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

H. Tim Breitfeld [a*], Robert Hall [a], Thomson Galin [a,b], Marcelle K. BouDagher-Fadel[c]

[a] *SE Asia Research Group, Department of Earth Sciences, Royal Holloway University of London, Egham, TW20 0EX, UK*

[b] *Minerals and Geoscience Department Malaysia (JMG) Sarawak, Jalan Wan Abdul Rahman, Kenyalang Park P.O. Box 560 93712 Kuching, Sarawak, Malaysia*

[c] Department of Earth Sciences, University College London, London, WC1H 0BT, UK

*Corresponding author: t.breitfeld@es.rhul.ac.uk

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Abstract

The Kuching Zone in West Sarawak consists of two different sedimentary basins, the Kayan and Ketungau Basins. The sedimentary successions in the basins are part of the Kuching Supergroup that extends into Kalimantan. The uppermost Cretaceous (Maastrichtian) to Lower Eocene Kayan Group forms the sedimentary deposits directly above a major unconformity, the Pedawan Unconformity, which marks the cessation of subduction-related magmatism beneath SW Borneo and the Schwaner Mountains, due to termination of the Paleo-Pacific subduction. The successions consist of the Kayan and Penrissen Sandstones and are dominated by fluvial channels, alluvial fans and floodplain deposits with some deltaic to tidally-influenced sections in the Kayan Sandstone. In the late Early or early Middle Eocene, sedimentation in this basin ceased and a new basin, the Ketungau Basin, developed to the east. This change is marked by the Kayan Unconformity. Sedimentation resumed in the Middle Eocene (Lutetian) with the marginal marine, tidal to deltaic Ngili Sandstone and Silantek Formation. Upsequence, the Silantek Formation is dominated by floodplain and subsidiary fluvial deposits. The Bako-Mintu Sandstone, a potential lateral equivalent of the Silantek Formation, is formed of major fluvial channels. The top of the Ketungau Group in West Sarawak is formed by the fluvially-dominated Tutoop Sandstone. This shows a transition of the Ketungau Group in time towards terrestrial/fluvially-dominated deposits.

Paleocurrent measurements show river systems were complex, but reveal a dominant southern source. This suggests uplift of southern Borneo initiated in the region of the present-day Schwaner Mountains from the latest Cretaceous onwards. Additional sources were local sources in the West Borneo province, Mesozoic melanges to the east and

potentially the Malay Peninsula. The Ketungau Group also includes reworked deposits of the Kayan Group. The sediments of the Kuching Supergroup are predominantly horizontal or dip with low angles and form large open synclines. Steep dips are usually restricted to faults, such as the Lupar Line.

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 Melawi Basin extends farther to the west into the Landak Basin (Doutch, 1992). The Mandai Basin to the east of the Ketungau Basin was suggested to be its eastern continuation (Doutch, 1992) and together with the West Kutai Basin they 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, which provide new insights into ages, environment of deposition and sediment sources. This publication is supported by studies of detrital heavy minerals including zircons reported by Breitfeld et al. (2014) and Breitfeld (2015), which will be summarised in another paper.

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

All clastic terrestrial sedimentary successions of Late Cretaceous to Late Eocene/?Early Oligocene 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) formed in an accretionary setting (Hutchison, 2005) interpreted as a Mesozoic Paleo-Pacific subduction margin (Breitfeld et al., 2017; Hennig et al., 2017).

Upper Oligocene to Upper Miocene rocks of the Sintang Suite have intruded the sediments of the Kuching Supergroup after their deposition, and formed various small dykes, stocks and sills (Williams and Harahap, 1987; Prouteau et al., 2001). Geochemically they are predominantly dacitic to granodioritic, or subordinately dioritic to granitic (Williams and Harahap, 1987). In the region south of Kuching, near the city Bau, they have an adakite character (Prouteau et al., 2001) and are associated with significant gold mineralisation (e.g. Wilford, 1955), that are interpreted as porphyry deposits similar to Carlin-type deposits in western United States (Percival et al., 1990; Schuh and Guilbert, 1990). However, this gold mineralisation seems to be restricted to the interaction of adakites with the Jurassic Bau Limestone Formation host rock and the adjacent Pedawan Formation in the Bau region along a NNE striking lineament, and include gold-bearing calcic skarns, veins carbonate-replacement ore bodies, epithermal gold deposits and disseminated sedimentary rock-hosted gold deposits (Percival et al., 1990; Schuh, 1993). Northeast of Bau, gold mineralisation extends into the Pedawan Formation and formed the high grade sedimentary rock-hosted disseminated gold deposit of Jugan (Schuh, 1993; Goh et al., 2014). Additionally, there is significant copper, antimony and mercury mineralisation associated with the gold deposits (e.g. Wilford, 1955; Percival et al., 1990; Schuh, 1993). There have been no reports of gold deposits associated with the Sintang Suite rocks and the sediments of the Kuching Supergroup in West Sarawak.

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, 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 (Zeijlmans van Emmichoven and ter Bruggen, 1935; 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), and 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 Middle Paleocene to 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 by Tan (1979) suggest an Eocene (probably Middle Eocene) age, while one sample from Haile (1957) from the scarp of Bukit Besai (upper section of the Marup Ridge) has an Upper Eocene assemblage after BouDagher-Fadel (2013). Nannofossils (nanno-plankton) reported by Tan (1979) include *Coccolithus* sp., *Pemma* sp. and *Prinsiaceae* sp., which indicate a Middle Eocene (Lutetian) age (Klumpp, 1953; Perch-Nielsen, 1985; Young and Bown, 1997; Bown, 2005; Young et al., 2014). The new age interpretations suggest that the lowermost part of the Silantek Formation was deposited in the Middle Eocene (Lutetian to Bartonian), while upsequence the formation is Late Eocene (Priabonian).

A Late Eocene to Early Oligocene 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). An extension into the Miocene was suggested by Tan (1979, 1981, 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 also 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.

Here we propose modification of the previous stratigraphy to incorporate new findings reported by Breitfeld (2015) and in this paper, and introduce the term Ketungau Group for the sediments of the Ketungau Basin. The Ketungau Group consists of the Silantek Formation and Tutoop Sandstone as well as new formations termed the Ngili Sandstone and Bako-Mintu Sandstone, previously included in other units. The Upper Silantek Redbed Member/Upper Kantu Beds/Upper Silantek Beds is considered to be part of the Tutoop Sandstone. We prefer the Kalimantan name Tutoop Sandstone instead of the West Sarawak name Plateau Sandstone because the term Plateau Sandstone has been used for different sequences in Sarawak and Kalimantan at different times (see e.g. ter Bruggen, 1935; Zeijlmans van Emmichoven, 1939; Milroy and Crews, 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 forearc 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). There are small variations in lithology in the Kayan Sandstone, which are described below from different locations. The Kayan Sandstone cannot be subdivided into members as outcrops are isolated and it is not possible to correlate between them. They could represent different stratigraphic intervals.

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 most complete sections were observed at the 'Buffer Wall' road (Fig. 7a) and around Bukit Snibong where it is mainly composed of sandstones, siltstone, reddish and greyish mudstone and coals. 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 area.

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 mainly of thick trough cross-bedded sandstones interbedded with thin carbonaceous dark mudstone layers. 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 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 cross-bedded sandstone. 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 overlies the Serabang Formation unconformably, and the Pueh batholith non-conformably (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 with thin coal layers and abundant plant fragments. The lithologies are similar to the lower parts exposed in the Gunung Serapi area or the Kayan Syncline. The top 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 composed mainly 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, possibly 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 and Kho, 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 conglomerates, pebbly sandstone and thickly bedded sandstone.

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 sub-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 is the lowermost unit of the Ketungau Group. It is exposed along a fault strand, with a similar orientation to 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 slightly from the Silantek Formation. Breitfeld et al. (2014) also reported a Kuching Supergroup unique U-Pb detrital zircon age spectra, which is dominated by Permian-Triassic zircons (see below), and indicates a different source for the sediments in comparison to other sediments from the Kuching Supergroup. 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 mainly of alternations of sandstone with carbonaceous mudstone and thin coal seams. About 100 m of the Ngili Sandstone are exposed, but the total thickness is greater 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. There are no age data for the Ngili Sandstone, and a Middle Eocene age is assumed in this study.

3.3.2. Silantek Formation

Based on subdivisions of Haile (1957) and Tan (1979), and new observations, we propose a modified stratigraphy. The mud-dominated exposures of the Silantek Formation (Lower and Upper Shale zone of Haile, 1957) are assigned to a Shale Member in this study. Two thick sand-dominated successions are assigned to the Marup Sandstone Member (corresponding to the Basal Sandstone of Haile, 1957; Tan, 1979) and the Temudok Sandstone Member (following 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 suggested by Tan (1979), and discussed below. A total thickness of approximately 2600 to 3000 m for the Silantek Formation is suggested by this study, less than the maximum thickness estimate by Haile (1957) of 6400 m. It is notable that fault strands with orientations similar to the Lupar Line cross-cut the Silantek Formation throughout, suggesting some movements on the Lupar Line are younger than 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 correlate with the Haloq Sandstone of the Mandai Basin (Pieters et al., 1987) and with the Bako-Mintu Sandstone (see below).

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 with the underlying Engkilili Formation is poorly exposed and is suggested to be either faulted or conformable (Haile, 1996). Other interpretations (e.g. Tan, 1979) assumed a faulted contact.

The member forms the sandstone and conglomerate dominated base of the Silantek Formation. 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 cannot be traced further. Haile (1957) reported microgranitic stocks and laccoliths, as well as granodioritic to dioritic varieties, which have been intruded at shallow depths. The sediments around the intrusions show contact-metamorphic overprint (hornfels). No ages have previously been reported, but the member is stratigraphically slightly higher than the Marup Sandstone Member.

The Temudok Sandstone Member forms a lenticular sand-dominated body, interbedded with organic-rich shale-siltstone alternations (Fig. 7g) of approximately 130 m thickness within the Silantek Formation, surrounded by the Shale Member. In close proximity to the Temudok Ridge there are several intrusions shown on the survey map (Heng, 1992), which could account for the indurated hornfelsic character the member has.

Shale Member

The Shale Member is conformably above the Marup Sandstone Member and is composed mainly of carbonaceous mudstone and fine coal seams occur within it. These are often mined in small open pit mines. Field observations suggest a total thickness of the Shale Member of possibly 1000 to 2000 m. It extends to the Klingkang Range, where it is conformably overlain by the Tutoop Sandstone.

3.3.3. 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 the Plateau Sandstone (e.g. Haile, 1957; Liechti et al., 1960; Wilford, 1965; Heng, 1992; Tan, 1993). However, no ages were reported, and its correlation with, or mapping as Plateau Sandstone, was based on lithology and assumed ages (Tan, 1979; Tan, 1993). Johansson (1999) separated the sandstones at Bako from the Plateau Sandstone as they are potentially related to another sub-basin, and introduced the name Bako Sandstone. This study follows Johansson (1999) and adds similar sediments on top of the Gunung Ngili range and in the Mintu area to the Bako-Mintu Sandstone.

However, the stratigraphic position of the formation is uncertain. The Bako-Mintu Sandstone overlies unconformably the Sejingkat Formation (a Mesozoic melange) at Telok Wangkong at Tanjung Bako (Tan, 1993). Breitfeld et al. (2017) suggested the Sejingkat Formation resembles lithologies in 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.

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 is an erosional surface at all locations.

3.3.4. 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 Sandstone, are assigned to the Bako-Mintu Sandstone (see above). The Upper Kantu Beds/Upper Silantek Redbed, previously assigned to the Silantek Formation (Haile, 1957; Tan, 1979), is considered here to be part of the Tutoop Sandstone (Fig. 7i). The contact with the underlying Silantek Formation was not observed in the field, but is reported to be conformable (Haile, 1957; Tan, 1979). The total thickness of the Tutoop Sandstone was assumed to be 1500 m (Heryanto and Jones, 1996), and approximately 800 m 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. Heavy minerals and U-Pb zircon data

Heavy mineral assemblages are often affected by either deep burial or acid dissolution (Morton, 1984; Mange and Maurer, 1992; Morton and Hallsworth, 1994), which may significantly alter the original composition of the observed sediments. The successions of the Kayan and Ketungau Group are generally dominated by ultra-stable heavy minerals including zircon, tourmaline and rutile (Breitfeld, 2015), reflecting such processes. Only the heavy mineral suite of the Penrissen Sandstone, which includes abundant less stable or unstable heavy minerals, including apatite, garnet, epidote and titanite (Breitfeld, 2015), seems unaffected. This is a clear contrast to the underlying Kayan Sandstone that contains only ultra-stable heavy minerals. Thus, with the exception of the Penrissen Sandstone, the heavy mineral assemblages do not distinguish the different sedimentary formations.

Detrital zircon U-Pb geochronological data from the formations described in this study show they are dominated by Cretaceous zircons (Breitfeld et al., 2014; Breitfeld, 2015). Differences include variations in the abundance and presence of older Mesozoic, Paleozoic or Precambrian zircons. Most of the formations have similar zircon populations, which do not aid identification of stratigraphic units, with the exception of the Ngili Sandstone of the Ketungau Group (Fig. 5), which contains only Permian-Triassic zircons with a few Paleoproterozoic zircons (Breitfeld et al., 2014; Breitfeld, 2015). However, the variations in heavy mineral assemblages and zircon populations do aid correlation of the terrestrial Kuching Supergroup and the deep marine Rajang Group, of similar age, and this is the subject of a separate paper (Breitfeld and Hall, submitted).

