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The Kuching Formation: A deep marine equivalent of the Sadong Formation, and its implications for the Early Mesozoic tectonic evolution of western and southern Borneo

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Abstract: The pre-Cretaceous history of Borneo remains relatively poorly studied. Limited exposures of Palaeozoic and lower Mesozoic rocks are located in NW Kalimantan and in West Sarawak, an area interpreted as the West Borneo basement. Lower Mesozoic sedimentary rocks in West Sarawak were analysed to study their depositional environments and implications for the tectonic evolution. Upper Triassic turbidites in West Sarawak, exposed in the northern part of Kuching city, informally named the Kuching Formation, are the deep marine equivalent to the more widespread, shallow marine Sadong Formation. The Kuching Formation comprises thinly-bedded stacked turbidites, consisting of incomplete Bouma sequences, with multiple, erosive channel sandstone bodies deposited under upper flow regime waning flows. Thin debrites with abundant coaly-material are interbedded with the channel sandstones. The Kuching and Sadong formations both contain volcaniclastic detritus that was derived from the westward-subducting Palaeo-Pacific plate, forming a Triassic Andean-type arc which extended from West Borneo in the south to southern China, Taiwan and Japan in the north. Palaeoproterozoic to Archean detrital zircons in the Kuching and Sadong formations reveal a Cathaysian basement source, providing insights into the nature of the West Borneo basement. Quartz-mica schists (Kerait Schist, Tuang Formation) in fault-contact with the two sedimentary successions may have formed during accretion.

Keywords: Kuching Formation turbidites, West Sarawak Metamorphics, Sadong Formation, Palaeo-Pacific subduction, Sarawak stratigraphy, Triassic active continental margin

INTRODUCTION

The pre-Cretaceous tectonic evolution of Borneo remains poorly understood largely due to the sparsity of exposed Palaeozoic and early Mesozoic rocks. Western and central Borneo are subdivided into several tectono-stratigraphic zones, comprising, from south to north: SW Borneo, the Kuching Zone, Sibu Zone, and Miri Zone (Haile, 1974). Of these, the Kuching Zone and SW Borneo contain several outcrops of pre-Cenozoic rocks. The Kuching Zone occurs in West Sarawak, as well as NW and Central Kalimantan, and is characterised by Cenozoic sedimentary basins filled with fluvial-tidal deposits, unconformably overlying pre-Cenozoic igneous, metamorphic and sedimentary rocks that range in age from Ordovician to Late Cretaceous (Figure 1) (Haile, 1974; Williams *et al*., 1988; Tate, 1991; Hutchison, 2005; Breitfeld *et al*., 2017, 2018; Hennig, J. *et al*., 2017; Zhu *et al*., 2022). The geology of SW Borneo is dominated by Cretaceous igneous and volcanic rocks of the Schwaner Mountains (Figure 1) (Haile, 1974; Haile *et al*., 1977; Williams *et al*., 1988; Hennig, J. *et al*., 2017; Breitfeld *et al*., 2020a; Qian *et al*., 2022).

The Palaeozoic and lower Mesozoic rocks of the Kuching Zone are assigned either to the Semitau block, a basement fragment interpreted to be derived from the East Asian margin during the Cretaceous or early Cenozoic (Metcalfe, 2013, 2017, 2021), or to the West Borneo part of Sundaland more or less in its current position since at least the Triassic (Breitfeld *et al*., 2017; Hall, 2017; Hennig, J. *et al*., 2017). SW Borneo is considered to have been derived from the Australian margin in the Jurassic (Hall, 2012; Metcalfe, 2013, 2017, 2021; Breitfeld *et al*., 2020a). Metamorphic rocks in these two continental fragments, e.g., the Pinoh Metamorphic Group of the Schwaner Mountains and the Kerait Schist of West Sarawak, were assumed to be

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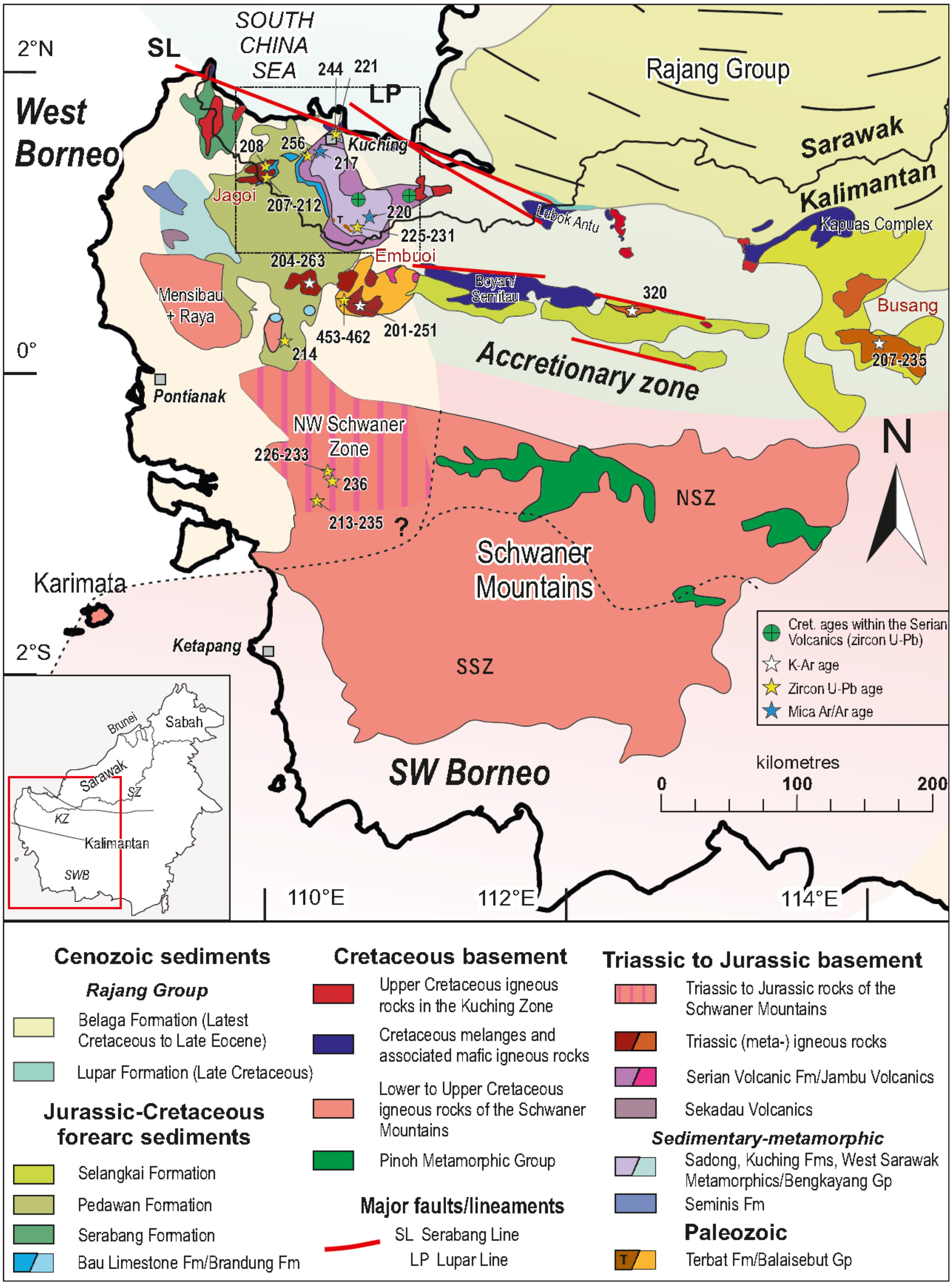

