed predominantly of sandstones and heterolithics, subsidiary are conglomerates and mudstone. Conglomerates are predominantly massive, polymict and matrix-supported conglomerates. Massive conglomerates are frequently observed within the Bungo Range and rarely observed in other areas of the Kayan Sandstone. However, in the area of Sungai Chupin (western end of the Kayan Syncline) a basal conglomerate (approx. 30 cm thick) above the Pedawan Unconformity forms the lowermost part of the Kayan Sandstone (Fig. 6e and f). The colour of the lithology is grey/white to yellow/red. Bed size varies from 10 to 500 cm. This lithology exhibits poor sorting and locally normal grading. Clasts are rounded to subrounded and predominantly composed of quartz pebbles, with subordinate mud rip-up clasts, other reworked sedimentary rocks, and igneous rocks. Maximum clast size is 10 cm. The clasts are in a fine- to medium-grained sandy matrix. Matrix grains are composed of quartz, feldspar and lithic fragments. The base of the unit is erosive. Bed geometry is either sheet-like or lenticular. Fossilised tree logs and lignite blocks have been observed at the top of mudflake conglomerates. Within the Bungo Range thin horizontal pebble layers are interbedded with medium-grained sandstone. The bedding is generally crudely developed and isolated clasts floating in sandstone can occur. Most of these conglomerate bands are less than 5 cm thick and interbedded with < 10 cm sandstone layers. Especially in the Bungo Range area abundant iron-oxide veins cross-cut conglomerate and sandstone beds.

Sandstones comprise massive, trough cross-bedded and planar cross-bedded sandstones, which are commonly quartzose to polymict and medium- to coarse-grained. Sorting is good to medium and grading is normal. Trough cross-bedding is the most abundant architecture element. Several co-sets are observed within a single bed as well as single bed-sets. Plant material at the top of the cross-beds is common. Mud rip-up clasts and thin mud interbeds were frequently observed, especially along the crests of cross-beds. Tree logs and lignite blocks are found within this lithofacies. Finer sandstone beds have rootlets. Bed sizes vary from 10 cm to 5 m. The basal contacts are sharp or erosive. Bed geometry is generally lenticular. Extension cracks are usually filled with upwelling mud. Finer grained sandstones are interbedded with silt- and mud layers to form heterolithics. Thin mud layers (<1 cm) are interbedded with silt to fine-grained sandstone beds of 1 to 5 cm size and form horizontal laminations. Mud layers can contain carbonaceous material. Maximum bed thickness of the heterolithics is approximately 1 m. These fine laminations can grade into asymmetrical ripples with ripple mud tops. Upper and lower boundaries of the beds are gradational. Rippled sandstones are commonly associated with mud rip-up clast conglomerates, and planar and trough cross-bedded sandstones. Convolute bedding and sedimentary injectites composed of sandstone within heterolithics were observed. Poorly preserved *skolithos* ichnofacies in some beds is present. Sandstone beds at the Buffer Wall location have well-developed honeycomb weathering surfaces.

Mudstones are predominantly of light grey to dark grey colour. Red to rusty orange mudstone varieties are also common. Especially in the upper parts of the Bungo Range, purple coloured mudstone was observed. Mudstone lithologies are either massive or thinly laminated. Laminae are formed by thin silt layers. Beds sizes vary from 5 to 20 cm. Plant fragments, rootlets and imprints of plants are present. Coal forms very thin seams in organic-rich mudstones. Iron nodules (potentially siderite) and iron veins were observed within the lithofacies. Rarely, mudstones are composed of white to pinkish fine ash layers, which are deeply weathered into clay. Ash bed sizes are up to 50 cm and bed geometry is lenticular.

Interpretation

The lowermost part of the succession is composed of a thin polymict basal conglomerate (Fig. 6e and f), deposited by debris flows which can be interpreted as alluvial fans because of the absence of bioclasts and the very low abundance of bioturbation in the whole succession. Abundant igneous, metamorphic and intraformational sedimentary clasts indicate various sources. Reworking of the underlying Pedawan Formation is evident. Moving upwards in the Kayan Sandstone, sandstone lithologies begin to dominate and the amount of alluvial fan deposits decreases. Multiple stacked channel deposits occur, composed of massive sandstone, cross-bedded sandstone (Fig. 8a) and horizontally laminated sandstone. No fossils, rarely bioturbation and rootlets suggest a fluvial dominated environment. These channelised fluvial sandstones can be interpreted as part of a complex braided or meandering river, or a distributive fluvial system (DFS) (Weissmann et al., 2010). Mudstones can be carbonaceous and immature coal indicates standing water swamp to floodplain environment. The fluvial channels dissected this muddy, low-lying and vegetated floodplain (Fig. 8b), which was subject to regular flooding events. Very limited bioturbation in some beds suggest a potential tidal flat to deltaic environment in some parts of the succession. Few ash layers indicate contemporaneous coeval volcanic activity potentially related to pyroclastic deposits. Mudstone lithologies represent either swamp deposits or suspension depositions on the floodplain (Nichols, 2009; Miall, 2013). Red mudstone indicates oxidation processes in early phase of diagenesis as a result of exposure to atmospheric conditions (Reading, 1996) and are interpreted as potential overbank deposition. The remains of root material suggest the formation of a paleosols in a floodplain or overbank environment. Coal present in thin seams indicates limited peat accumulation in restricted swamps in a coastal floodplain. Within the Bungo Range, thick polymict conglomerates are interbedded with massive sandstones and mudstone throughout the succession (Fig. 8c).

Soft-sediment deformation, e.g. water escape structures, are common in the deposits and indicate high sedimentation rates or liquefaction as result of seismic activity. Frequent reworking of the deposits is indicated by intra-basinal (mudflake) conglomerates. A large syn-sedimentary fault was observed in the sedimentary sequence in the Matang area (Fig. 8d). The fault cross-cuts and displaces the lower section of the exposure, while the upper beds are unaffected. Instability of the underlying sediments due to water oversaturation at the time of deposition is indicated by upwelling mud (Fig. 8e) and sedimentary injectites (Fig. 8f). Honeycomb weathering at the Buffer Wall was produced by exposure of the section to wind flow in combination with salt crystallisation often observed in a coastal section (Mustoe, 1982; Rodriguez-Navarro et al., 1999). This could suggest that the Buffer Wall formed a former sea-cliff.

The Kayan Sandstone within the Bungo Range is interpreted to be composed of a more proximal fluvial system. Towards the north (e.g. Kayan Syncline) the more distal parts of the fluvial system are deposited. No fossils and restricted bioturbation in only a low number of beds indicate still a fluvial dominated environment and only minor deltaic or tidal influence.