Since the earliest geological reports from Sarawak there have been mentions of diamond placer deposits in the area north of the Bungo Range (e.g. Hart Everett, 1878), although no commercial mining has been undertaken. Other diamond placer deposits are known from Kalimantan in the Landak area of the Kuching Zone, and from the Kelian, Meratus and Cempaka areas in SE Borneo (van Bemmelen, 1949; Spencer et al., 1988; Smith et al., 2009; van Leeuwen, 2014; Kueter et al., 2016; White et al., 2016), but like the alluvial diamonds in Sarawak their source is unknown. Haile (1954), Wilford (1955) and Wilford and Kho (1965) suggested the Sarawak diamonds were derived from the Kayan Sandstone or the Penrissen Sandstone in the Bungo Range, essentially because these are the closest clastic sedimentary rocks that could be their source. However, no diamonds or diamond-related minerals have been found in the Kayan Sandstone or the Penrissen Sandstone during this study.

5. Field relations and environment of deposition

5.1. Kayan Sandstone

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. Khan et al. (2017) interpreted a fluvio-deltaic to tidal environment for the Kayan Sandstone at Santubong and in the Kayan Syncline.

5.1.1. Description

The Kayan Sandstone is formed predominantly of sandstones and heterolithics, subsidiary conglomerates and mudstone. Conglomerates are predominantly massive, polymict and matrix-supported conglomerates. Massive conglomerates are common in the Bungo Range (Fig. 8a) and rarely observed in other areas of the Kayan Sandstone. 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). It is grey/white to yellow/red and exhibits poor sorting and locally normal grading. Clasts are up to 10 cm in size, rounded to subrounded and composed predominantly of quartz pebbles, with subordinate mud rip-up clasts, other reworked sedimentary rocks, and igneous rocks in a fine- to medium-grained sandy matrix. Matrix grains are 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. In the Bungo Range thin horizontal pebble layers are interbedded with medium-grained sandstone. Most of these conglomerate bands are less than 5 cm thick and interbedded with < 10 cm sandstone layers. Especially in the Bungo Range abundant iron-oxide veins cross-cut conglomerate and sandstone beds.

Sandstones are massive, with trough cross-bedding and planar cross-bedding, and are commonly quartzose to polymict and medium- to coarse-grained. Sorting is good to medium and grading is normal. Trough cross-beds are abundant and plant material at the top of the cross-beds is common (Fig. 8b). 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. The basal contacts are sharp or erosive. Bed geometry is generally lenticular and stacking of lenticular bodies occurs (Fig. 8c). 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. 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, upwelling mud (Fig. 8d) and sedimentary injectites composed of sandstone (Fig. 8e) within heterolithics were observed. Poorly preserved *Skolithos* ichnofacies is present in some beds. 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. 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. Tuffaceous bed sizes are up to 50 cm and bed geometry is lenticular.

5.1.2. Interpretation

The lowermost part of the succession (Fig. 6e and f) is interpreted as alluvial fan deposits or coarse channel infill. Abundant igneous, metamorphic and intra-basinal sedimentary clasts indicate various sources. Reworking of the underlying Pedawan Formation is evident. Moving upwards in the Kayan Sandstone, sandstones become dominant and conglomerates decrease. Exception is the Kayan Sandstone at the Bungo Range, which shows thick conglomerates interpreted as alluvial fans, coarse channel fills or longitudinal bars (Miall, 1985) throughout the succession and indicates proximity to a mountainous source area. Multiple stacked channels indicate channel migration and aggradation with high sedimentation rates, in combination with decreasing accommodation space. No fossils, rare bioturbation and rootlets suggest a dominant fluvial environment. The channelised fluvial sandstones are interpreted as part of a complex braided or meandering river, or a distributive fluvial system (DFS) (Weissmann et al., 2010). The fluvial channels dissected a muddy, low-lying and vegetated floodplain, which was subject to regular flooding events. Very limited bioturbation in some beds suggest a potential tidal flat to deltaic environment of deposition in some parts of the succession. Mudstones can be carbonaceous, and immature coal indicates a standing water swamp to floodplain environment (Nichols, 2009; Miall, 2013). Red mudstones indicate oxidation in the early phase of diagenesis as a result of exposure to atmospheric conditions (Reading, 1996) and are interpreted as potential overbank deposits. The remains of root material suggest the formation of paleosols. Coal present in thin seams indicates limited peat accumulation in restricted swamps in a coastal floodplain. A few ash layers indicate contemporaneous coeval volcanic activity of pyroclastic character.

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. Instability of the underlying sediments due to water oversaturation at the time of deposition is indicated by syn-sedimentary faulting (Fig. 8f), upwelling mud and sedimentary injectites. 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). The Buffer Wall may have formed a former sea-cliff.

The Kayan Sandstone within the Bungo Range is interpreted to be a more proximal fluvial system. Towards the north (e.g. Kayan Syncline) there are more distal deposits of a fluvial system with minor deltaic or tidal influence.

5.2. Penrissen Sandstone

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

5.2.1. Description

In contrast to the Kayan Sandstone, where conglomerates are subordinate, they are abundant within the Penrissen Sandstone. Sandstones and mudstones are subsidiary lithologies. Massive conglomerates, horizontally bedded with planar cross-bedding, are the dominant unit. They are mainly matrix-supported with poor sorting. Clast-supported conglomerates are subsidiary. Clasts are up to 5 cm size, rounded to subrounded and composed of igneous lithics, quartz, shale and reworked sedimentary rocks. Matrix grains are feldspar, quartz and lithic fragments. Tops of the beds are gradational into or sharp against sandstones (Fig. 8g), while bases are erosive. 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 (Fig. 8h). Planar cross-bedded conglomerates were only rarely observed. The inclined conglomerate layers alternate with medium- to coarse-grained sandstones, which are moderately sorted with some normal grading.

Sandstones include massive, planar cross-bedded and horizontally laminated types. They are usually fine to medium grained. Massive sandstones are 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.

Mudstones are light to dark grey and massive, but only rarely observed in the Penrissen Sandstone. Iron nodules (potentially siderite) and iron veins were observed. Beds are overlain by sandstones or conglomerates sharp or erosive contacts.

5.2.2. Interpretation

The Penrissen Sandstone is composed predominantly of thick conglomerates and massive sandstones. Conglomerates are interpreted as large debris flows. In combination with the other lithologies a terrestrial setting is evident and they are interpreted as alluvial fan deposits. Minor occurrence of clast-supported conglomerates indicates bedload deposition from stream flows (Reading, 1996). Sheet flood deposition is suggested by floating large clasts 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. The lower part of the Penrissen Sandstone includes abundant alluvial fan deposits, which pass in the upper part into large fluvial channels. Massive sandstones can form the base of a fluvial channel (e.g. Collinson, 1969; McCabe, 1987). Planar cross-bedded sandstones represent basal channel-confluence bars or lobate linguoid bars within a fluvial system (Steel and Thompson, 1983; Miall, 1985; Khadkikar, 1999). 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 (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 interpreted as lacustrine facies.

5.3. Ngili Sandstone

The term is introduced in this study. There have been no previous accounts of the Ngili Sandstone.

5.3.1. Description

The Ngili Sandstone is formed of thick conglomerates at the base, sandstones, abundant heterolithics and mudstones. There are massive and planar cross-bedded conglomerates. The lowermost exposed part of the Ngili Sandstone is formed by a thick basal conglomerate with thinner conglomerate beds through the succession. Conglomerates are matrix-supported polymict and intra-basinal (Fig. 9a). Clasts are up to 5 cm size, 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. Plant fragments were also observed. This lithofacies exhibits poor sorting, and normal and inverse grading. The matrix is composed predominantly of weathered clay minerals and volcanic lithic fragments. The basal contacts are erosive. Planar cross-bedded conglomerates are formed by inclined pebble layers and fining upwards.

Sandstones are massive (Fig. 9b) and trough cross-bedded. Medium- to coarse-grained sandstones with medium to good sorting and normal grading are common. Grains are predominantly quartz and lithic fragments. Thin layers of carbonaceous mudstone with flaser-like structures are present within thicker beds. The base of massive sandstone beds is commonly erosive. Bed geometry is generally elongated to lenticular, while trough cross-bedded sandstones have sharp basal contacts. Sheet-like deposits were also observed. Massive sandstones grade into sand-dominated heterolithics (Fig. 9b). Finer-grained sandstone deposits have abundant plant fragments and imprints of plant material on the bedding planes. Trough cross-bedded sandstones are exposed at the top of the Ngili Sandstone sequence.

Heterolithic sandstone-mudstone alternations are either formed by horizontally laminated sand-, silt- and mud layers (< 2 cm) or rippled fine grained deposits (Fig. 9c). Grains are predominantly quartz and lithic fragments. Plant material was observed on the bedding planes of the mud-dominated laminae and ironstone layers (Fig. 9d) are common. Small-scale ripples include symmetrical, asymmetrical and climbing types (Fig. 9c). Ripple tops are usually mud and thin silt layers truncating the ripple crests. Upper and lower boundaries of the beds are usually sharp. *Skolithos* ichnofacies is present in some beds.

There are light to dark grey carbonaceous mudstones and shales with abundant plant material and plant imprints present on the bedding planes. Darker coloured shales are often interbedded with thin coal layers, which can laterally extend over several metres.

5.3.2. Interpretation

The lowermost exposed part of the Ngili Sandstone is formed by thick conglomerates and thick coarse sandstones, interbedded with thin mud layers. Volcanic rock clasts and volcanic lithics indicate an immature volcanic source. Deposition was probably in close proximity to a mountainous area, while quartzose sediments suggest multiple recycling. Unsorted conglomerates were 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 was 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 it was dissected by channels. Extensive swamp areas in the floodplain formed a coal-producing environment, possibly in a coastal setting (Miall, 1985; McCabe, 1987; Miall, 2013). Ironstone layers 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 and asymmetrical ripples in opposing directions indicate opposing flow conditions (Boggs, 2012), and are interpreted as a tidally-influenced part of the Ngili Sandstone. Climbing ripples record high rates of bed aggradation (Allen, 1971). No fossils were found, and only rare bioturbation may suggest a stressed environment possibly with brackish water influence. The uppermost part of the Ngili Sandstone includes large channels with internal bedforms (trough cross-beds), which indicate bar development. No fossils or bioturbation were found in the upper section interpreted as fluvial deposits.

5.4. Silantek Formation

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.

5.4.1. Description

The Silantek Formation is dominated by sandstone and heterolithic lithologies with subsidiary conglomerates and mudstone beds. There are polymict matrix-supported massive conglomerates and pebbly sandstones with clasts dominated by grey to light grey mud rip-up clasts and minor quartz pebbles with a maximum clast size of 2 cm. Mud clasts are elongated and subrounded, while quartz clasts are commonly rounded. Sorting is poor to medium. Basal contacts are usually erosive. Inverse grading in the lowermost parts was observed, but normal grading is more common. This lithology was observed only within the Marup Sandstone Member and its occurrence is restricted.

Sandstones are medium- to coarse-grained and massive, and are medium to well sorted, normally graded, and rhythmically interbedded with finer sediments. Grains are usually feldspar, quartz, and lithic fragments, but quartzose sandstones are also common. Some lithic fragments are likely to be of volcanic origin. The beds are laterally very extensive. Sheet-like geometries were observed for most 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 possibly *Ophiomorpha* (Fig. 9e). 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. 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. There is differential compaction around nodules and 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, whereas symmetrical ripples are predominant within the Marup Sandstone Member (Fig. 9f and g). Typically, the heterolithics of the Marup Sandstone Member show also wavy bedding (Fig. 9g), lenticular bedding and flaser bedding (Fig. 9h), 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.

Mudstones are light to dark grey and carbonaceous with thin coaly seams. 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. 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. 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 possibly *Ophiomorpha* are present (Fig. 9e).

5.4.2. Interpretation

The exposures of the Silantek Formation indicate extensive floodplain and swamp environments that were periodically flooded by near-by fluvial systems or influenced by tides in a deltaic setting. The lowermost part of the Silantek Formation is the Marup Sandstone Member. The occurrence of *Skolithos* and *Ophiomorpha*-like trace fossils indicate a sandy shore (littoral zone) to shelf (sub-littoral zone) environment (Buatois and Mángano, 2011). Symmetrical wave ripples indicate a shallow water environment with oscillatory flow conditions (Boggs, 2012). Wavy to lenticular bedding is produced by variations in current or wave activity, or changes in sediment supply and commonly associated with a tidal environment (Nichols, 2009). Asymmetrical ripples 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 as result of changing current strength or wave power (Sellwood, 1972; de Jong, 1977; Hendriks, 1986; Flores & Sykes, 1996; Chakraborty et al., 2003; Dalrymple & Choi, 2007; Truong et al., 2011). Isolated mud drapes are deposited from suspension and small sand ripples are the result of rapid flow (Nichols, 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 fluvially-influenced deposition or fluvio-marine deposits if they are interbedded with shallow marine deposits. Volcanic lithics indicate limited contemporaneous volcaniclastic input into the basin. The environment of deposition for the Marup Sandstone Member is interpreted as marginal marine to subtidal.