Figure 1: Basement map of southwest Borneo illustrating the different tectonic zones (modified from Breitfeld *et al*., 2020a; Breitfeld, 2021). Lower Mesozoic and Palaeozoic rocks are located in West Borneo. SW Borneo consists mainly of Cretaceous igneous and metamorphic rocks. The basement of the eastern Kuching Zone is formed by accreted material. The Rajang Group turbidite fan forms the sedimentary cover of the Sibu Zone. Age results (in Ma) and location of Pre-Cretaceous rocks from Embuoi-Semitau-Busang (K-Ar): Williams *et al*. (1988), Bladon *et al*. (1989); Embuoi schists (U-Pb): Zhu, J. *et al*. (2022); NW Schwaner Zone: Setiawan *et al*. (2013), Hennig J. *et al*. (2017), Batara & Xu (2022), Wang, Y. *et al*. (2021a); NW Kalimantan & West Sarawak: Breitfeld *et al*. (2017), Wang, Y. *et al*. (2021a), Zhou *et al*. (2023). Cretaceous ages of volcanics mapped as Serian Volcanic Formation from Wang, Y. *et al*. (2021b). (Insert figure: KZ-Kuching Zone, SZ-Sibu Zone, SWB-SW Borneo). Insert box is location of Figure 2.

the pre-Permian or pre-Carboniferous basement of Borneo, based solely on the fact that they were metamorphosed, while the surrounding rocks exhibit little or no deformation (Pimm, 1965; Tate, 1991; Tate & Hon, 1991; Amiruddin & Trail, 1993; Pieters & Sanyoto, 1993; Hutchison, 2005). The lack of age dating of these rocks has long been problematic and hindered development of a comprehensive stratigraphy of western and southern Borneo, as well as understanding of their tectonic history.

In recent years several age dating studies using zircon U-Pb, mica Ar/Ar or whole rock Ar/Ar analyses have presented new ages for pre-Cenozoic igneous, metamorphic and sedimentary rocks of western Borneo (Davies *et al*., 2014; Breitfeld *et al*., 2017, 2020a; Hennig, J. *et al*., 2017; Wang, Y. *et al*., 2021a, 2021b, 2022a, 2022b; Zhu, J. *et al*., 2022) that help to better constrain the tectonic evolution of Borneo, and resolve miscorrelations and age assumptions (e.g., Mohamad *et al*., 2020; Breitfeld & Hall, 2021). Many of the supposed Palaeozoic basement schists revealed much younger ages, e.g., Pinoh Metamorphic Group is dated as Cretaceous (Breitfeld *et al*., 2020a) and schists in West Sarawak are of Late Triassic age (Breitfeld *et al*., 2017), indicating that current tectonic models require rethinking.

This paper presents results of fieldwork undertaken on a Triassic turbidite succession from the Kuching Zone in West Sarawak that was previously included in the metamorphic Tuang Formation, formerly thought to be pre-Carboniferous based on the presence of a ‘dubious fossil tentaculid’ and its metamorphic grade (Tate, 1991; Tate & Hon, 1991). As the occurrences of these rocks are restricted to the Kuching District, mainly below Plio-/Pleistocene river terraces of the Sungai Santubong in northern Kuching (Tate & Hon, 1991; Tan, 1993; Breitfeld, 2021), Breitfeld *et al*. (2017) suggested the term Kuching Formation for the turbidites. This contribution further develops ideas presented in Breitfeld *et al*. (2017) and provides more detailed description and discussion on dating and provenance of these deep water Triassic strata. For this, available zircon U-Pb data and white mica Ar/Ar data from Breitfeld (2015) and Breitfeld *et al*. (2017) are reviewed in detail, and zircon morphology information is added to the dataset. Zircon U-Pb data from one sample of the Kuching Formation presented by Zhou *et al*. (2023) is also considered. In addition, the age relationships of the turbidites with the Upper Triassic Sadong Formation and West Sarawak Metamorphics (Kerait Schist and Tuang Formation) are discussed in detail.