4.2. Penrissen Sandstone

Literature interpretation

Muller (1968) regarded the sections that are discussed in this study as Penrissen Sandstone as fluvial to lacustrine, based on pollen palynomorphs.

Description

In contrast to the Kayan Sandstone, where conglomerates are only subordinate, this lithology is abundant within the Penrissen Sandstone. Sandstones and mudstones form here the subsidiary lithologies. Conglomerates are formed of massive, horizontally bedded and planar cross-bedded conglomerates. Massive conglomerates are thereby the dominant unit. They are mainly matrix-supported with poor sorting. Clast-supported conglomerates are subsidiary. Clasts are rounded to subrounded and composed of igneous lithics, quartz, shale and reworked sedimentary rocks. The maximum clast size is 5 cm. Matrix grains are composed of feldspar, quartz and lithic fragments. The bed size varies from 20 cm to 8 m with commonly erosive bases. Tops of the beds are gradational into or sharp against sandstones. Horizontally bedded conglomerates are formed by crudely developed thin, often less than 5 cm thick, horizontally aligned bands of conglomerate interbedded with medium grained sandstone layers which are usually less than 10 cm thick. Those horizontal beds can grade into isolated large clasts, up to 15 cm in size, floating within a sandstone matrix. Planar cross-bedded conglomerates were only rarely observed. The inclined conglomerate layers alternate with medium- to coarse-grained sandstone. Sorting in this lithology is medium and normal grading was observed.

Sandstones are composed of massive sandstone, planar cross-bedded sandstone and horizontally laminated sandstone. Sandstones are usually fine to medium grained. Massive sandstones are also coarse grained. Sorting is medium to good with normal grading. Grains are composed of feldspar, quartz and lithic fragments. Horizontal laminations are formed by very thin layers of dark silt or mud. Bed geometries are sheet-like elongated to lenticular. Basal contacts are sharp to erosive. Bed sizes vary from 10 cm to 1 m.

Mudstones are composed of light grey to dark grey coloured massive mudstone. Iron nodules (potentially siderite) and iron veins were observed. Bed sizes vary from 5 to 40 cm and are overlain sharp or erosive by sandstones or conglomerates. The mudstone lithology was only rarely observed in the Penrissen Sandstone.

Interpretation

The Penrissen Sandstone is predominantly composed of thick conglomerates and massive sandstones (Fig. 8g). Conglomerates are interpreted as large debris flows. In combination with the other lithologies a terrestrial setting is evident and they are interpreted as alluvial fans. Minor occurrence of clast-supported conglomerates indicates bedload deposition from stream flows (Reading, 1996). Sheet flood deposition is suggested by floating large clasts (Fig. 8h) in a sandy matrix (Laming, 1966; Nemec & Steel, 1984; Nichols, 2009). The thickness and immaturity of the conglomerates indicate a setting proximal to a mountainous region. Especially the lower part of the Penrissen Sandstone shows abundant alluvial fan deposits. Towards the upper parts of the succession the alluvial fans develop into large fluvial channels. Massive sandstones can form the base of a fluvial channel (e.g. Collinson, 1969; McCabe, 1977). Planar cross-bedded sandstone represents channel bars (e.g. Steel and Thompson, 1983; Miall, 1985). Horizontally laminated sandstones at the top of channel units were deposited either by rolling and saltation of grains along a surface in the lower flow regime or by washing out of ripples and dune bedforms in the upper flow regime (Reading, 1996; Nichols, 2009). Bar development is evident from horizontally laminated and planar cross-bedded conglomerates. The difference in observed bedforms and grain sizes could be attributed to a distributive fluvial system (DFS) (Weissmann et al., 2010) or could indicate channel migration of a braided river system (Smith, 1974; Forbes, 1983). Interbedded with channels and debris flows are mudstones, which can be interpreted as lacustrine facies.

The Penrissen Sandstone is composed of very thick alluvial fans interbedded with fluvial channels. Floodplain or lacustrine deposits are rarely preserved. The thickness of the fan conglomerates indicates a setting proximal to a mountainous region.

4.3. Ngili Sandstone

Literature interpretation

The term is introduced in this study. There have been no previous discussions or descriptions about the deposits of the Ngili Sandstones.

Description

The Ngili Sandstone is formed of thick conglomerates at the base, sandstones, abundant heterolithics and mudstones. Conglomerates are composed of massive and planar cross-bedded conglomerate. The lowermost exposed part of the Ngili Sandstone is formed by a thick basal conglomerate and thinner conglomerate beds occur throughout the succession. Conglomerates are matrix-supported polymict and intraformational. Clasts are rounded to subrounded and composed of quartz pebbles, mud rip-up clasts (white and black coloured), other reworked sedimentary rocks, metamorphic, igneous and volcanic lithics. Maximum clast size is 5 cm. Plant fragments were also observed. This lithofacies exhibits poor sorting, and normal and inverse grading. The matrix is predominantly composed of weathered clay minerals and volcanic lithic fragments. Bed size varies from 20 to 100 cm. The basal contacts are erosive. Planar cross-bedded conglomerates are formed by inclined pebble layers and fining upwards.

Sandstones are composed of massive and trough cross-bedded sandstone lithologies. Medium- to coarse-grained sandstone with medium to good sorting and normal grading are common. Grains are predominantly composed of quartz and lithic fragments. Beds sizes vary from 10 cm to 5 m. Thin layers of carbonaceous mudstone with flaser-like structures are present within thicker beds. The base of the beds is commonly erosive. Bed geometry is generally elongated to lenticular. Sheet-like depositions were also observed. Massive sandstones grade into sand-dominated heterolithics. Finer-grained sandstone deposits have abundant plant fragments and imprints of plant material on the bedding planes. Trough cross-bedded sandstones are only exposed at the top of the Ngili Sandstone sequence. Beds are less thick than the massive sandstone and rarely exceed a thickness of 50 cm. Bed geometry is lenticular and bases of the beds are commonly sharp.

Heterolithic sandstone-mudstone alternations are either formed by horizontally laminated sand-, silt- and mud layers (< 2 cm) or rippled fine grained deposits. Grains are predominantly composed of quartz and lithic fragments. Plant material was observed on the bedding planes of the mud-dominated laminae and iron stone layers are common. Small-scale ripples consist of symmetrical, asymmetrical and climbing ripples. Ripple tops are composed usually of mud and thin silt layers truncate the ripple crests. Bed thickness of the heterolithics is approximately 5 to 50 cm. Upper and lower boundaries of the beds are usually sharp. *Skolithos* ichnofacies is present in some beds.

Mudstone lithologies are composed of light grey to dark grey carbonaceous mudstones to shale with bed sizes varying from 5 to 20 cm. Abundant plant material and plant imprints are present on the bedding planes. Darker coloured shales are often interbedded with thin coal layers, which can laterally extend over several metres.