Higher in the formation, the Temudok Sandstone Member is composed predominantly 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. Asymmetrical ripples in sandstones 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, possibly in a near-coastal environment with small swamps and mires (Miall, 2013) or tidal flats in a fluvio-deltaic environment (Hassan et al., 2017). The Temudok Sandstone Member is interpreted to record floodplain deposition with restricted peat formation. The succession indicates periodic flooding events which formed thicker sandstone bodies.

5.5. Bako-Mintu Sandstone

The Bako-Mintu Sandstone is a newly introduced stratigraphic unit from this study. Sections of the succession were previously described as Plateau Sandstone. Tan (1993) interpreted a braided river setting with episodic deltaic influence for the succession at Tanjung Bako, like Johansson (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, indicating some marine influence.

5.5.1. Description

The Bako-Mintu Sandstone is predominantly sandstone with subsidiary conglomerate and mudstone. Conglomerates were observed only at Tanjung Bako, where there are massive and planar cross-bedded types. Massive conglomerates are usually matrix-supported and 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. Planar cross-bedded conglomerates have inclined layers of mostly rounded pebbles.

Sandstones are massive and trough cross-bedded and dominated by quartzose medium-grained varieties. Sorting is predominantly good to medium and grading is normal. 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 (Fig. 10a). Trough cross-bedded sandstones form very large outcrops, exposed in prominent sea cliffs at Tanjung Bako. Trough cross-bed tops are truncated by newer bounding surfaces (Fig. 10b). Bed geometry is elongated to lenticular and the basal contact of the beds is sharp. Convolute bedding was observed in this lithology. A typical feature of the sandstones is honeycomb weathering surfaces (Fig. 10c).

Fine- to medium-grained sandstone interbedded with mud layers form heterolithics in which there are small-scale ripples and horizontal laminations. Thin mud layers (<3 cm) are interbedded with siltstone to fine sandstone beds of 1 to 5 cm size. 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 grey to dark grey and often carbonaceous material or with coal fragments and form laterally persistent beds. Those are more frequent in the Mintu area, but occur also at Tanjung Bako. Iron nodules (potentially siderite) and iron veins are observed. 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 (Fig. 10d). Soft-sediment deformation includes fine- to medium-grained sandstone dykes which are injected into this lithofacies.

5.5.2. Interpretation

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. Conglomerates represent coarse channel fills or linguoid bars (Miall, 1985, 2013). The sandstones indicate large-scale, often stacked, potentially braided channels, or are part of a distributive fluvial system. Multiple stacked channels 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) and soft-sediment deformation results from instability due to water oversaturation at the time of deposition. 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. Abundant plant material and nodular or 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 periodic flooding events. Typical honeycomb weathered surfaces, indicate exposure of the sections to wind flow in combination with salt crystallisation often in a coastal section (Mustoe, 1982; Rodriguez-Navarro et al., 1999).

5.6. Tutoop Sandstone

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

5.6.1. Description

The Tutoop Sandstone in West Sarawak is composed mainly of sandstones and subsidiary mudstones. Conglomerates are exposed only in a few locations and are matrix-supported and massive. Clasts are entirely mud rip-up clasts from underlying mud units (Fig. 10e). The clasts are predominantly angular to subrounded with maximum clast sizes up to 3 cm in length. The conglomerates exhibit poor to medium sorting and are usually red to grey coloured. Beds have usually erosive bases. No other conglomerates were observed in this study, but have been reported by Heryanto and Jones (1996) from NW Kalimantan.

Sandstones are the dominant lithology. They are quartzose fine- to medium-grained with good to medium sorting, normally graded and either massive or trough cross-bedded with erosive or sharp basal contacts. Bed geometries are either sheet-like elongated or lenticular.

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 common (Fig. 10f and g) with usually sharp contacts. Ripple tops are composed of mud. Ripple forms are straight and sinuous as well as climbing ripples (Fig. 10h) with crudely developed flaser and wavy bedding.

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

5.6.2. Interpretation

The lowermost part of the Tutoop Sandstone is red mudstone-sandstone alternations with plant fragments interpreted as overbank deposits. 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 and overbank facies. Massive sandstones form the base of a fluvial channel (e.g. Collinson, 1969; McCabe, 1987) and are a product of rapid deposition from suspension during floods (Reading, 1996). Trough cross-bedded sandstones are interpreted as 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. Climbing ripples record high rates of bed aggradation (Allen, 1971). Flaser 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 and result from unstable ripples. There are no indications that the Tutoop Sandstone is estuarine or tidally-influenced and the observed flaser bedding is restricted to a few thin beds, therefore a fluvial interpretation is favoured. Towards the top of the formation fine material decreases and complex thick channel deposits are more abundant. Grey mudstones throughout the formation may be related to a backswamp environment with reducing conditions (Miall, 1985) or lacustrine environment. Intra-basinal conglomerates (mudflakes) indicating reworking of floodplain sediments related to channel migration or aggradation over swamp or overbank facies.

6. Paleocurrent data

This study adds a small number of paleocurrent observations to earlier 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.

Paleocurrents 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, 1993). Paleocurrent data from the Bako-Mintu Sandstone at Tanjung Bako indicates a dominant flow towards the north (NNE and NNW) and subordinate SSE directions, which suggest partly bimodal currents (Tan, 1993). For the Silantek Formation, paleocurrents indicate bimodal north-south currents with subordinate bimodal E-W to unimodal towards the west flow (Tan, 1979).

Measurements obtained in this study are displayed in Fig. 11. The Kayan Sandstone shows some local variation in flow directions. Within the Kayan Syncline, a dominant flow towards NNE and WNW was recorded. A flow towards NNE and N (Ø= 047 ˚, Ø = 007˚ n = 29) 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 paleocurrents is the Gunung Serapi area where a SW-directed flow (Ø = 233˚ n = 17) was observed. Data in Tan (1984) for the Kayan Syncline suggests a more dominant western-directed flow. Variations in the paleocurrent 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 paleo-river system.

Paleocurrents 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. Paleocurrent 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 paleocurrents 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 paleocurrent 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 paleocurrents 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 deposition of these sedimentary successions flow directions changed, indicating 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 paleocurrents 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 was possibly influenced by active movement along the Lupar Line.

7. Discussion

7.1. Source areas

The character of most observed sediments suggests proximity to an elevated area with some localised contemporaneous magmatism. It also indicates reworking of older sedimentary units with igneous and/or metamorphic sources. Paleocurrent measurements summarised by Tan (1984) and in this study show river systems were complex, but reveal a dominant southern source with a subordinate eastern source. Fig. 12 displays a simplified block diagram that summarises potential source areas, environments of deposition and orientation of the river system.

To the south of the research area the Schwaner Mountains (Fig. 13) was considered a potential source area by Zeijlmans van Emmichoven (1939), and Davies et al. (2014) and Hennig et al. (2017) reported abundant Cretaceous zircons from the Schwaner granites and the Pinoh Metamorphics. Breitfeld et al. (2014) demonstrated that the majority of zircons of the Kayan and Ketungau Group sediments are Cretaceous, suggesting this region as a source. It is unknown when uplift of southern Borneo initiated, but this study supports a source area in the region of the present-day Schwaner Mountains from the latest Cretaceous onwards. Galin et al. (2017) reported abundant Cretaceous zircons in the Rajang Group, which is the deep marine equivalent of the Kuching Supergroup, and also suggested the Schwaner Mountains as a source area. Abundant Cretaceous zircons in younger sedimentary successions in other parts of Borneo, e.g. the Barito Basin in East Kalimantan and the Crocker Formation of Sabah, have also been interpreted as derived from the Schwaner Mountains (Witts et al., 2012; van Hattum et al., 2013).

However, other closer source regions are also possible. Local sources for the Kayan Group were suggested by Liechti et al. (1960) and Tan (1984). Uplift of the Pedawan Formation initiated in the latest Cretaceous, as indicated by the Pedawan Unconformity, and therefore recycling of the Pedawan Formation, as well as other Mesozoic rocks in West Sarawak and NW Kalimantan (Fig. 13) (e.g. Sadong Formation, Jagoi Granodiorite), as reported by

Williams et al. (1988), Breitfeld et al. (2017) and Hennig et al. (2017), is also likely. East of the research area, Mesozoic melanges (e.g. Boyan Melange, Lubok Antu Melange, Kapuas Complex) and a forearc basin fill unit, the Selangkai Formation, an age equivalent of the Pedawan Formation, are widely exposed (Fig. 13) (Pieters et al., 1993; Heryanto and Jones, 1996) and are potential sources. Erriyantoro et al. (2011) also suggested the Mesozoic Kapuas Complex/Lubok Antu Melange as a source, based on a provenance study of the Kantu Beds/Silantek Formation. As the Kayan Group is older than the Ketungau Group it could also be a source for the sediments of the Ketungau Basin, especially the Tutoop Sandstone, since its compositional maturity indicates reworking of sediments.

It is unclear if material was also derived directly from the Malay Peninsula (Malay-Thai Tin Belt) as suggested for the Rajang Group by Galin et al. (2017) or for the younger upper Paleogene to lower Neogene Crocker Formation by van Hattum et al. (2013). Breitfeld et al. (2014) and Breitfeld (2015) suggested the Malay Peninsula as possible source region. Permian-Triassic zircons, which are typical of the Southeast Asian Tin Belt of the Malay Peninsula (Sevastjanova et al., 2011; Searle et al., 2012), are reported from sediments of the Kuching Zone in West Sarawak by Breitfeld et al. (2014) and from Rajang Group sediments of the Sibu Zone by Galin et al. (2017) and therefore could indicate the Malay Peninsula as source area. However, such zircons are also known from e.g. West Borneo (Breitfeld et al., 2017; Hennig et al., 2017) and are not restricted to the Malay Peninsula. More research is needed, but some paleocurrent observations indicate transport from the SW which could support a West Sarawak or Malay Peninsula source.

Hutchison (1996, 2005) suggested the uplifted Rajang Group to the north as source area for the Silantek Formation, a conclusion supported by Erriyantoro et al. (2011). However, this is very unlikely, considering the paleocurrent observations of Tan (1984) and those obtained in this study, and the similar ages of deposition for 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). There is no evidence to support uplift and erosion of the Rajang Group during deposition of the Kuching Supergroup.

7.2. Deformation of the sedimentary rocks

In the Kuching Zone sedimentary rocks are predominantly horizontal or dip at low angles, and form large open synclines with fold axes that trend broadly WNW-ESE east of Kuching. West of Kuching fold axes are more varied, which could reflect basement structures or underlying overpressured sequences. Kayan Sandstone beds dip at about 30° to 60° in the Bungo Range and are steeply dipping at the Buffer Wall (Fig. 2), which is a fault at the southern margin of the Kayan Syncline. At the Marup Ridge (Fig. 2) close to and south of the Lupar valley the Silantek Formation beds are steeply dipping and locally overturned near the Lupar Line. The steep dips suggest a significant vertical component of displacement on a linear strike-slip fault. Some paleocurrent orientations in the Marup Sandstone Member are parallel to the Lupar Line (Fig. 11), suggesting it was active at the time of deposition (Lutetian).

7.3. Unconformities

The Pedawan Unconformity indicates a major tectonic event before deposition of the terrestrial sediments in the Kayan Basin. Palynological 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). Hall et al. (2009) and Hall (2012) interpret termination of subduction in SE Asia after collision of the East Java-West Sulawesi block with the SE margin of the SW Borneo at c. 90 Ma. Breitfeld et al. (2017) and Hennig et al. (2017) suggested cessation of Paleo-Pacific subduction at this time, which is interpreted to have been extended beneath SW Borneo and formed the Schwaner granites, as well as the Pedawan and Selangkai forearc basins.

Within the Kayan Group, changes in dip, lithologies exposed, material within the succession and different paleocurrent directions suggest an unconformity between the Kayan Sandstone and the Penrissen Sandstone, accompanied by a change in provenance and environment of deposition. This unconformity is named here the Bungo Unconformity (Fig. 5) based on the Bungo Range location. Morley (1998) suggested an Early Eocene age for the Penrissen Sandstone, based on the palynological records of Muller (1968). This would indicate a Late Paleocene age for the unconformity.

The relationship between the Kayan Group and the Ketungau Group is not clear. The Ngili Sandstone might be the oldest part of the Ketungau Group. No contacts with underlying formations have been observed, but steeply dipping undated shales have been observed in close proximity to the Ngili Sandstone. This suggests an unconformity below the Ngili Sandstone. The underlying shales likely belong to the pre-Pedawan Unconformity strata (Fig. 5). The Eocene Silantek Formation rests unconformably (Haile, 1957) or with a fault contact on Cretaceous melange-type rocks (Tan, 1979; Pieters et al., 1993), or above the very locally exposed Middle Paleocene to Early Eocene Engkilili Formation (Haile, 1957; Tan, 1979; Basir and Taj Madira (1995). The Bako-Mintu Sandstone also rests unconformably on possible Cretaceous melange rocks at Tanjung Bako (Tan, 1993) and is reported by Haile (1954) to locally rest conformably on the Ngili Sandstone. The contact between the Kayan and Ketungau Group sediments is not exposed, and is in this study assumed to be unconformable. The unconformity is termed here the Kayan Unconformity (Fig. 5) of early Middle Eocene age and predates the Silantek Formation of Middle to Late Eocene age. Stratigraphic and field relations indicate that the Kayan and Penrissen Sandstones were either not deposited in the area east of Kuching or were completely eroded before deposition of the lower parts of the Ketungau Group. This suggests the Kayan Unconformity is the top of the Penrissen Sandstone which is thought to be Early Eocene (Morley, 1998). The calcareous Engkilili Formation could represent the marine equivalent of the upper parts of the Kayan Sandstone, since Muller (1968) reported similar pollen from the Engkilili Formation and the *Proxapertites* zone of the Kayan Sandstone, or possibly the Penrissen Sandstone.