REGIONAL SETTING

The island of Borneo was assembled by amalgamation of several continental fragments throughout the Mesozoic and Cenozoic (Hamilton, 1979; Hutchison, 1989; Metcalfe, 1996, 2013; Hall, 2012; Breitfeld *et al*., 2017; Hennig, J. *et al*., 2017). It now consists of the microcontinental blocks SW Borneo, West Borneo (or Semitau), the west part of East Java-West Sulawesi, NW Sulawesi-East Sabah, Mesozoic accreted material, and extended South China crust (e.g., Hall, 2012, 2017; Metcalfe, 2013; Hennig, J. *et al*., 2016, 2017; Breitfeld *et al*., 2017).

The majority of basement rocks in southern Borneo are the Cretaceous Schwaner Mountain batholiths associated with the Palaeo-Pacific subduction (Williams *et al*., 1988; Hennig, J. *et al*., 2017; Breitfeld *et al*., 2020a; Batara & Xu, 2022; Qian *et al*., 2022; Wang, Y. *et al*., 2022b). The metamorphosed volcanic rocks of the Pinoh Metamorphic Group, long assumed to be Palaeozoic (e.g., van Bemmelen, 1949; Haile, 1974; Tate, 1991; Amiruddin & Trail, 1993) or pre-Early Cretaceous (Supriatna *et al*., 1993), have been dated as Cretaceous and were also associated with the Schwaner subduction arc (Breitfeld *et al*., 2020a). Older basement rocks are rare, and the pre-Jurassic evolution of southern Borneo is poorly studied although in recent years knowledge of the Triassic has improved (e.g., Setiawan *et al*., 2013; Breitfeld *et al*., 2017; Hennig, J. *et al*., 2017). Recent age dating of the metamorphic rocks in West Sarawak established a Late Triassic depositional age (Breitfeld *et al*., 2017) and the Cretaceous age of the Pinoh Metamorphic Group (Breitfeld *et al*., 2020a) indicates that the stratigraphy and tectonic evolution of southern Borneo requires a new interpretation.

West Sarawak – Triassic stratigraphy

The distribution of Triassic rocks in West Sarawak is displayed in Figure 2 and a revised stratigraphic chart for the Carboniferous to Palaeocene is shown in Figure 3. Triassic rocks are widespread in West Sarawak (Figure 1) and consist predominantly of volcaniclastic sedimentary and meta-sedimentary rocks of the Sadong Formation. These include mudstones, siltstones, sandstones, shales, conglomerates, metasediments, thin limestone beds, marl and coal (Liechti *et al*., 1960; Wilford & Kho, 1965; Hutchison, 2005). Tuffaceous mudstone and volcanic rock fragments are commonly interbedded throughout the succession (Wilford & Kho, 1965), and record contemporaneous volcaniclastic input. The Sadong Formation is interpreted to represent an estuarine to neritic deposit (Liechti *et al*., 1960) with periodic brackish water influence (Wilford & Kho, 1965). The age of deposition is considered to be Carnian to Norian (Late Triassic; Figure 3) based on a limited assemblage of plant material, named the Krusin flora, which has a Cathaysian affinity (Kon’no, 1972), and from fossil bivalves (in particular *Halobia* sp.) reported from the succession (Liechti *et al*., 1960; Pimm, 1965; Wilford & Kho, 1965). Breitfeld *et al*. (2017) presented maximum depositional ages from Carnian to Norian for the Sadong Formation based on the youngest zircon grains (Table 1), indicating contemporaneous or near-contemporaneous magmatism during deposition of the Sadong Formation.

The Serian Volcanic Formation (see Figures 1 & 2) represents the most widespread mapped Triassic igneous formation that extends also into NW Kalimantan (e.g., Heng,