Interpretation

The lowermost exposed part of the Ngili Sandstone is formed by thick conglomerates (Fig. 9a) and thick coarse sandstones interbedded with thin mud layers (Fig. 9b). Volcanic rock clasts and volcanic lithics indicate an immature volcanic source. Deposition was probably in close proximity to a mountainous area, while quartzose sediments may suggest multiple recycling. The unsorted conglomerate was deposited by debris flows or sheet floods potentially in an alluvial fan setting. Moving upwards, smaller fluvial systems and extensive floodplain areas developed. The floodplain is characterised by high mud content and heavy vegetation, evident from plant fragments, coal seams and plant imprints. Periodically, it was subjected to flooding events as indicated by the elongated interbedded sandstones or dissected by channels. Extensive swamp areas in the floodplain formed a coal-producing environment, potentially in a coastal setting (Miall, 1985; McCabe, 1987; Miall, 2013). Iron stone layers (Fig. 9c) suggest deposition in extensive lacustrine bodies on the floodplains or in isolated channels (ox-bow lakes) (e.g. Boardman, 1989; Reading, 1996). Sets of symmetrical (wave) and asymmetrical (current) ripples in opposing directions (Fig. 9d) indicate opposing flow conditions (Boggs, 2012) and can be interpreted as tidal-influenced part of the Ngili Sandstone. Climbing ripples (Fig. 9d) record high rates of bed aggradation (Allen, 1971). No fossils were found, but some bioturbation may suggest a stressed environment potentially with brackish water influence. The uppermost part of the Ngili Sandstone was formed by large channels with internal bedforms (trough cross-beds), which indicate bar development. No fossils or bioturbation was found in the upper section which indicates a fluvial environment.

4.4. Silantek Formation

Literature interpretation

Haile (1957) suggested an estuarine environment for the lower parts of the Silantek Formation and Kanno (1978) reported brackish water molluscs, which indicate an estuarine or mangrove swamp environment from a section within the Shale Member. Tan (1979) interpreted a brackish environment with occasional freshwater input for the Silantek Formation.

Description

The Silantek Formation is dominated by sandstone and heterolithic lithologies. Subsidiaries are conglomerates and mudstone beds. Conglomerates of the Silantek Formation are composed of polymict matrix-supported massive conglomerates to pebbly sandstones. Clasts are dominated by grey to light grey mud rip-up clasts and minor quartz pebbles. Mud clasts are elongated and subrounded. Quartz clasts are commonly rounded. Maximum clast size is 2 cm. Sorting is poor to medium. Bed size is usually below 10 cm and the basal contact is erosive. Inverse grading in the lowermost parts was observed, however normal grading is more common. This lithology was only observed within the Marup Sandstone Member and its occurrence is restricted.

The sandstone lithologies are composed of medium- and coarse-grained massive sandstone, which are medium to well sorted and normal graded. This lithology is rhythmically interbedded with finer sediments. Grains are usually composed of feldspar, quartz, and lithic fragments, but quartzose sandstones are also common. Some lithic fragments are likely of volcanic origin. Bed sizes vary from 5 cm to 100 cm and the beds are laterally very extensive. Sheet-like geometries were observed for most sandstone beds, especially for sandstones of the Temudok Sandstone Member. Basal contacts are usually sharp and bed tops are gradational. However, sandstones of the Marup Sandstone Member have commonly erosive basal contacts and bioturbation is common at the Marup Ridge. Trace fossils consist of vertical or inclined tubes of *Skolithos* and potentially *Ophiomorpha*. Remnants of plants were found commonly. A typical weathering structure is onion-skin weathering of thicker sandstone beds.

Heterolithics form the most abundant lithology of the Silantek Formation. They are composed of fine- to medium-grained sandstone, siltstone and mudstone alternations. Sandstones are polymict to quartzose. Thin mud layers (<3 cm) are interbedded with silt- to fine-grained sandstone beds of 1 to 5 cm size and form horizontal laminations. Maximum bed thickness of the sand-mudstone alternations is approximately 50 cm. The bed geometry is laterally persistent to lenticular. Upper and lower contacts of the heterolithics are sharp. Iron-oxide nodules were observed within the sand- to siltstone layers. Differential compaction as a result of the nodules is present. Water escape structures and soft-sediment deformation was observed. Multiple normal faults formed as a result of the water escape structures and displace the horizontal layering. The laminae can develop small-scale ripples with organic material deposited on top of the ripple crests. Rippled beds are up to 30 cm in thickness. Asymmetrical ripples dominate in the Silantek Formation. However, symmetrical ripples are predominant within the Marup Sandstone Member. Typically, the heterolithics of the Marup Sandstone Member show also wavy bedding, lenticular bedding and flaser bedding, where isolated thin mud drapes are on top of small-scale ripples. Weathered sections of the Marup Sandstone Member heterolithics are red coloured and Liesegang rings were frequently observed.

Mudstone lithologies consist of light grey to dark grey carbonaceous mudstone with thin seams of coaly horizons. The best exposures were found in an abandoned coal mine near the small village of Pantu part of the Shale Member, but the lithofacies occurs throughout the whole Silantek Formation. Mudstone bed sizes vary from 5 to 10 cm. Abundant plant material and plant imprints as well as fossilised tree logs were found on the bedding planes. Pyrite veins, thin pyrite layers, iron nodules (potentially siderite) and iron veins are common. Coal horizons are composed of immature coal material, which extend laterally over several metres to tens of metres. Locally, the occurrence of coal is restricted to lenticular exposures or floating fragments. Bed thickness of coal horizons/seam thickness ranges from 0.5 to 20 cm. At the Marup Ridge within the Marup Sandstone Member, several vertical burrows of *Skolithos* and potentially *Ophiomorpha* are present.

Interpretation

The exposures of the Silantek Formation are composed of alternations of fine-grained sandstone, horizontal laminated fine sediments, fine-grained rippled sandstone, massive carbonaceous mudstone and coal. These lithologies are dominant in the Shale Member throughout the whole Silantek Formation and indicate extensive floodplain and swamp environments that were periodically flooded by near-by fluvial systems or influenced by tides in a deltaic setting. Coarser clastic material was observed in the Marup and Temudok Sandstone Member.