The youngest rocks dated in the Ketungau Group are the Middle to Late Eocene Silantek Formation. The Tutoop Sandstone is interpreted here to be the undated upper part of the Ketungau Group, overlain only by the undated Ketungau Formation in Kalimantan. The top of the Bako-Mintu Sandstone is an erosional surface, which could be correlated with the contact of the Silantek Formation and the Tutoop Sandstone. The Rajang Unconformity at c. 40 Ma (Hall and Breitfeld, 2017; Galin et al., 2017), which marks the end of deep water sedimentation of the turbiditic Rajang Group, is not clearly identifiable in the Kuching Supergroup. It could be represented by the top of the Bako-Mintu Sandstone and the contact of the Silantek Formation and Tutoop Sandstone. However, it could also be above the Tutoop Sandstone (Fig. 5) or above the Ketungau Formation, or be diachronous in the terrestrial sediments.

The Tutoop Sandstone is generally reported to be conformable above the Silantek Formation (e.g. Haile, 1957; Tan, 1979). Red mudstone alternations previously assigned to the Silantek Formation are here considered part of the Tutoop Sandstone, as also implied by Tan (1979). The contact of the Silantek Formation with the Tutoop Sandstone is therefore below the red mudstones. It marks a change of depositional environment from the estuarine-deltaic Silantek Formation to the fluvial Tutoop Sandstone, which is similar to the Bako-Mintu Sandstone. The top of the Tutoop Sandstone in West Sarawak is a younger erosional surface.

More research is needed concerning correlation of the Kayan and Ketungau Groups and major unconformities with equivalents in Kalimantan (e.g. Ketungau Formation of the Ketungau Basin, Mandai Group of the Mandai Basin, and Kapuas, Melawi and Suwang Groups of the Melawi Basin). Most of the Kalimantan sediments are unfossiliferous, their age of deposition is not exactly known, and different stratigraphic schemes have been proposed for similar successions (see Pieters et al., 1987; Doutch, 1992; Heryanto and Jones, 1996). At present it is not possible to correlate West Sarawak with Kalimantan until more detailed studies in Kalimantan have been carried out.

8. Conclusions

1. The Pedawan Unconformity separates deep marine Cretaceous deposits from terrestrial uppermost Cretaceous to Eocene sediments. Terrestrial deposition began with the Kayan Sandstone, probably 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 the Penrissen Sandstone, which may be separated from the Kayan Sandstone by an unconformity.

3. The Kayan Sandstone is a fluvial to tidal succession with a basal conglomerate and thick floodplain deposits. The Penrissen Sandstone is composed predominantly of alluvial fans and fluvial deposits with minor finer-grained material which is possibly a lacustrine facies.
4. There was either no clastic deposition in the area of the Ketungau Basin in the Late Cretaceous to Early Eocene or the Kayan and Penrissen Sandstones there were completely eroded, suggesting an unconformity at the top of the Penrissen Sandstone. The Engkilili Formation may represent the marine equivalent of the upper Kayan Group.
5. The Ketungau Group in West Sarawak is composed of the Ngili Sandstone, the Bako-Mintu Sandstone, the Silantek Formation and the Tutoop Sandstone. They are unconformably above or faulted against Cretaceous melange rocks, and are also unconformably above or in faulted contact with the Kayan Group. Sedimentation of the Ketungau Group initiated in the Middle Eocene (Lutetian to Bartonian).
6. The Ngili Sandstone is formed of volcaniclastic conglomerates in the lower part, which indicates either fresh input or recycling of older volcaniclastics, overlain by extensive floodplain to estuarine deposits. The overlying Bako-Mintu Sandstone is mainly composed of fluvial deposits.
7. The Silantek Formation is composed of a Shale Member, which forms the main part of the succession and indicates extensive floodplain to possibly estuarine environments, the Marup Sandstone Member, deposited in an estuarine-tidal

environment, and the Temudok Sandstone Member, which indicates a fluvial to floodplain environment.

8. The Tutoop Sandstone is composed mainly of fluvial deposits and indicates a change from the near-coastal deposition of the Silantek Formation to a more proximal fluvial system.
9. Paleocurrents indicate a predominantly southern source for all sediments, a subordinate eastern source and some possible input from the SW. 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, West Borneo and possibly elevated melange-type rocks to the east. An input of material from the Malay Peninsula is also possible.

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Figure captions

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

Figure 2: Distribution of the uppermost Cretaceous to Upper Eocene/ ?Lower Oligocene sedimentary deposits of the Kayan and Ketungau Groups in West Sarawak (modified 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 (based on 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 (based on 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 relationship to the underlying formations (based on new observations; and on Haile, 1957; Liechti et al., 1960; Wilford and Kho, 1965; Muller, 1968; Tan, 1979; Tumanda et al., 1993; Basir and Taj Madira, 1995; Basir and Aziman, 1996; Haile, 1996; Morley, 1998; Basir and Uyop, 1999; Breitfeld et al., 2014; Breitfeld, 2015; Galin et al., 2017).

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: 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. b) 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). c) Kayan Sandstone: two massive sandstone channels dissect a thick mudstone in the Kayan Syncline. d) Kayan Sandstone: cracks are filled by upwelling mud. *Ophiomorpha* trace fossils in the sandstone. Location: Kayan Syncline. e) Kayan Sandstone: sedimentary dyke composed of medium grained sandstone cuts through thick mudstone-siltstone alternations. Location: Matang area (Gunung Serapi). f) 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). 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 horizontally bedded sandstone-mudstone alternation at Gunung Ngili. c) Ngili Sandstone: rippled sandstone predominantly composed of current and climbing ripples. Symmetrical wave ripple are in the uppermost part. A single, possibly *Skolithos*, trace fossil is disrupting the bedding. Location: Gunung Ngili. d) Ngili Sandstone: ironstone layer bands within fine grained sandstone-siltstone alternations at Gunung Ngili. e) Silantek Formation: *Skolithos* and

Ophiomorpha trace fossils in Marup Sandstone Member at the Marup Ridge. f) Silantek Formation: ripple surface consisting of sinuous symmetrical ripples in the Marup Sandstone Member at the Marup Ridge. g) Silantek Formation: wavy bedding consisting of wave, current ripples and climbing ripples in the Marup Sandstone Member at the Marup Ridge. h) Silantek Formation: lenticular bedding in the Marup Sandstone Member at the Marup Ridge.

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

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

Figure 12: Schematic model showing the depositional environments of the Kayan and Ketungau Groups, their stratigraphic context, and their interpreted source regions (not to scale). a) Kayan Sandstone in the latest Cretaceous to Early Eocene is characterised by extensive floodplain deposits, fluvial channels, some alluvial fan conglomerates and estuarine deposits. The dominant paleocurrent is towards the north with some towards the west. b) Penrissen Sandstone in the Early Eocene is characterised by alluvial fan

conglomerates, fluvial channels and some lacustrine deposits. The dominant paleocurrent is towards the west-northwest. c) Ketungau Group (Ngili Sandstone, Silantek Formation, Bako-Mintu Sandstone and Tutoop Sandstone) in the Middle to Late Eocene/ ?Early Oligocene is characterised by estuarine, tidal, fluvial and extensive floodplain deposits of the Silantek Formation, by the predominantly fluvial Bako-Mintu Sandstone, by the estuarine and extensive floodplain deposits of the Ngili Sandstone, and by the predominantly fluvial Tutoop Sandstone. Bidirectional northwest-southeast paleocurrents are dominant in the tidal and estuarine deposits. North to northeast directed paleocurrents are dominant in the fluvial deposits.

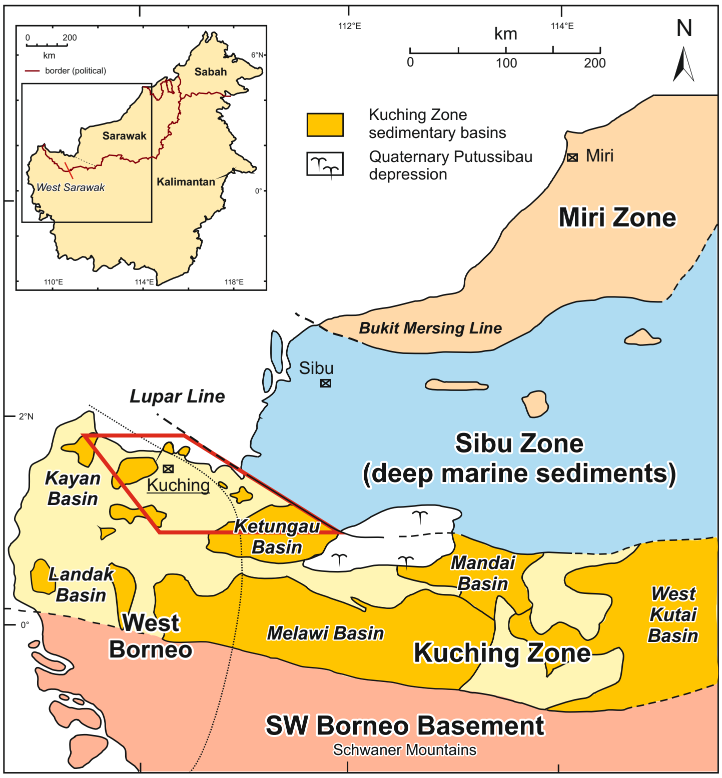
Figure 13: Geological map of western Borneo, showing Mesozoic basement rocks and Cretaceous forearc sediments, which both are possible source rocks for the Kuching Supergroup and the Rajang Group, and the position of Cenozoic sedimentary basins (based on Williams et al., 1988; Doutch, 1992; Heng, 1992; Rusmana et al., 1993; Pieters et al., 1993; Breitfeld et al., 2017; Hennig et al., 2017; Hall and Breitfeld, 2017). [1] Kayan, Ketungau, Mandai and Melawi Basins; Landak and West Kutai Basins are possibly equivalents. [2] i.a. Pueh, Gading and Era intrusions. [3] i.a. Boyan Melange, Lubok-Antu Melange, Kapuas Complex, Sejingkat Formation. [4] i.a. Serian Volcanics, Sadong Formation, Kuching Formation, West Sarawak Metamorphics (Kerait Schist, Tuang Formation), Bau Limestone Formation, Balaisebut Group, Bengkayang Group.

Table captions

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

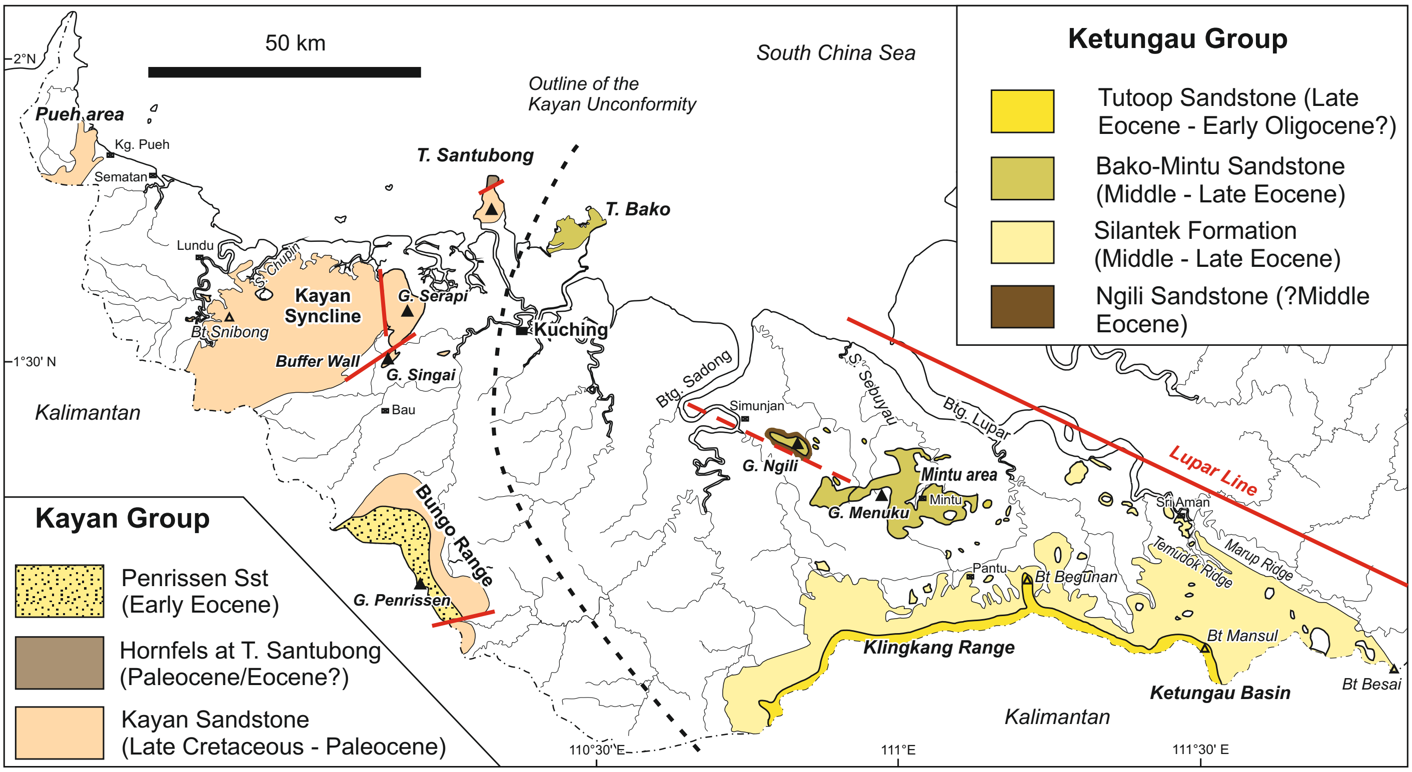
BouDagher-Fadel (2013). (Note: Tan (1979) reported also *Miliammina fusca* (Brady) which is a Holocene form. This might be a misidentification and is omitted from the table).