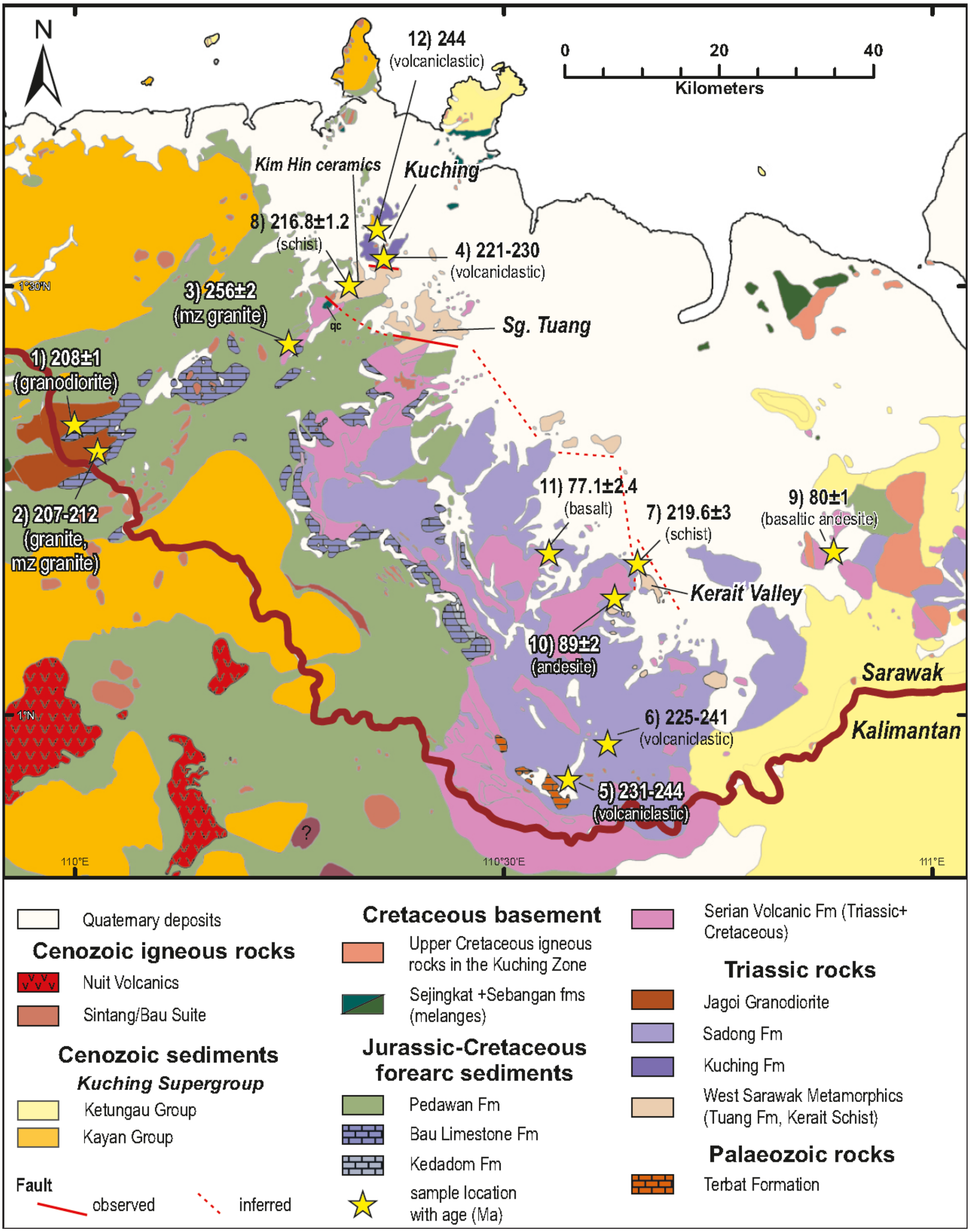

Figure 2: Map of central West Sarawak, showing the distribution of the Upper Triassic Sadong and Kuching formations, along the belt of Upper Triassic metamorphic rocks (based on Liechti *et al*., 1960; Heng, 1992; Breitfeld *et al*., 2017). Recent age data: 1 and 2: Jagoi Granodiorite (Breitfeld *et al*., 2017; Wang, Y. *et al*., 2021a), 3: Monzogranite within the Serian Volcanic Formation (Wang, Y. *et al*., 2021a), 4: Kuching Formation (Breitfeld *et al*., 2017); 5 and 6: Sadong Formation (Breitfeld *et al*., 2017), 7 and 8: Kerait Schist and Tuang Formation (West Sarawak Metamorphics) (Breitfeld *et al*., 2017). 9-11: Upper Cretaceous basic volcanics mapped as Serian Volcanic Formation (Wang, Y. *et al*., 2021b), 12: Kuching Formation (Zhou *et al*., 2023). (mz granite-monzo granite). Location of map is shown in Figure 1. (Sg. – Sungai).

1992; Supriatna *et al*., 1993). Up until recently no age data from the formation was available and it was interpreted as Triassic based on an interfingering relationship with the sedimentary Triassic Sadong Formation (Pimm, 1965; Wilford & Kho, 1965), although Liechti *et al*. (1960) considered the Sadong Formation to be above the Serian Volcanic Formation. The formation consists mainly of andesite, tuff and basalt (Pimm, 1965; Wilford & Kho, 1965). Recently, Wang, Y. *et al*. (2021b) reported two Late Cretaceous U-Pb zircon ages (80 ± 1 Ma, 89 ± 2 Ma) and a whole rock Ar/Ar age (77.1 ± 2.4 Ma) for andesite and basalt mapped as Serian Volcanics (Table 1) near the town of Serian (Figures 1 & 2), which placed into question the assumed Triassic age of the formation and its equivalents in NW Kalimantan. In contrast, the Binong tuff bed, thought to be part of the Serian Volcanic Formation, yielded Lower Jurassic radiolaria (Basir *et al*., 1996; Basir & Uyop, 1999). Pimm (1965) and Wilford & Kho (1965) also reported that the Serian Volcanic Formation is unconformably overlain by the Jurassic limestones of the Kedadom and Bau formations and by the clastic sedimentary rocks of the Upper Jurassic to Cretaceous Pedawan Formation. A monzonitic granite within the Serian Volcanic Formation south of Kuching (Figures 1 & 2) has been dated as 256 ± 2 Ma (Table 1; Wang, Y. *et al*., 2021a), indicating that within the predominantly mafic extrusive formation there is also felsic plutonic material that is pre-Cretaceous. Wang, Y. *et al*. (2021a) suggested that the Serian Volcanic Formation should be sub-divided into the Cretaceous Serian Volcanics and Triassic volcanic rocks

Table 1: Sarawak age data table.

No	Sample ID	Lithology	Formation/ pluton	Age (Ma)	Error (1σ)	Method	Longitude	Latitude	Reference
Permian-Triassic									
1	TB114	granodiorite	Jagoi Granodiorite	208	1	zr U-Pb	109.99646	1.33366	Breitfeld *et al.* (2017)
2	17MY-81B$_1$	granite	Jagoi Granodiorite	207	1	zr U-Pb	109.98722	1.32139	Wang, Y. *et al.* (2021a)
2	17MY-81A	monzonitic granite	Jagoi Granodiorite	212	1	zr U-Pb	109.98722	1.32139	Wang, Y. *et al.* (2021a)
3	17MY-84A1	monzonitic granite	Intrusive equivalent to Serian Volcanic Fm?	256	2	zr U-Pb	110.26778	1.43778	Wang, Y. *et al.* (2021a)
4	TB250	volcaniclastic sediment	Kuching Fm	221-230*		zr U-Pb	110.36448	1.53395	Breitfeld *et al.* (2017)
5	712	volcaniclastic sediment	Sadong Fm	231-244*		zr U-Pb	110.54335	0.94992	Breitfeld *et al.* (2017)
6	713b	volcaniclastic sediment	Sadong Fm	225-241*		zr U-Pb	110.60248	0.99672	Breitfeld *et al.* (2017)
7	combined	volcaniclastic sediment	Sadong-Kuching fms	230.7	1.1	zr U-Pb	-	-	this study
8	TB35	q-mica schist	West Sarawak Metamorphics (Kerait Schist)	219.6	3	mica Ar-Ar	110.65461	1.17556	Breitfeld *et al.* (2017)
9	TB249	q-mica schist	West Sarawak Metamorphics (Tuang Fm)	216.8	1.2	mica Ar-Ar	110.32029	1.49617	Breitfeld *et al.* (2017)
Late Cretaceous (previously assumed Triassic Serian Volcanic Formation)									
10	17MY-68A$_1$	basaltic andesite	younger ‘Serian V. Fm’?	80	1	zr U-Pb	110.88417	1.17667	Wang, Y. *et al.* (2021b)
11	17MY-70A$_2$	andesite	younger ‘Serian V. Fm’?	89	2	zr U-Pb	110.63306	1.13306	Wang, Y. *et al.* (2021b)
12	17MY-71A$_1$	basalt	younger ‘Serian V. Fm’?	77.1	2.4	WR Ar-Ar	110.57	1.14139	Wang, Y. *et al.* (2021b)