The lowermost part of the Silantek Formation is formed by the Marup Sandstone Member. The occurrence of *Skolithos* and *Ophiomorpha*-like trace fossils (Fig. 9e) indicates a sandy shore (littoral zone) to shelf (sub-littoral zone) environment (Buatois and Mángano, 2011). Symmetrical wave ripples (Fig. 9f) indicate a shallow water environment with oscillatory flow conditions (Boggs, 2012). Wavy to lenticular bedding (Fig. 9g) is produced by variations in current or wave activity, or changes in sediment supply (Nichols, 2009). It is commonly associated with a tidal environment (Nichols, 2009). Asymmetrical ripples (Fig. 9f and h) are usually formed by unidirectional flow, but could also be produced by unequal intense currents in opposite direction. Flaser bedding is commonly observed in intertidal environments such as intertidal and subtidal flats, and tidal channels (Sellwood, 1972; de Jong, 1977; Hendriks, 1986; Flores & Sykes, 1996; Chakraborty et al., 2003; Dalrymple & Choi, 2007; Truong et al., 2011). Flaser bedding results from changing current strength or wave power. Isolated mud drapes are deposited from suspension and small sand ripples are the result of rapid flow (Nichols, 2009; Tucker, 2009). Soft sediment deformation results from differences in cohesive character, water content and densities of the interbedded lithologies. These may develop from different rates of sediment accumulation and are common within tidal sedimentary environments (Klein, 1977; Põldsaar & Ainsaar, 2015). The restricted occurrence of bioturbation and beds with current ripples may indicate an estuarine environment. Thicker cross-bedded sandstone beds which show no fossils and unidirectional flow reflect fluvial-influenced deposition or fluvio-marine deposits if they are interbedded with shallow marine deposits. Volcanic lithics suggest contemporaneous volcaniclastic input into the basin. The environment of deposition for the Marup Sandstone Member is interpreted as marginal marine to subtidal.

Upwards in the formation, the Temudok Sandstone Member is predominantly composed of laterally extensive sandstone bodies which are interpreted as sheet flood deposits interbedded with finer-grained material. The member is devoid of fossils and bioturbation. Abundant plant material and fossil wood debris indicate a terrestrial influenced environment. Rippled sandstones are composed of asymmetrical ripples which are interpreted as current ripples. As there are no channels observed in this member, this lithology may reflect crevasse splay deposition on the floodplain (Boggs, 2012). Carbonaceous mudstones and coaly layers indicate floodplain deposition possible in a near-coastal environment with small swamps and mires (Miall, 2013). The Temudok Sandstone Member is interpreted to record floodplain deposition with restricted peat formation. The succession was subject of periodically flooding events which form thicker sandstone bodies.

The Silantek Formation represents a coastal deposition, potentially a tidal influenced fluvial to deltaic system (estuarine).

4.5. Bako-Mintu Sandstone

Literature interpretation

The Bako-Mintu Sandstone term is newly introduced in this study. Sections of the succession were previously described as Tutoop (Plateau) Sandstone. Tan (1993) interpreted a predominant fluvial environment for the sedimentary succession at Tanjung Bako in a braided river setting with episodic deltaic influence. A similar observation was made by Johannson (1999). In Tan (1979), a brackish water mollusc fauna is mentioned for the upper part of Gunung Ngili, which is part of the Bako-Mintu Sandstone and would indicate an at least partly marine influence.

Description

The Bako-Mintu Sandstone is predominantly composed of sandstone. Subsidiary lithologies are conglomerate and mudstone. Conglomerates were only observed at Tanjung Bako where massive and planar cross-bedded conglomerates are present. Massive conglomerates are usually matrix-supported polymict. Clasts are subrounded to rounded, and are composed predominantly of quartz, mud rip-up clasts, granitic material, chert and quartzites. Bed geometry is generally lenticular and wash-out structures were observed. The basal contacts of the beds are sharp or erosive. Generally, sorting is poor, but some beds show medium sorting with normal grading. Maximum bed size is 20 to 50 cm. Planar cross-bedded conglomerates were formed by inclined layers of mostly rounded pebbles.

Sandstones are composed of massive and trough cross-bedded sandstone lithologies and dominated by quartzose medium-grained varieties. Sorting is predominantly good to medium and grading is normal. Massive sandstones have bed thicknesses from 20 cm to 1 m. The bases of the beds are commonly erosive and the bed geometry is generally lenticular. Multiple lenticular massive sandstones can be stacked on top of each other and form channels. Trough cross-bedded sandstones form very large outcrops, exposed in prominent sea cliffs at Tanjung Bako. Trough cross-bedded sandstones have bed thicknesses from 20 cm to 5 m. Several co-sets were observed within a single bed as well as single bed-sets. Trough cross-bed tops are truncated by newer bounding surfaces. Bed geometry is elongated to lenticular and the basal contact of the beds is sharp. Convolute bedding was observed in this lithology. A typical weathering feature of the sandstones is honeycomb weathering surfaces.

Fine- to medium-grained sandstone interbedded with mud layers form heterolithics. Main sedimentary structures are small-scale ripples and horizontal laminations. Thin mud layers (<3 cm) are interbedded with silt to fine sandstone beds of 1 to 5 cm size. Maximum bed thickness of the sand-mudstone alternations is approximately 1 m. Ripples are usually asymmetrical and ripple tops are formed of mud. The basal contacts are usually sharp. Iron-oxide nodules were observed within the sand- to siltstone layers.

Mudstones are composed of grey to dark grey often carbonaceous material or coal fragments in mudstone to siltstone lithologies. Those are more frequent in the Mintu area, but occur also at Tanjung Bako. Iron nodules (potentially siderite) and iron veins are observed. Bed sizes vary from 5 to 50 cm and are laterally persistent. Plant material and plant imprints were found on the bedding planes. The occurrence of coal is restricted to thin layers or small lenticular shaped beds. Soft-sediment deformation includes fine- to medium-grained sandstone dykes which are injected into this lithofacies as a result of instability due to water oversaturation at the time of deposition.

Interpretation

The Bako-Mintu Sandstone is predominantly composed of trough cross-bedded sandstones (Fig. 10a), conglomerates, and carbonaceous mudstones. The conglomerates record coarse channel fills or linguoid bars (Miall, 1985, 2013). The sandstones indicate large-scale channels, often stacked, potentially braided channels or are part of a DFS. Multiple stacked channels (Fig. 10b) indicate channel migration and aggradation with high sedimentation rates in combination with decreasing accommodation space. Water escape structures in coarser sandstone indicate high rates of sedimentation (Nichols, 2009). Asymmetrical ripples indicate a unidirectional flow which is mainly associated with a fluvial setting (Miall, 2013). Towards the upper part of the succession, the amount of finer-grained sediments increases. Mudstones are often carbonaceous and contain thin coal seams (Fig. 10c). Abundant plant material and nodular and bedded siderite suggest deposition in extensive lacustrine environment on the floodplains or in abandoned channels (ox-bow lakes) (e.g. Boardman, 1989; Reading, 1996). Peat-forming environments are often located along deltas and shorelines, just above the marine water table (McCabe, 1987). Thicker beds of this lithofacies may record extensive swamps and mires close to the coastline, while thinner layers of coaly material record short-lived swamps and mires or short-lived overbank settings. Intercalated clastic input indicates periodical flooding events. The lower part of the Bako-Mintu Sandstone, exposed at Tanjung Bako, consists of abundant fluvial channel deposits, while the upper part in the Mintu area shows extensive floodplain and lacustrine deposits interbedded with fluvial channels. A typical weathering feature of the sandstones is honeycomb weathering surfaces (Fig. 10d), produced by exposure of the sections to wind flow in combination with salt crystallisation often in a coastal section (Mustoe, 1982; Rodriguez-Navarro et al., 1999).