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.



0
200
km
border (political)
Sabah
Sarawak
West Sarawak
Kalimantan
6°N
0°
110°E
114°E
118°E
112°E
114°E
km
0
100
200
N
Kuching Zone
sedimentary basins
Quaternary Putussibau
depression
Miri
Miri Zone
Bukit Mersing Line
Sibu
Lupar Line
2°N
Sibu Zone
(deep marine sediments)
Kayan
Basin
Kuching
Ketungau
Basin
Mandai
Basin
Landak
Basin
West
Borneo
0°
Melawi Basin
Kuching Zone
West
Kutai
Basin
SW Borneo Basement
Schwaner Mountains

Fig. 1



50 km
South China Sea
Outline of the
Kayan Unconformity
Ketungau Group
Tutoop Sandstone (Late
Eocene - Early Oligocene?)
Bako-Mintu Sandstone
(Middle - Late Eocene)
Silantek Formation
(Middle - Late Eocene)
Ngili Sandstone (?Middle
Eocene)
Kayan Group
Penrissen Sst
(Early Eocene)
Hornfels at T. Santubong
(Paleocene/Eocene?)
Kayan Sandstone
(Late Cretaceous - Paleocene)
2°N
1°30' N
110°30' E
111°E
111°30' E
Pueh area
Kg. Pueh
Sematan
Lundu
S. Chupin
Kayan
Syncline
Bt Snibong
G. Serapi
Buffer Wall
G. Singai
Bau
Kalimantan
T. Santubong
T. Bako
Kuching
Bungo Range
G. Penrissen
Btg. Sadong
Simunjan
G. Ngili
S. Sebuyau
Btg. Lupar
Mintu area
G. Menuku
Mintu
Lupar Line
Sri Aman
Temudok Ridge
Marup Ridge
Pantu
Bt Begunan
Klingkang Range
Bt Mansul
Ketungau Basin
Bt Besai
Kalimantan

Fig. 2

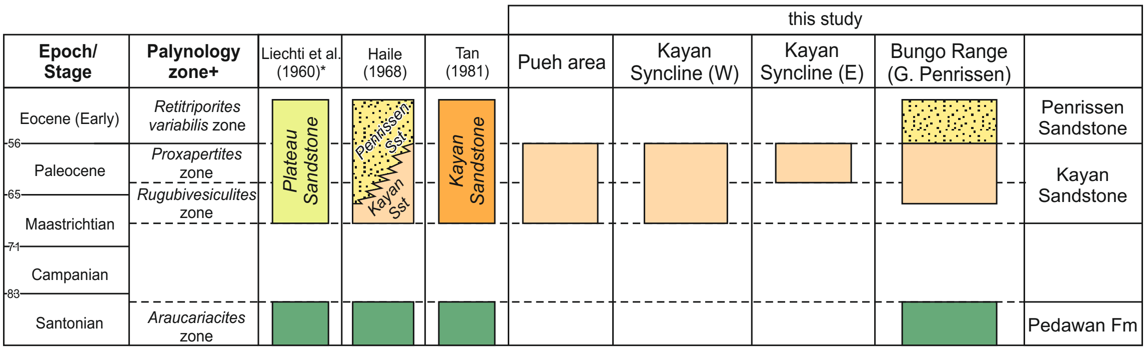
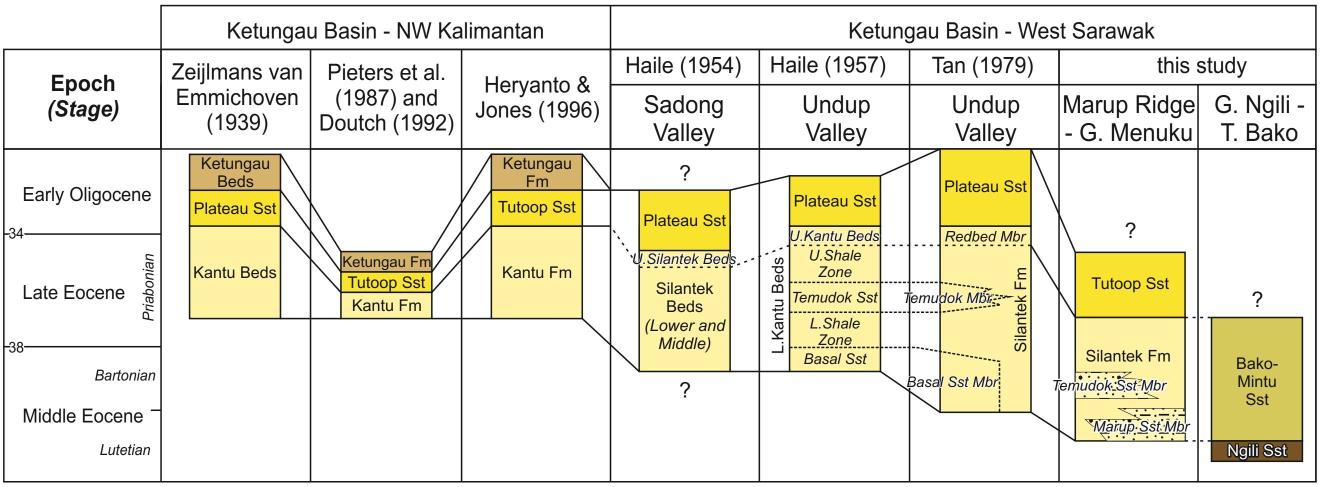
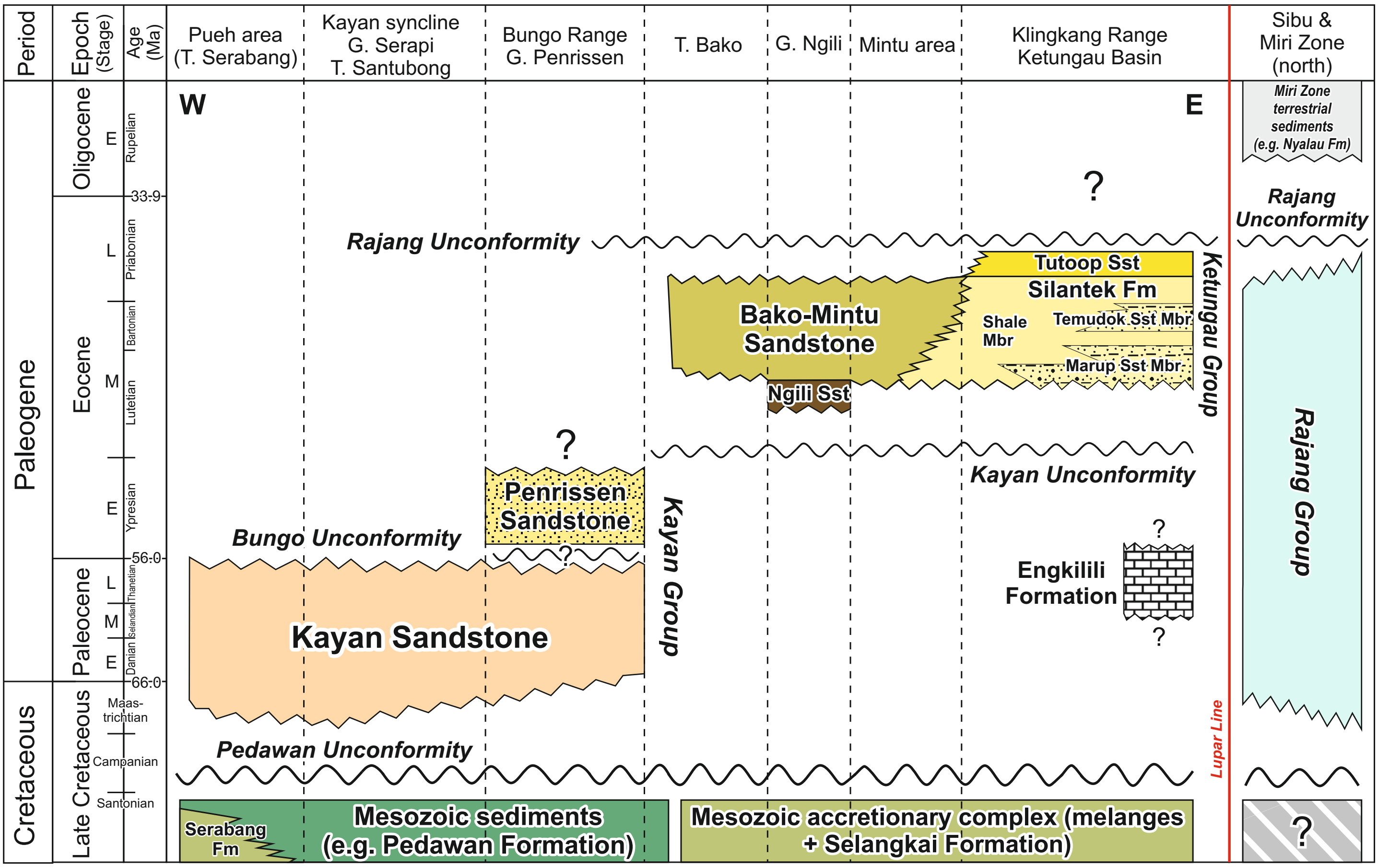

this study
Epoch/ Stage
Palynology zone+
Liechti et al. (1960)*
Haile (1968)
Tan (1981)
Pueh area
Kayan Syncline (W)
Kayan Syncline (E)
Bungo Range (G. Penrissen)
Eocene (Early)
56
Paleocene
65
Maastrichtian
71
Campanian
83
Santonian
Retitriporites variabilis zone
Proxapertites zone
Rugubivesiculites zone
Araucariacites zone
Plateau Sandstone
Penrissen Sst.
Kayan Sst
Kayan Sandstone
Penrissen Sandstone
Kayan Sandstone
Pedawan Fm

Fig. 3



Ketungau Basin - NW Kalimantan
Ketungau Basin - West Sarawak
Epoch
(Stage)
Zeijlmans van Emmichoven (1939)
Pieters et al. (1987) and Doutch (1992)
Heryanto & Jones (1996)
Haile (1954)
Haile (1957)
Tan (1979)
this study
Sadong Valley
Undup Valley
Undup Valley
Marup Ridge - G. Menuku
G. Ngili - T. Bako
Early Oligocene
34
Late Eocene
Priabonian
38
Bartonian
Middle Eocene
Lutetian
Ketungau Beds
Plateau Sst
Kantu Beds
Ketungau Fm
Tutoop Sst
Kantu Fm
Ketungau Fm
Tutoop Sst
Kantu Fm
?
Plateau Sst
U.Silantek Beds
Silantek Beds
(Lower and Middle)
?
Plateau Sst
U.Kantu Beds
U.Shale Zone
Temudok Sst
L.Shale Zone
Basal Sst
L.Kantu Beds
Plateau Sst
Redbed Mbr
Temudok Mbr
Silantek Fm
Basal Sst Mbr
?
Tutoop Sst
Silantek Fm
Temudok Sst Mbr
Marup Sst Mbr
?
Bako-Mintu Sst
Ngili Sst

Fig. 4



Period
Epoch (Stage)
Age (Ma)
Pueh area (T. Serabang)
Kayan syncline G. Serapi T. Santubong
Bungo Range G. Penrissen
T. Bako
G. Ngili
Mintu area
Klingkang Range Ketungau Basin
Sibu & Miri Zone (north)
Paleogene
Cretaceous
Oligocene
Eocene
Paleocene
Late Cretaceous
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maas-trichtian
Campanian
Santonian
33.9
56.0
66.0
W
E
Miri Zone terrestrial sediments (e.g. Nyalau Fm)
Rajang Unconformity
Tutoop Sst
Silantek Fm
Shale Mbr
Temudok Sst Mbr
Marup Sst Mbr
Ketungau Group
Bako-Mintu Sandstone
Ngili Sst
Kayan Unconformity
Penrissen Sandstone
Kayan Group
Bungo Unconformity
Engkilili Formation
Kayan Sandstone
Rajang Group
Lupar Line
Pedawan Unconformity
Serabang Fm
Mesozoic sediments (e.g. Pedawan Formation)
Mesozoic accretionary complex (melanges + Selangkai Formation)