associated with the Sadong Formation, which in future could be assigned to different formations (Figure 3). New detailed mapping is required to determine the extent and stratigraphic relationships of the Cretaceous andesites.

Similar granitoids with Triassic ages are known from West Borneo (e.g., Williams *et al*., 1988). The Jagoi Granodiorite (Figures 1 & 2) is dated by zircon U-Pb analysis as 209 ± 1 Ma (Breitfeld *et al*., 2017), and, along the border with Kalimantan, Wang, Y. *et al*. (2021a) presented zircon U-Pb ages of 207-212 Ma (Table 1). Middle Permian to Triassic granitoid and meta-granitoid plutons have also been identified in NW Kalimantan in the Embuoi Complex (Williams *et al*., 1988; Bladon *et al*., 1989; Wang, Y. *et al*., 2021a) and in the NW Schwaner Zone farther to the south (Setiawan *et al*., 2013; Hennig, J. *et al*., 2017; Wang, Y. *et al*., 2021a; Batara & Xu, 2022). These Triassic granitoids mark the southernmost extension of the West Borneo basement (Breitfeld *et al*., 2017; Hennig, J. *et al*., 2017).

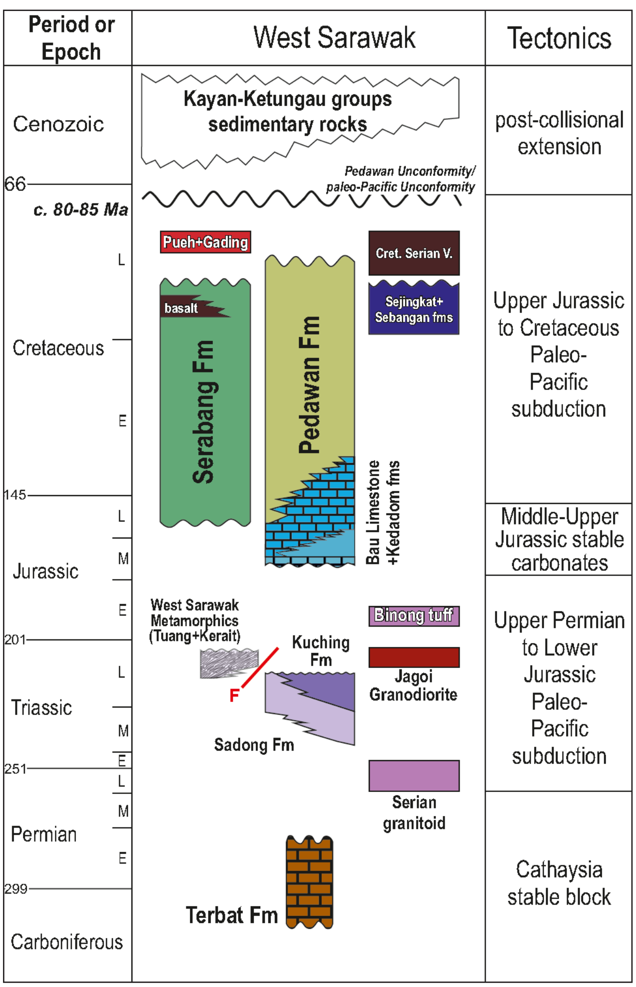

Figure 3: Pre-Cenozoic stratigraphy chart of West Sarawak (based on Liechti *et al*., 1960; Hutchison, 2005; Breitfeld *et al*., 2017). Note that the Kuching Formation is the deep-water lateral equivalent of the Sadong Formation. (V. – Volcanics; Fm – Formation; fms - formations).

TUANG FORMATION - KERAIT SCHIST - KUCHING FORMATION

Metamorphic rocks in West Sarawak, named the Tuang Formation and the Kerait Schist, were interpreted to represent Palaeozoic schists that formed the Borneo basement (e.g., Tate, 1991; Tate & Hon, 1991; Hutchison, 2005). However, Breitfeld *et al*. (2017) reported Triassic Ar/Ar cooling ages from white mica and interpreted these to represent Upper Triassic metamorphism (Table 1) of a potentially Upper Triassic volcaniclastic protolith. Due to the poor exposure of the metamorphic rocks and the inclusion of various rock types into the Tuang Formation, the successions are insufficiently studied. Breitfeld *et al*. (2017) suggested modification to the stratigraphy of the two formations as the turbiditic meta-sedimentary rocks in the Kuching city outcrops lack the schistose character of the Kerait Schist and the Tuang Formation at its type locality (Figure 2).