4.6. Tutoop Sandstone

Literature interpretation

Haile (1957) interpreted deposition in a continental environment and Heryanto and Jones (1996) suggested a fluvial setting for the Tutoop Sandstone.

Description

The Tutoop Sandstone in West Sarawak is mainly composed of sandstones and subsidiary mudstones. Conglomerates are only exposed in a few locations and are composed of matrix-supported massive conglomerate. Clasts are entirely made up of mud rip-up clasts from underlying mud units. The clasts are predominantly angular to subrounded with maximum clast sizes up to 3 cm in length. The lithology exhibits poor to medium sorting and is usually red to grey coloured. Bed size varies from 20 to 50 cm with beds usually have an erosive base. No other conglomerates were observed in this study, but have been reported by Heryanto and Jones (1996) from NW Kalimantan.

Sandstones form the most dominant lithology in the Tutoop Sandstone. They are composed of quartzose fine- to medium-grained sandstone which exhibits good to medium sorting and normal grading. Architecture elements are either massive or trough cross-bedding. Beds sizes vary from 20 cm to 1 m with basal contacts are erosive or sharp. Bed geometries are either sheet-like elongated or lenticular. Trough cross-bedding is formed usually by single bed-sets.

Interbedded fine- to medium-grained sandstones with thin mud and silt layers form heterolithics, dominated by rippled architecture. Especially in the lower part of the Tutoop Sandstone red mudstone and reddish to white siltstone alternations are typically. Bed size varies from 10 to 30 cm and contacts are sharp. Ripple tops are composed of mud. Ripple forms are straight, sinuous and linguoid as well as climbing ripples. Rarely, flaser and wavy bedding probably as a result of unstable ripples was observed.

Mudstones are either massive or thinly laminated and are of grey to red colour with bleached parts are white to light grey. The red mudstone is abundant in the lower part of the formation. Bed thickness varies from 5 to 20 cm. Plant material and imprints of plant material are abundant. Flame structures are present at the contact between the mudstone and the sandstone.

Interpretation

The lowermost part of the Tutoop Sandstone is predominantly formed by red mudstone-sandstone alternations (Fig. 10e). The abundant red mudstones with plant fragments indicate overbank deposits, which are separated by multiple reddish or bleached silt layers (Fig. 10f) or thicker sandstone beds. The red colour indicates oxidation during the early phase of diagenesis (Reading, 1996). The silt layers may have been deposited by sheet floods on the floodplain/overbank or by crevasse splays when the discharge of a river exceeded the capacity of the channel and sediment-filled water flows over the overbank deposits (Boggs, 2012). Sandstones form multiple channels which dissected the mud-dominated floodplain. Compositionally, the sandstones are predominantly quartzose and indicate reworking of underlying units. Massive sandstone can form the base of a fluvial channel (e.g. Collinson, 1969; McCabe, 1977) and are a product of rapid deposition from suspension during floods (Reading, 1996). Trough cross-bedded sandstone can be interpreted channel bars and sinuous or isolated subaqueous dunes (Tucker, 1991; Nichols, 2009; Boggs, 2012) or as a product of small scale current ripple migration (Boggs, 2012). Rippled sandstone commonly occurs at the top of channel units under weak current processes. Observed climbing ripples (Fig. 10g) record high rates of bed aggradation (Allen, 1971). Flaser (Fig. 10g) and wavy bedding are produced by variations in current or wave activity, or changes in sediment supply (Nichols, 2009). They are commonly associated with a tidal environment. However, e.g. Martin (2000) and Dalrymple & Choi (2007) reported flaser and wavy bedding in fluvial environments, which are related to fluctuations in water level. There are no indications that the Tutoop Sandstone is estuarine or tidal-influenced and the observed flaser bedding is restricted to a few small beds, therefore the fluvial interpretation is favoured here. Towards the top of the formation the preservation of fine material decreases and complex thick channel deposits are more abundant. Grey mudstones are exposed throughout the formation and may be related to a backswamp environment with reducing conditions (Miall, 1985) or lacustrine environment. Observed conglomerates are formed entirely of intraformational mudflake conglomerate deposits (Fig. 10h), indicating reworking of floodplain sediments related to channel migration or aggradation over swamp or overbank facies.

5. Palaeocurrent data

Palaeocurrents reported for the Kayan Sandstone in the Kayan syncline (Kong, 1970; Tan, 1971; Kloni, 1978; Kijam, 1978) summarised by Tan (1984) indicate a dominant flow towards the W and WNW. At the Bungo Range the dominant flow direction is towards the ENE (Stauffer, 1969; Tan, 1984) and at Tanjung Santubong it is towards the NNE (Stauffer, 1969; Kasumajava, 1979; Tan, 1984; Tan, 1993). Paleocurrent data from the Bako-Mintu Sandstone at Tanjung Bako indicates a dominant flow towards the north (NNE and NNW). Subordinate SSE directions are also common and suggest a partly bimodal current (Tan, 1993). For the Silantek Formation, palaeocurrents indicate a bimodal north-south current with subordinate bimodal E-W to unimodal towards the west flow (Tan, 1979).

This study adds a small number of palaeocurrents to the available records. Dip direction and angle were measured from the lee sides of planar cross-beds and foresets of trough cross-beds. Trough cross-beds were plotted in a Schmidt net to reconstruct the orientation of the channel axis. Orientations of symmetrical and asymmetrical ripples were recorded in places.

Palaeocurrents obtained in this study are displayed in Fig. 11. The Kayan Sandstone shows some local variations in flow directions. Within the Kayan syncline, a dominant flow towards NNE and WNW was recorded. A flow towards NNE and N (Ø= is recorded in the Pueh area and at Tanjung Santubong a flow towards NW to N (Ø = 322˚, Ø = 006˚ n = 18) is dominant. In contrast to these northern-directed palaeocurrents is the Gunung Serapi area where a SW-directed flow (Ø = 233˚ n = 17) was observed. Literature data by Tan (1984) for the Kayan syncline suggest a more dominant western-directed flow for the Kayan syncline sediments. Variations in the palaeocurrent data may reflect sampling at different locations within a meandering fluvial system or sampling different migrating channel systems. The Gunung Serapi area may indicate a major bend within the palaeo-river system.