Fig. 5

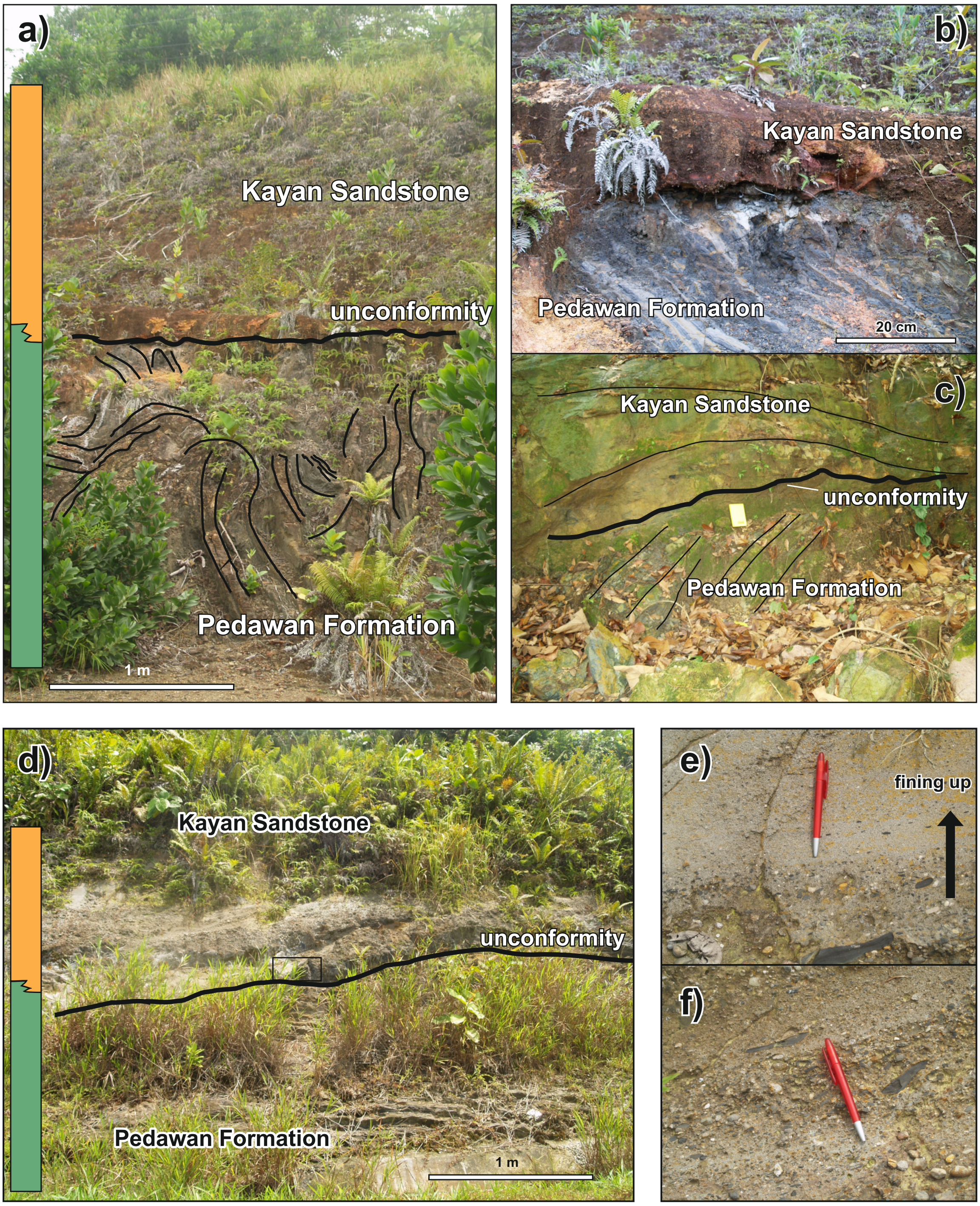
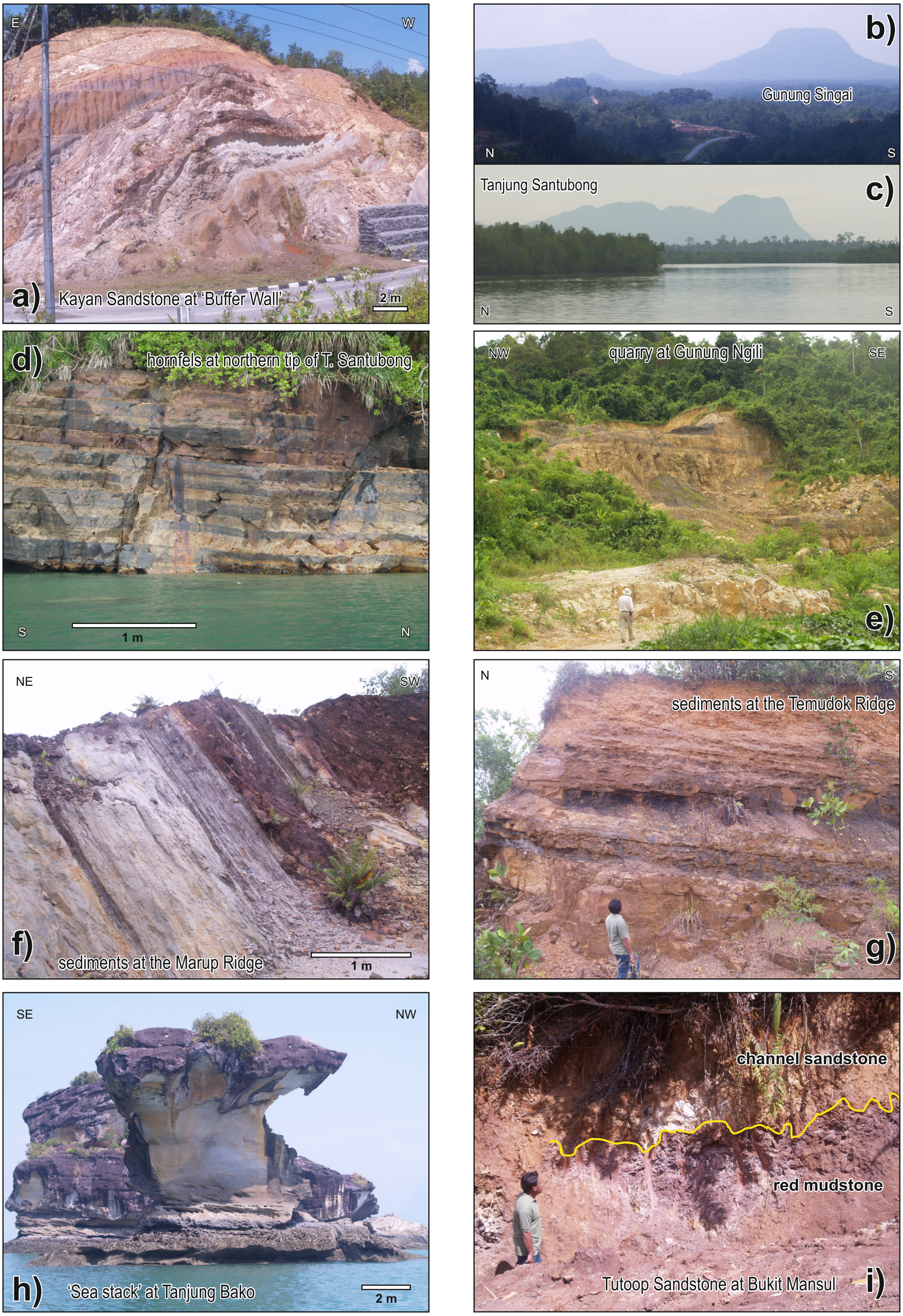

a)
Kayan Sandstone
unconformity
Pedawan Formation
1 m
b)
Kayan Sandstone
Pedawan Formation
20 cm
c)
Kayan Sandstone
unconformity
Pedawan Formation
d)
Kayan Sandstone
unconformity
Pedawan Formation
1 m
e)
fining up
f)

Fig. 6



E
W
a)
Kayan Sandstone at 'Buffer Wall'
2 m
b)
Gunung Singai
N
S
Tanjung Santubong
c)
N
S
d)
hornfels at northern tip of T. Santubong
S
1 m
N
NW
quarry at Gunung Ngili
SE
e)
NE
SW
f)
sediments at the Marup Ridge
1 m
N
S
sediments at the Temudok Ridge
g)
SE
NW
h)
'Sea stack' at Tanjung Bako
2 m
channel sandstone
red mudstone
Tutoop Sandstone at Bukit Mansul
i)

Fig. 7

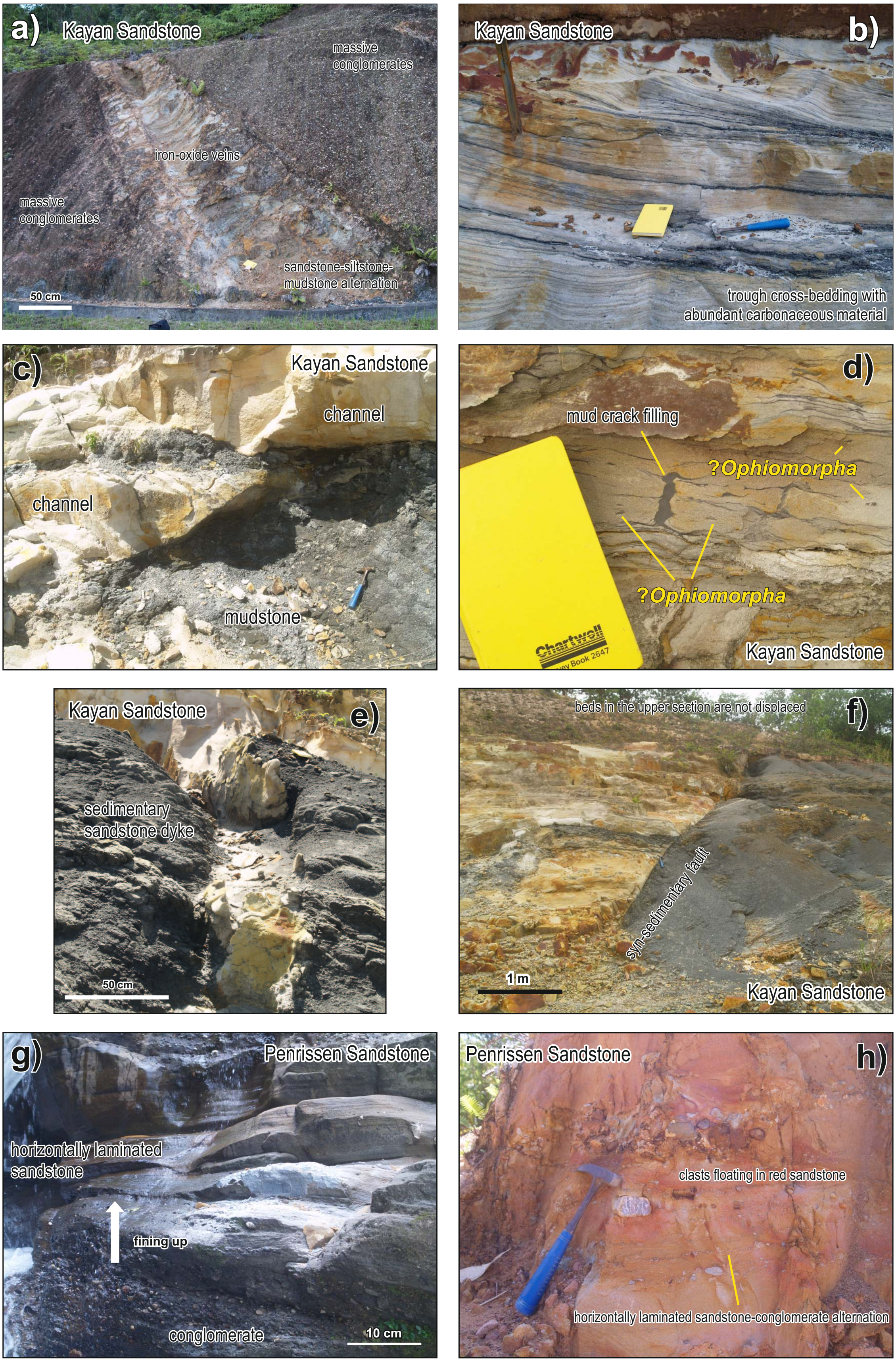
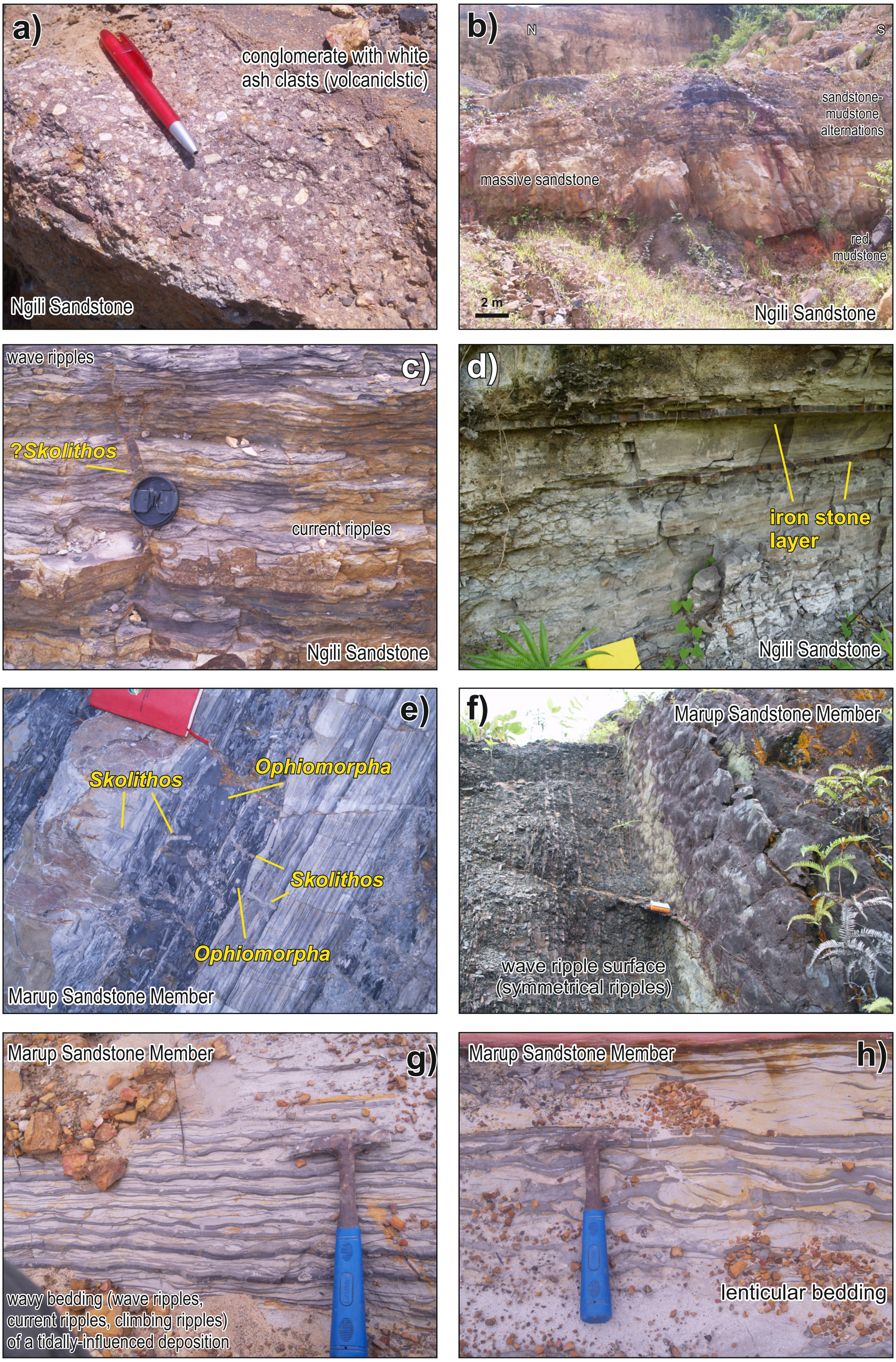