The Tuang Formation, as it is currently mapped, includes Triassic turbidites in the Kuching area, Triassic quartz-mica schists and mylonites in the Kuap-Sungai Tuang area (Figure 2), as well as a Cretaceous quartz-chlorite schist fault block at Jalan Datu Stephen Yong in southern Kuching (Tate & Hon, 1991; Tan, 1993; Breitfeld *et al*., 2017). The Triassic quartz-mica Kerait Schist in the Kerait Valley (Figure 2) is lithologically and structurally similar to the quartz-mica schist in the Kuap area (Tate & Hon, 1991; Tan, 1993; Breitfeld *et al*., 2017). Breitfeld *et al*. (2017) suggested these two quartz-mica schists and associated metamorphic rocks from the Tuang Formation and Kerait Schist are included into the Triassic West Sarawak Metamorphics. The Triassic meta-sedimentary rocks of the Kuching area were suggested to be a new formation, named the Kuching Formation, and the quartz-chlorite fault block (Figure 2) was interpreted to be related to the Sejingkat Formation and the Cretaceous accretionary complex associated with the Cretaceous Palaeo-Pacific subduction (Breitfeld *et al*., 2017). The turbiditic nature of the meta-sedimentary rocks in the Kuching area were already noted by Tate & Hon (1991), Tate (1991) and Tan (1993), but they were nevertheless included into the Tuang Formation. Although the West Sarawak Metamorphics could be metamorphosed Kuching Formation, they also could represent metamorphosed Sadong Formation, which led Breitfeld *et al*. (2017) to separate the turbiditic meta-sedimentary rocks from the metamorphic rocks. A maximum depositional age of Norian for the Kuching Formation (Figure 3) was reported by Breitfeld *et al*. (2017). The sedimentary structures of the Kuching Formation and its relation to other units are further considered in this study.

FIELD DESCRIPTION OF THE KUCHING FORMATION TURBIDITES

Exposures of the Kuching Formation tubidites are restricted to the area around Kuching city (Figures 2 and 4). The outcrops were either mapped as Tuang Formation (Tan, 1993) or were previously not identified. In contrast to

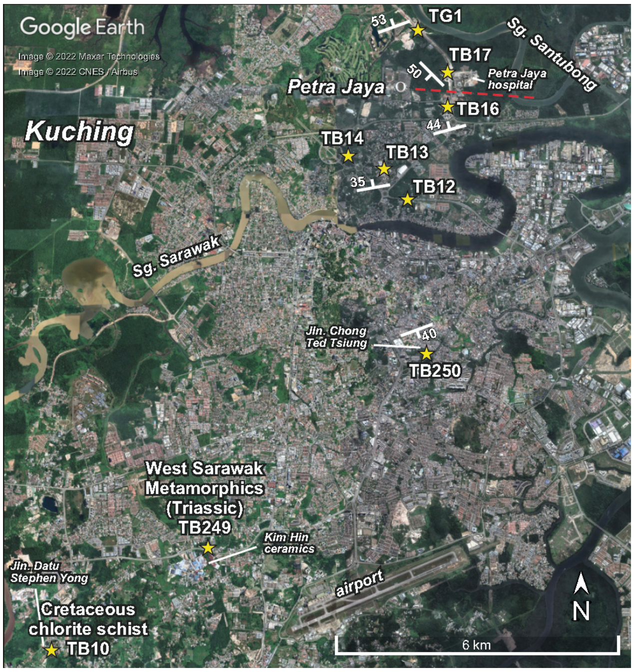

Figure 4: Location of studied section in Kuching City (from Google Earth, earth.google.com/web/) with dipping of beds. Cretaceous chlorite mica schists (TB10) were mapped as Tuang Formation, but likely represents an equivalent to the Sejingkat Formation (Breitfeld *et al*., 2017). (Jl. – Jalan/road; Sg. – Sungai/river).

the Tuang Formation, schistosity, cleavage or foliation are poorly developed in the Kuching Formation. Many of the deformation features observed in the Kuching Formation tubidites and shales can be attributed to soft-sediment remobilisation with only a few being likely related to tectonic deformation. Tan (1993) also noted the difference of the meta-sedimentary rocks in the Kuching area (proposed Kuching Formation) to the schistose character in the Tuang Formation type locality in the Kuap area (proposed part of West Sarawak Metamorphics).

There are no published estimates of the thickness of the Kuching Formation. The Sadong Formation, which is the shallow water estuarine to inner neritic equivalent of the Kuching Formation, is estimated to be c. 2200 to 3000 m in total thickness (Pimm, 1965; Wilford & Kho, 1965), and thus a considerable thickness for the Kuching Formation is probable. Outcrops around Kuching city are discontinuous and only a few metres of the succession are exposed at any one locality. Figure 4 details the location of outcrops observed in this study in Kuching city. They generally dip to the north-northwest, at 35-55^{o}, but they are too scattered for realistic estimates of sediment thickness to be made. Outcrops in the south of the city dip to the south, at ~40^{o}. However, these scattered outcrops do provide insight into the metamorphic character and sedimentary facies of the formation. Metamorphic grade is low, although extensional quartz veining is common. The mudstones have thin laminations and a slight phyllitic character, with a poorly developed cleavage, and are referred to here as shale. White mica is visible under a hand lens. The summary logs compiled for the scattered outcrops in Figure 5 therefore, do not imply lateral correlation or vertical continuity. Rather, they are indicative of the representative lithologies, and sandstone:shale ratios.

Based on lithology, sedimentary structures and grain size, four distinct lithofacies are identified within the Kuching Formation succession: (i) thick-bedded, massive coarse-grained sandstone, with poorly developed low angled cross-bedding, (ii) clast-rich, poorly sorted, coarse-grained sandstones, (iii) thin bedded, graded sandstone, often with rippled tops and (iv) laminated shales/siltstones. Compositionally, sandstones are usually fine grained and quartz-rich, often with a high matrix content. However, the coarser-grained sandstones (facies i and ii) contain lithic fragments including coal, shale, schist, chert and volcanic fragments. Feldspar is usually completely altered to illite or smectite in the exposed road cut sections but has been reported as fresh by Tan (1993) in other locations. Syn-depositional slumping and strong between-bed folding is common in the shale-rich outcrops.