Palaeocurrents for the Penrissen Sandstone record a dominant flow towards the WNW and SW (Ø = 306˚, Ø = 228˚ n = 20). The dominant WNW trend is continued in the Ngili Sandstone and the Silantek Formation. Palaeocurrent measurements of the Ngili Sandstone indicate a WNW-ESE bidirectional flow (Ø = 294˚, Ø = 134˚ n = 12). A similar trend is seen in the Marup Sandstone Member of the Silantek Formation (Ø = 297˚, Ø = 112˚ n = 23), while palaeocurrents within the upper parts of the Shale Member indicate a unidirectional flow towards the WNW (Ø = 305˚ n = 5). A change is recorded in the Bako-Mintu Sandstone from Tanjung Bako where palaeocurrent measurements indicate a dominant flow towards NE and NW (Ø = 043˚, Ø = 346˚ n = 58). The Tutoop Sandstone at the Klingkang Range also records a prominent flow towards the NE (Ø = 049˚ n = 39). Literature palaeocurrents from the Silantek Formation by Tan (1979) also show a bidirectional N-S flow, suggesting at least partly similar flow directions for the Ketungau Group (Silantek Formation, Bako-Mintu Sandstone, Tutoop Sandstone).

Throughout time of deposition of these various sedimentary successions the flow directions changed, indicating the formation of several river systems, possible related to different uplift events which influenced the river geometry and the source areas. Overall most successions show a predominant source to the SW with subordinate southern or south-eastern sources. However, several palaeocurrents also indicate an eastern source. Interestingly, the observed flow directions in the Ngili Sandstone and Marup Sandstone Member are similar to the present-day Batang Lupar, suggesting a potential proto-Lupar river which is possibly influenced by active movement along the Lupar Line.

6. Discussion

6.1. Source areas

The character of most observed sediments suggests a proximity to an elevated area potentially with restricted localised contemporaneous magmatism. The overall quartzose-dominated successions, intra-basinal clasts and sedimentary lithic fragments thereby indicate a reworking of older units. Polymict conglomerates, feldspar and other lithic fragments indicate uplifted igneous and/or metamorphic rocks as potential sources. Palaeocurrents summarised by Tan (1984) and in this study show some variations and indicate a complexity of the various river systems. However, for most sediments a dominant southern source is evident and a subordinate eastern source. To the south of the research area the Schwaner Mountains form a present-day elevated region and, together with the Malay Tin Belt, were suggested to be the source for the Neogene Crocker Formation in Sabah (van Hattum et al., 2013). It is unknown when uplift of southern Borneo initiated. The data of this study suggest a potential source area in the region of the present-day Schwaner Mountains from the latest Cretaceous onwards. Among other areas, the Schwaner Mountain region was already considered by Zeijlmans van Emmichoven (1939) as a potential source area. However, more proximal source regions are also possible. Uplift of the Pedawan Formation initiated in the latest Cretaceous, as indicated by the Pedawan Unconformity, and therefore recycling of the Pedawan Formation is a potential source, as well as other Mesozoic rocks in West Sarawak and NW Kalimantan, as reported by Williams et al. (1988), Breitfeld et al. (2017) and Hennig et al. (2017). A local source for the Kayan Group was also suggested by Liechti et al. (1960) and Tan (1984). Eastwards of the research area, Mesozoic melanges and the fore-arc basin fill unit, the Selangkai Formation, a potential equivalent of the Pedawan Formation, are widely exposed (Pieters et al., 1993; Heryanto and Jones, 1996) and are potential sources. Erriyantoro et al. (2011) also suggested the Kapuas Complex/Lubok Antu Melange (Mesozoic melange) as a potential source based on a provenance study of the Silantek Formation (Kantu Beds). As the Kayan Group is older as the Ketungau Group it could likely be a source for the sediments of the Ketungau Basin. Especially the Tutoop Sandstone, as it is of compositional maturity and indicates reworking of sediments. It is unclear if material could also be derived from the Malay Peninsula in a similar setting to the Crocker Formation. More research is needed; however, some palaeocurrents indicate a possible source area in the SW. Breitfeld et al. (2014) and Breitfeld (2015) suggested the Malay Peninsula as potential source region. Galin et al. (2017) interpreted the Schwaner granites, Mesozoic rocks in West Borneo and the Malay Peninsula (Indochina) as source regions for the Rajang Group, which is likely the deeper marine equivalent to the Kuching Supergroup. They also discussed a contribution from Sibumasu (western Malay Peninsula). Fig. 12 displays a simplified block diagram that summarises potential source areas and environments of deposition.

Hutchison (1996, 2005) suggested the uplifted Rajang Group to the north as source area for the Silantek Formation. This conclusion was also supported by Erriyantoro et al. (2011). However, this seems very unlikely, considering the palaeocurrents obtained in this study and presented by Tan (1984) and the similar ages of deposition for the sediments of the Kuching and Sibu Zones (e.g. Kirk, 1957; Liechti et al., 1960; Wolfenden, 1960; Muller, 1968; Tan, 1979; Morley, 1998; Breitfeld et al., 2014; Galin et al., 2017).

6.2. Deformation within the sediments

The bedding of sedimentary successions of the Kuching Zone is predominantly horizontal or inclination is associated with large broad synclines. These synclines have typically curved margins and varying strike of the fold axes. This could reflect basement structures, different compression directions or underlying overpressured sequences. Inclined Kayan Sandstone strata can be observed at the Bungo Range and within the Kayan syncline (Buffer Wall). Inclined Silantek Formation strata forms the Marup Ridge south of the Lupar valley (Marup Sandstone Member).

Part of this deformation can be attributed to movement along the Lupar Line. The Marup Sandstone Member (Silantek Formation) is steeply dipping to overturned near the fault zone and suggests a significant vertical component of displacement, while the straight linear character of the fault may suggest a strike-slip character. Paleo-currents within the Marup Sandstone Member in similar direction as the present-day Lupar River, suggests the Lupar Fault was active at the time of deposition (Lutetian).