a)
Kayan Sandstone
massive conglomerates
iron-oxide veins
massive conglomerates
sandstone-siltstone-mudstone alternation
50 cm
Kayan Sandstone
b)
trough cross-bedding with abundant carbonaceous material
c)
Kayan Sandstone
channel
channel
mudstone
d)
mud crack filling
?Ophiomorpha
?Ophiomorpha
Kayan Sandstone
Kayan Sandstone
e)
sedimentary sandstone dyke
50 cm
beds in the upper section are not displaced
f)
syn-sedimentary fault
1 m
Kayan Sandstone
g)
Penrissen Sandstone
horizontally laminated sandstone
fining up
conglomerate
10 cm
Penrissen Sandstone
h)
clasts floating in red sandstone
horizontally laminated sandstone-conglomerate alternation

Fig. 8



a)
conglomerate with white ash clasts (volcaniclstic)
Ngili Sandstone
b)
N
S
sandstone-mudstone alternations
massive sandstone
red mudstone
2 m
Ngili Sandstone
wave ripples
c)
?Skolithos
current ripples
Ngili Sandstone
d)
iron stone layer
Ngili Sandstone
e)
Skolithos
Ophiomorpha
Skolithos
Ophiomorpha
Marup Sandstone Member
f)
Marup Sandstone Member
wave ripple surface (symmetrical ripples)
Marup Sandstone Member
g)
wavy bedding (wave ripples, current ripples, climbing ripples) of a tidally-influenced deposition
Marup Sandstone Member
h)
lenticular bedding

Fig. 9

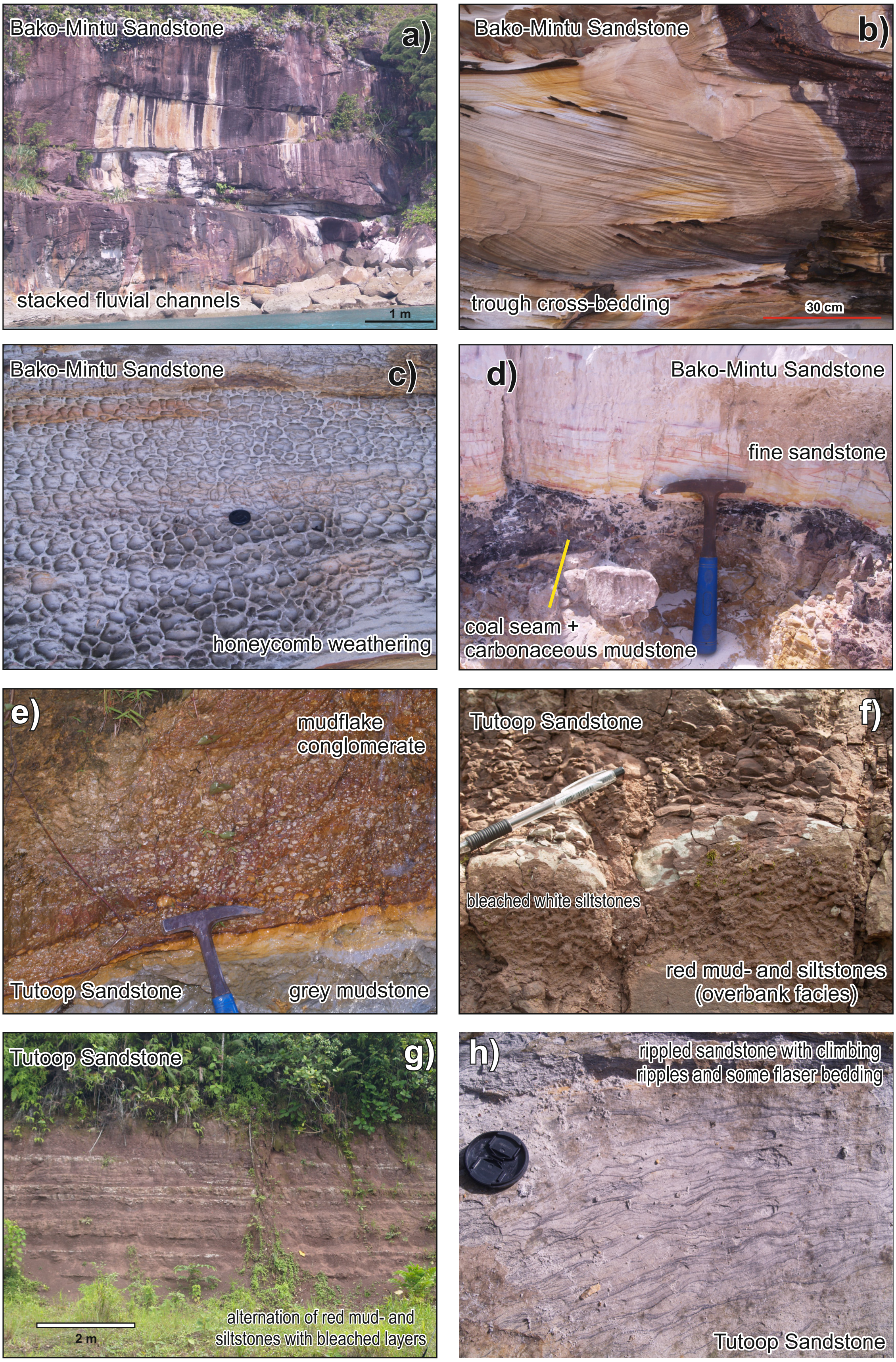

Bako-Mintu Sandstone
a)
stacked fluvial channels
1 m
Bako-Mintu Sandstone
b)
trough cross-bedding
30 cm
Bako-Mintu Sandstone
c)
honeycomb weathering
d)
Bako-Mintu Sandstone
fine sandstone
coal seam +
carbonaceous mudstone
e)
mudflake
conglomerate
Tutoop Sandstone
grey mudstone
Tutoop Sandstone
f)
bleached white siltstones
red mud- and siltstones
(overbank facies)
Tutoop Sandstone
g)
2 m
alternation of red mud- and
siltstones with bleached layers
h)
rippled sandstone with climbing
ripples and some flaser bedding
Tutoop Sandstone

Fig. 10

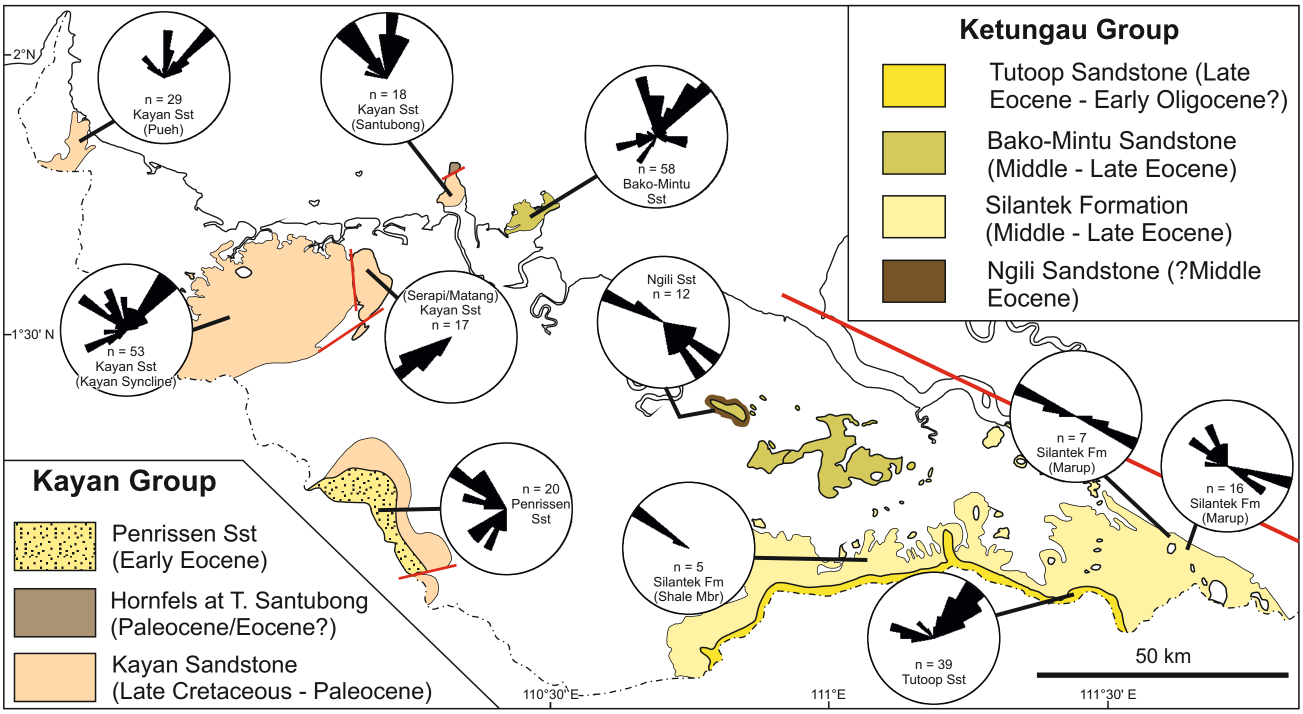
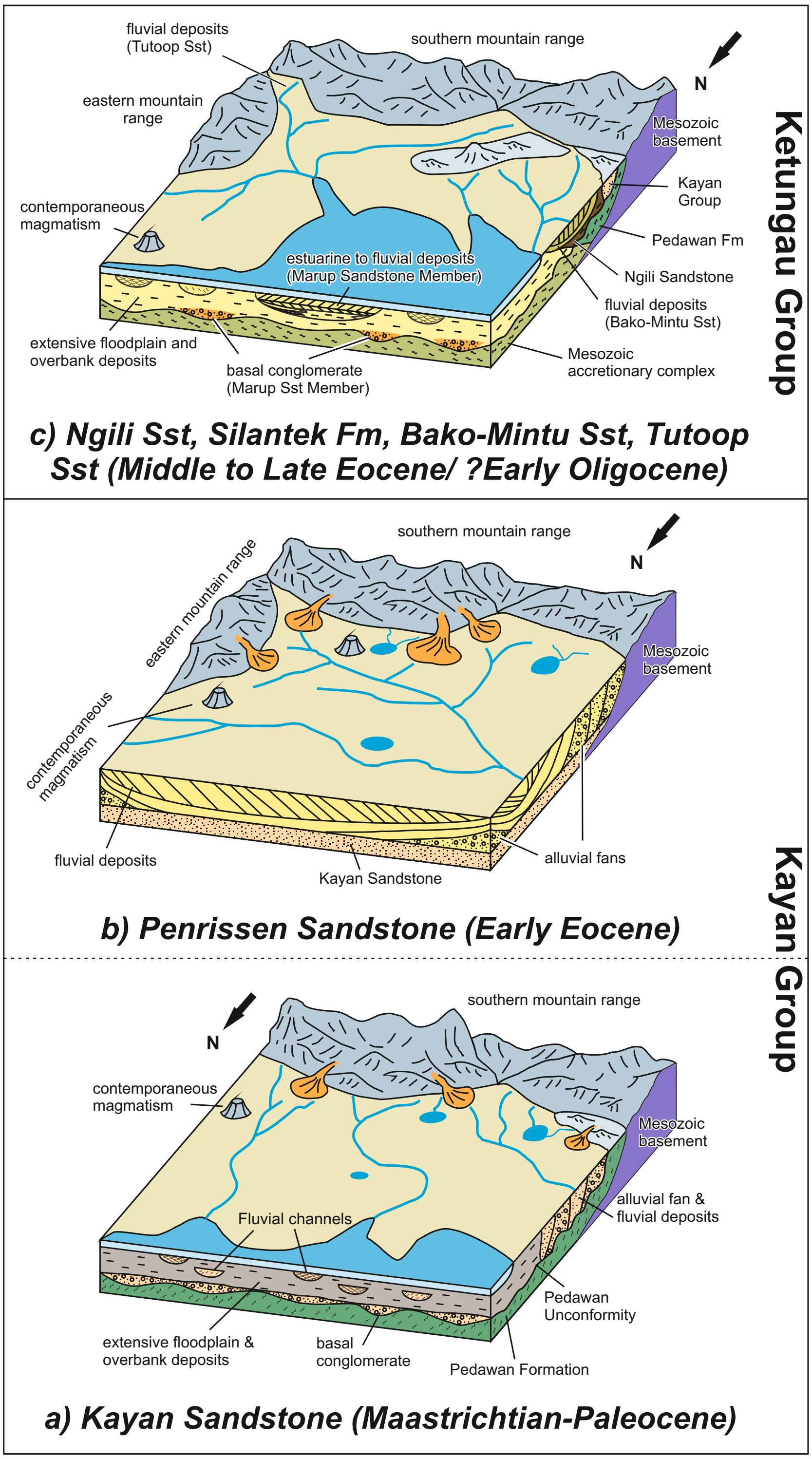