For most of the outcrops, thin-bedded, graded sandstones (facies iii) dominate the exposed Kuching Formation (Figure 5) and are associated with laminated shale beds (facies iv), occasionally exceeding 1 m in thickness (profiles TB-12 and TB-16). Thicker, massive sandstones (facies i) are well developed in profile TB-17, whilst clast-rich sandstones (facies ii) are only present in profiles TB-250 and TG-1 (Figure 5). Section TG-1 on Jalan Casuarina, is dominated by thicker-bedded, coarser-grained sandstones (facies i) up to 2 m in thickness (Figure 5).

Lithofacies

Thick-bedded, medium- to coarse-grained, massive sandstone (facies i)

Massive sandstones are less frequently present within the formation, and only observed in sections TB-17 and TG-1 (Figure 5) with a single bed in TB250. They are characteristically medium-grained, clean white-coloured quartz-rich sandstone with moderate to poor sorting, although the upper part of section TG-1 is dominated by coarse-grained massive sandstones, many of which contain pebbly basal lags (Figures 6A & 6B). Bed thickness is typically 30-50 cm but can be up to 2 m, and bed geometry is often concave upward, forming laterally extensive channels, but also sheet-like bed geometry is present. Channels are stacked, often with thin shale beds between them (Figures 6B & 6C), but sandstone bases are often recognised by the presence of pebble lags. Thicker beds are the result of amalgamated sandstone deposits (Figure 6C). No obvious grading as in a Bouma T_a unit has been observed. Bed bases are generally sharp but lack clear evidence of erosion (Figure 6D). Although most of these beds are structureless and appear massive, low-angled and plane bedding is locally preserved

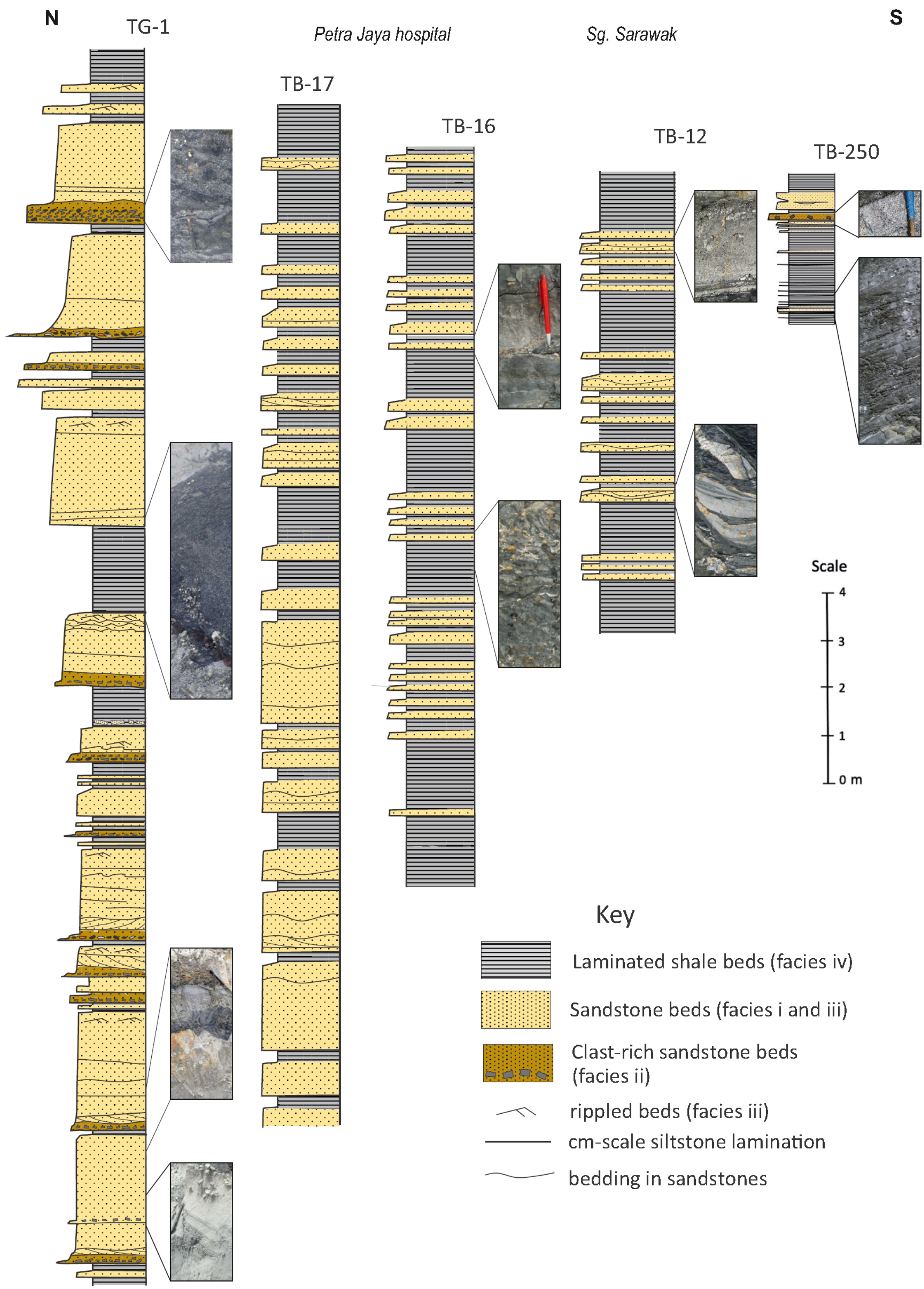

Figure 5: Graphic logs showing lithology, grain size and sedimentary structures of the exposed sections in and around the city of Kuching. No lateral correlation is implied by the juxtaposition of logs.