6.3. Unconformities

The Pedawan Unconformity indicates a major tectonic event before sedimentation of the terrestrial sediments in the Kayan Basin initiated. Palynology dating of the Pedawan Formation and the Kayan Sandstone suggests a hiatus in the Late Cretaceous between the Santonian and Maastrichtian (Muller, 1968; Morley, 1998). The age coincides with the termination of subduction-related magmatism in SW and West Borneo (Williams et al., 1988; Moss, 1998; van Hattum et al., 2013; Davies, 2013; Davies et al., 2014; Hennig et al., 2017) and could be related to a collisional event at this time. Hall (2012) shows collision of SW Borneo with a Luconia-Dangerous Grounds province at c. 90 Ma. Breitfeld et al. (2017) and Hennig et al. (2017) interpreted the cessation of the Paleo-Pacific subduction at this time, and termed it the Paleo-Pacific Unconformity (Hennig et al., in prep). This collision must have been followed by large scale extension, possible as response to uplift in south, to form the Kayan Group.

Within the Kayan Group, there may be an unconformity between the Kayan Sandstone and the Penrissen Sandstone. Change in dip, lithologies exposed, material within the succession and different palaeocurrents suggests a change in provenance and environment of deposition. Morley (1998) suggested an age of Late Paleocene to Early Eocene based on the palynology records of Muller (1968) for the Penrissen Sandstone. This would indicate a Late Paleocene age for the unconformity.

The relation between the Kayan Group and the Ketungau Group is not clear. No contacts have been observed or reported. The Ngili Sandstone might be the oldest sediments of the Ketungau Basin. No contacts to the underlying formations have been observed, but in close proximity steeply dipping shales have been observed. This suggests an unconformity to the underlying rocks. However, no age data is available, but the underlying shales are likely to belong to the pre-Pedawan Unconformity strata. The Eocene Silantek Formation rests unconformably or with a fault contact above Cretaceous melange type rocks (Tan, 1979; Pieters et al., 1993). The Bako-Mintu Sandstone also rests unconformably above possible Cretaceous melange rocks at Tanjung Bako (Tan, 1993) and is conformably on top of the Ngili Sandstone. This suggests that the Kayan and Penrissen Sandstones were either not deposited in the area of the Ketungau Basin or were completely eroded during the deposition of the lower parts of the Ketungau Group. This indicates an unconformity at the top of the Penrissen Sandstone before sedimentation in the Ketungau Basin initiated. This unconformity is termed here the Kayan Unconformity and is of possibly Middle Eocene age, as the Penrissen Sandstone is thought to be Early Eocene (Morley, 1998) and the Silantek Formation is Middle Eocene (Breitfeld et al., XXX). Large scale extension to form the Ketungau Basin and possible the Melawi Basin to the south is evident.

The top of the Ketungau Group could not be analysed in West Sarawak, but at c. 40 Ma the Rajang Unconformity (Galin et al., 2017) marks the end of the turbiditic Rajang Group. It is unclear if this unconformity is traceable in the Ketungau Group, as the top of the Bako-Mintu Sandstone and the top of the Tutoop Sandstone is marked by an erosional surface. The relation to the youngest unit, the Ketungau Formation, is not very well studied.

7. Conclusions

1. The Pedawan Unconformity separates deep marine Cretaceous deposits from terrestrial uppermost Cretaceous to Eocene sediments. Sedimentation re-initiated with the Kayan Sandstone, possible in the Maastrichtian.
2. There are two major sandstone successions in the western part of West Sarawak, which were previously assigned to the Kayan Sandstone or the informal Kayan 'Basin'. For the older part, the term Kayan Sandstone is maintained in this study. The younger (?Early Eocene) part is termed Penrissen Sandstone, which is possibly separated from the Kayan Sandstone by an unconformity.
3. The Kayan Sandstone is a fluvial-dominated deposition with a basal conglomerate and thick floodplain deposits. The Penrissen Sandstone is predominantly composed of alluvial fans and fluvial deposits with low fine material preservation. Finer-grained material within the Penrissen Sandstone is possibly related to lacustrine facies.
4. There was no deposition in the area of the Ketungau Basin in the Late Cretaceous to Early Eocene or the Kayan and Penrissen Sandstones have been completely eroded. This suggests an unconformity at the top of the Penrissen Sandstone.
5. The sediments of the Ketungau Basin are unconformably above or faulted against Cretaceous melange rocks. They are also unconformably above or in faulted contact with the Kayan Group. The Ketungau Basin in West Sarawak is composed of the Ngili Sandstone, the Bako-Mintu Sandstone, Silantek Formation and the Tutoop Sandstone.
6. The Ngili Sandstone is formed of volcaniclastic conglomerates in the lower part which indicates either fresh input or recycling of older volcaniclastics, and extensive floodplain to estuarine deposits in a near-coastal environment. The Bako-Mintu Sandstone on top is mainly composed of fluvial deposits.
7. The Silantek Formation is composed of the Shale Member, which forms the main part of the succession and indicates extensive floodplain to possibly estuarine deposits, the Marup Sandstone Member, which indicates estuarine-tidal environment, and the Temudok Sandstone which indicates fluvial to floodplain environment.
8. The Tutoop Sandstone is composed mainly of fluvial deposits and indicates a change from the near-coastal depositions of the Silantek Formation towards a more proximal fluvial system.

9. Palaeocurrents indicate a predominant southern source for all sediments and a subordinate eastern source. They also indicate bidirectional flow related to a tidal environment for the Silantek Formation and the Ngili Sandstone, while unidirectional flows dominate the Kayan Group, the Bako-Mintu Sandstone and the Tutoop Sandstone. Source regions were likely elevated areas in the present-day Schwaner Mountains region and possibly elevated melange-type rocks to the east.

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References

Figure captions

Figure 1: The structural zones of NW Borneo with sedimentary basins of the Kuching Zone (modified after Haile, 1974; Heng, 1992; Doutch, 1992). The research area is displayed in the red box.

Figure 2: Distribution of the uppermost Cretaceous to ?Late Eocene sedimentary deposits of the Kayan and Ketungau Groups in West Sarawak (adapted from Liechti et al., 1960; Tan, 1981; Heng, 1992).

Figure 3: Palynology zones of the Kayan Group and the underlying youngest part of the Pedawan Formation (adapted from Muller, 1968; Morley, 1998) and correlation of the in the literature used terms for the Kayan Group. The area Kayan Syncline (W) is located near Lundu and Sungai Chupin; and the Kayan syncline (E) area comprises exposures around the Buffer Wall locality. Older sections of the Pedawan Formation (not displayed) underlie the Kayan Sandstone in the Pueh area and Kayan Syncline.

Figure 4: Correlation of different terms and ages used in the literature for the Ketungau Group (adapted from Zeijlmanns van Emmichhoven, 1939; Haile, 1954, 1957; Tan, 1979; Pieters et al., 1987; Doutch, 1992; Heryanto and Jones, 1996) and comparison to the revised stratigraphy of this study.