Ketungau Group
Tutoop Sandstone (Late Eocene - Early Oligocene?)
Bako-Mintu Sandstone (Middle - Late Eocene)
Silantek Formation (Middle - Late Eocene)
Ngili Sandstone (?Middle Eocene)
Kayan Group
Penrissen Sst (Early Eocene)
Hornfels at T. Santubong (Paleocene/Eocene?)
Kayan Sandstone (Late Cretaceous - Paleocene)
2°N
1°30' N
110°30' E
111°E
111°30' E
50 km
n = 29 Kayan Sst (Pueh)
n = 18 Kayan Sst (Santubong)
n = 58 Bako-Mintu Sst
n = 53 Kayan Sst (Kayan Syncline)
(Serapi/Matang) Kayan Sst n = 17
Ngili Sst n = 12
n = 7 Silantek Fm (Marup)
n = 16 Silantek Fm (Marup)
n = 20 Penrissen Sst
n = 5 Silantek Fm (Shale Mbr)
n = 39 Tutoop Sst

Fig. 11



fluvial deposits (Tutoop Sst)
southern mountain range
N
eastern mountain range
Mesozoic basement
Kayan Group
contemporaneous magmatism
Pedawan Fm
estuarine to fluvial deposits (Marup Sandstone Member)
Ngili Sandstone
fluvial deposits (Bako-Mintu Sst)
extensive floodplain and overbank deposits
Mesozoic accretionary complex
basal conglomerate (Marup Sst Member)
c) Ngili Sst, Silantek Fm, Bako-Mintu Sst, Tutoop Sst (Middle to Late Eocene/ ?Early Oligocene)
Ketungau Group
southern mountain range
eastern mountain range
N
Mesozoic basement
contemporaneous magmatism
fluvial deposits
alluvial fans
Kayan Sandstone
b) Penrissen Sandstone (Early Eocene)
Kayan Group
southern mountain range
N
contemporaneous magmatism
Mesozoic basement
alluvial fan & fluvial deposits
Fluvial channels
Pedawan Unconformity
extensive floodplain & overbank deposits
basal conglomerate
Pedawan Formation
a) Kayan Sandstone (Maastrichtian-Paleocene)

Fig. 12

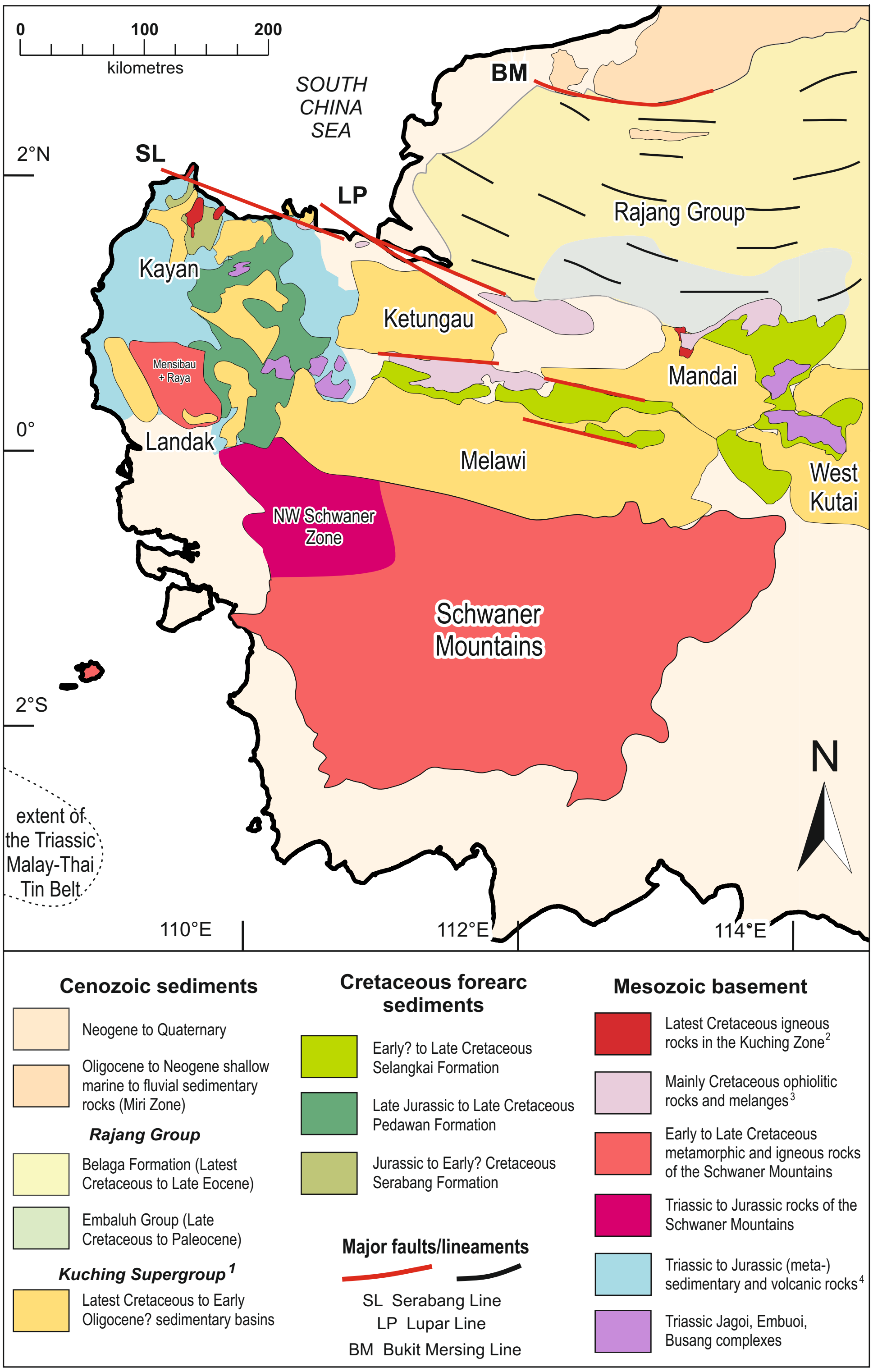

0
100
200
kilometres
SOUTH CHINA SEA
2°N
0°
2°S
SL
LP
BM
Rajang Group
Kayan
Ketungau
Mensibau + Raya
Mandai
Landak
Melawi
West Kutai
NW Schwaner Zone
Schwaner Mountains
N
extent of the Triassic Malay-Thai Tin Belt
110°E
112°E
114°E
Cenozoic sediments
Neogene to Quaternary
Oligocene to Neogene shallow marine to fluvial sedimentary rocks (Miri Zone)
Rajang Group
Belaga Formation (Latest Cretaceous to Late Eocene)
Embaluh Group (Late Cretaceous to Paleocene)
Kuching Supergroup 1
Latest Cretaceous to Early Oligocene? sedimentary basins
Cretaceous forearc sediments
Early? to Late Cretaceous Selangkai Formation
Late Jurassic to Late Cretaceous Pedawan Formation
Jurassic to Early? Cretaceous Serabang Formation
Major faults/lineaments
SL Serabang Line
LP Lupar Line
BM Bukit Mersing Line
Mesozoic basement
Latest Cretaceous igneous rocks in the Kuching Zone 2
Mainly Cretaceous ophiolitic rocks and melanges 3
Early to Late Cretaceous metamorphic and igneous rocks of the Schwaner Mountains
Triassic to Jurassic rocks of the Schwaner Mountains
Triassic to Jurassic (meta-) sedimentary and volcanic rocks 4
Triassic Jagoi, Embuoi, Busang complexes

Fig. 13

Author	Sample Nos	Assemblage	Fossils	Age
Haile (1957)	S4392	**1**	*Actinocyclina* sp.	Late Eocene
			Nummulites spp. (small type with few coils)	
			Heterostegina sp.	
			Rotalia sp.	
	My 1426-7	**2**	*Ammodiscus* sp.	Paleocene to Holocene
	My 1435-6		*Ammobaculites 9*	
	My 1676-1678		*Anomalia 12*	
	Alt 881-883		*Cyclammina* cf. *8*	
	Alt 888-892		*Haplophragmoides 6*	
	Jal-4; H 1077; H 1079;		*Quinqueloculina* sp.	
	H 1081-1085		*Sigmoilina* sp.	
	H1186		*Trochammina* sp.	
	My 1518-1522	**3**	*Haplophragmoides* sp.	Cretaceous to Holocene
			Trochammina sp.	
	T79; T101; T102; T106	**4**	*Glomospira* sp.	indet.
Tan (1979)	K6852	**5**	*Amphistegina* spp.	Eocene
			Asterigerina spp.	
			Operculina spp.	
			Elphidium spp.	
			Quinqueloculina spp.	
			Discocyclina spp.	
	K6871	**6**	*Assilina* sp. aff. *A. praespira* Douville	Late Paleocene (planktonic zone P4) to Middle Eocene (planktonic zone P14)
	K6290	**7**	*Anomalina* spp.	Late Paleocene - Eocene
	K6293		*Operculina* spp.	
	K6457		*Operculinella* sp.	
	K6922		*Sigmoilina* sp.	
			Miliammina sp.	
			Nonion sp.	
			Quinqueloculina sp.	

Sadong Valley (Haile, 1954)	Undup Valley (Haile, 1957)	Undup Valley (Tan, 1979)	this study	
			Marup Ridge - G. Menuku	**G. Ngili - T. Bako**
Plateau Sandstone Formation (> 300 m)	Plateau Sandstone Formation (> 150 m)	Plateau Sandstone (150 m)	Tutoop Sandstone (800 m)	
Upper Silantek Beds (0-61 m)	Upper Kantu Beds (305 m)	Upper Silantek Redbed Member (300 m)		
Middle Silantek Beds (915 m)	Lower Kantu Beds (total c. 4100 m)	Silantek Formation (total c. 4800 m)	Silantek Formation (total 2600-3000 m)	Bako-Mintu Sandstone (> 250 m)
	Upper Shale Zone; 1524 m	*main Silantek; 3000 m*	*Shale Member; 1000-2000 m*	*140 m in Mintu area*
	Temudok Sandstone; 152 m	*Temudok Member; 200 m*	*Temudok Sst Member; 130 m*	*160 m at G. Ngili*
	Lower Shale Zone; 1220 m			*240 m at T. Bako*
Lower Silantek Beds (152 m)	*Basal Sandstone; 1220 m*	*Basal Sandstone Member; 1600 m*	*Marup Sandstone Member; 800 m*	
				Ngili Sandstone (100 m)