Figure 5: Revised stratigraphy of the uppermost Cretaceous to ?Late Eocene sedimentary deposits of the Kuching Zone in West Sarawak that form the Kayan and Ketungau Groups, and their relation to the underlying formations (based on new observations; and adapted from Haile, 1957; Wilford and Kho, 1965; Muller, 1968; Tan, 1979; Tumanda et al., 1993; Basir and Aziman, 1996; Haile, 1996; Morley, 1998; Basir and Uyop, 1999; Breitfeld et al., 2014; Breitfeld, 2015).

Figure 6: The Pedawan Unconformity. a) Steeply dipping, slumped Pedawan Formation unconformably overlain by the horizontally bedded Kayan Sandstone at the western margin of the Kayan syncline (south of Lundu). b) Zoomed in section showing the angular unconformity. c) The unconformity exposed at the southern end of Tanjung Santubong. d) Vertical shale-siltstone alternations of the Pedawan Formation are unconformably overlain by slightly dipping Kayan Sandstone with a massive basal conglomerate in the Sungai Chupin area. e) Fining up of the basal conglomerate into pebbly sandstone. f) Zoom in of the polymict basal conglomerate, showing elongated mud clasts and rounded pebbles of various compositions.

Figure 7: a) Kayan Sandstone at the Buffer Wall exposure. Multiple sandstone beds alternate with silt- and mudstones. b) Gunung Singai (left) separated by a NE-SW trending fault from the southern Serapi range. c) Gunung Santubong forms Tanjung Santubong (probably the northern continuation

of the Serapi range). d) Hornfels at the northern tip of Tanjung Santubong, showing alternations of sand- and mudstone beds. e) Abandoned quarry at Gunung Ngili. The lower part is composed of volcaniclastic conglomerate. The upper section is composed of sandstone-mudstone alternations. f) Steeply dipping sandstone-mudstone alternations at the Marup Ridge (Marup Sandstone Member) near Sri Aman. g) Gently to moderately dipping sheet-like sandstones interbedded with carbonaceous mudstone at the Temudok Ridge (Temudok Sandstone Member) south of Sri Aman. h) Bako-Mintu Sandstone forms the 'Sea stack' in Bako National Park. i) Tutoop Sandstone in the lower ascends of Bukit Mansul: red mudstone is overlain by channel sandstone with an erosive base.

Figure 8: a) Kayan Sandstone: Large scale trough cross-bedding in sandstone. Abundant mud and organic material is along the crests of the trough cross-beds. Location: Matang area (Gunung Serapi). b) Kayan Sandstone: two massive sandstone channels dissect a thick mudstone in the Kayan Syncline. c) Kayan Sandstone: massive conglomerates consisting mainly quartz pebbles, shale clasts and igneous clasts are interbedded with sandstone-siltstone-mudstone alternations. Abundant iron oxide veins cross-cut the finer grained alternations. Location: Bungo Range. d) Kayan Sandstone: large syn-sedimentary fault cross-cuts and displaces the lower section of the exposure. Sandstone-mudstone alternations are faulted against thick mudstone deposits. The upper part of the exposure is not affected. Location: Matang area (Gunung Serapi). e) Kayan Sandstone: cracks are filled by upwelling mud. Potentially *ophiomorpha* trace fossils in the sandstone. Location: Kayan Syncline. f) Kayan Sandstone: sedimentary dyke composed of medium grained sandstone cuts through thick mudstone-siltstone alternations. Location: Matang area (Gunung Serapi). g) Penrissen Sandstone: Conglomerate grades into horizontally laminated sandstone. Clasts are predominantly quartz pebbles and igneous material. Location: Gunung Penrissen. h) Penrissen Sandstone: Large quartz clasts floating in red sandstone. Horizontally laminated sandstone-conglomerate alternation with crudely developed bedding is in the lower part of the outcrop. Location: Gunung Penrissen.

Figure 9: a) Ngili Sandstone: coarse conglomerate composed of volcaniclastic material, in particular white ash/mud clasts. Location: Gunung Ngili. b) Ngili Sandstone: thick massive sandstone overlays massive reddish mudstone and is overlain by horizontal bedded sandstone-mudstone alternation at Gunung Ngili. c) Ngili Sandstone: iron stone layer bands within fine grained sandstone-siltstone alternations at Gunung Ngili. d) Ngili Sandstone: rippled sandstone predominantly composed of current and climbing ripples. Symmetrical wave ripple are in the uppermost part. Potentially a single *skolithos* trace fossil is disrupting the bedding. Location: Gunung Ngili. e) Silantek Formation: *skolithos* and *ophiomorpha* trace fossils in Marup Sandstone Member at the Marup Ridge. f) Silantek Formation: wavy bedding consisting of wave, current ripples and climbing ripples in the Marup Sandstone Member at the Marup Ridge. g) Silantek Formation: lenticular bedding in the Marup

Sandstone Member at the Marup Ridge. h) Silantek Formation: asymmetrical (current) ripple surface in the Marup Sandstone Member at the Marup Ridge.

Figure 10: a) Bako-Mintu Sandstone: large scale trough cross-bedding in sandstone beds at Tanjung Bako. b) Bako-Mintu Sandstone: several stacked channels at Tanjung Bako formed by massive to trough cross-bedded sandstones. c) Bako-Mintu Sandstone: Persistent thin coal seam and carbonaceous mud overlain by white fine sandstone in the Mintu area. d) Bako-Mintu Sandstone: honeycomb weathering structures on surface of sandstone beds at Tanjung Bako. e) Tutoop Sandstone: red mudstone alternating with red and bleached white siltstone at Bukit Begunan. f) Tutoop Sandstone: close up of intercalations of bleached white siltstones in red siltstone and mudstone at Bukit Begunan. g) Tutoop Sandstone: rippled to flaser bedded sandstone with climbing ripples at Bukit Mansul. h) Tutoop Sandstone: mudflake conglomerate overlaying grey mudstone at Bukit Mansul.

Figure 11: Palaeocurrent data of this study from the Kayan and Ketungau Groups displayed in their respective sample locations. Bin size is 10˚ on all plots.

Figure 12: Model showing the depositional environments of the a) Kayan Group (Kayan Sandstone) in the Uppermost Cretaceous to Paleocene and b) Ketungau Group (Ngili Sandstone, Silantek Formation, Tutoop Sandstone) in the Middle to ?Upper Eocene, their stratigraphic context, and their interpreted source regions.

Tables

Table 1: Foraminifera reported by Haile (1957) and Tan (1979) from the lowermost part of the Silantek Formation (Marup Sandstone Member) and new age interpretation based on BouDagher-Fadel (2013).

Table 2: Summary and thickness of the different subdivisions used for the Silantek Formation in West Sarawak (Haile, 1954; Haile, 1957; Tan, 1979) and comparison to the new classification.