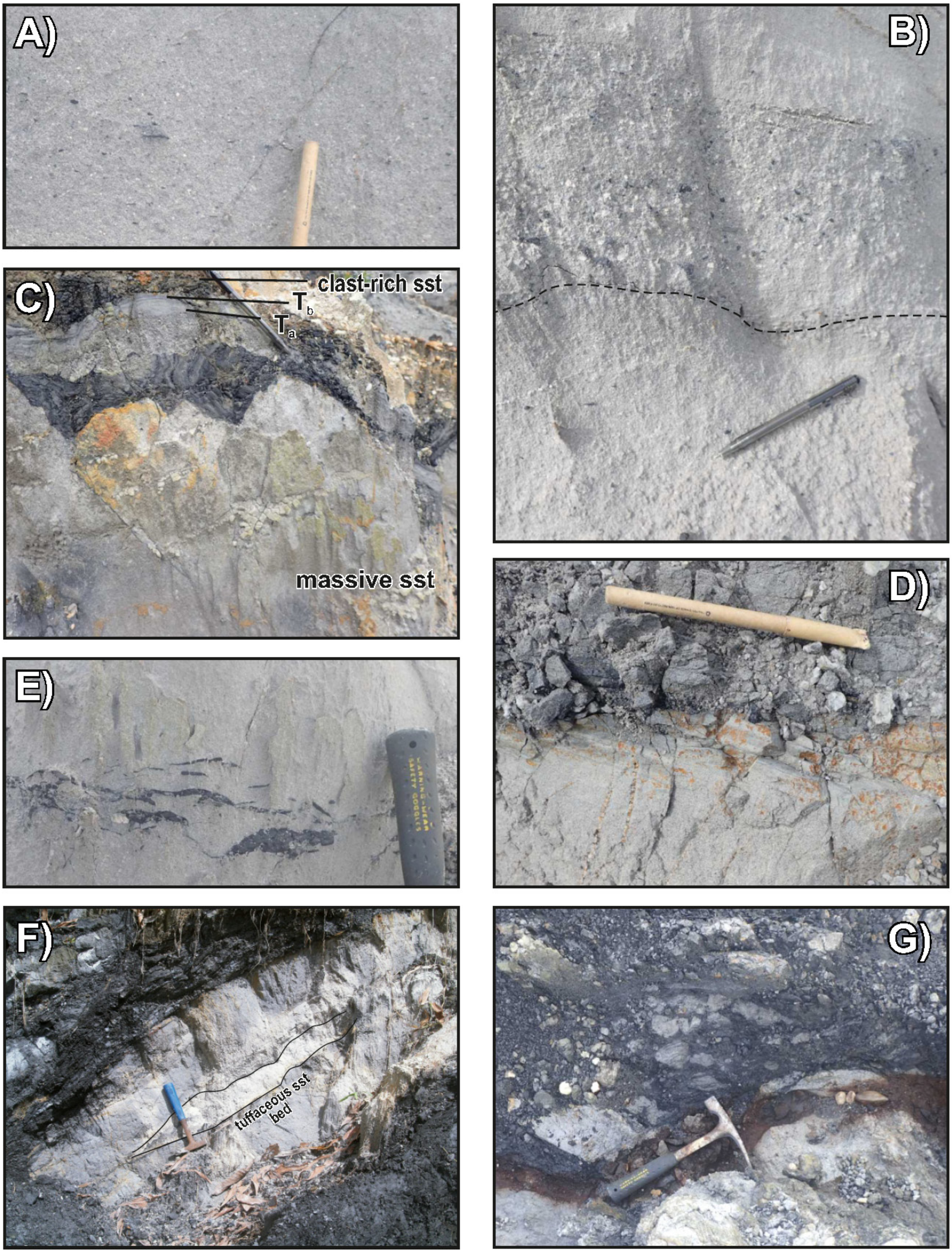

Figure 6: Examples of coarse-grained sandstones and debris flows. A) coarse grained basal sandstone with angular volcaniclastic grains. B) Two stacked coarse-grained sandstones, sharp base highlighted with dashed line. C) Amalgamated sandstone package, sharply overlain by slumped laminated siltstone-shale. A coarse-grained sandstone truncates the slumped siltstone-shale alternations sharply and is sharply overlain in turn by an incomplete Bouma sequence consisting of T_a and T_b. Top section consists of a clast-rich sandstone with abundant shale and coal clasts. D) Basal lag of coal fragments above a sharp contact with fine to medium-grained turbidite (T_a and T_b). E) Angular coal fragments entrained within medium grained sandstone. F) Structureless sandstone enclosing a white tuffaceous clay channel. Contacts to overlying and underlying dark shale are sharp. G) Sandstone fragments in a shale-matrix of a debris flow deposit.

and occasionally, low-angled cross-beds can be seen. The uppermost part of some of these beds sometimes contain current ripples. The thicker, coarse-grained sandstones in section TG-1 are typically poorly sorted and contain abundant angular to sub-angular lithic fragments that include coal, shale, schist, chert and volcanic fragments either concentrated in lag accumulations (Figures 6A to 6C) or scattered sporadically within the sandstone beds (Figure 6E). A clean white, very fine-grained tuffaceous sandstone bed was observed at TB250 within a succession of lateral extensive structureless sandstones (Figure 6F).

This facies most likely represents deposition by high-density turbidity flows in channelised systems where rapid deposition has insufficient time to produce typical turbidite bedform structures (Kuenen, 1966; Lowe, 1982; Mulder & Alexander, 2001; Talling *et al*., 2012; Kuswandaru *et al*., 2019). Alternatively, comparable deposits have been described as a result of progressive aggradation beneath flows in which turbulence was suppressed by high sediment concentrations (Kneller & Branney, 1995). Characteristic of this sedimentation are rapid aggradation and layer-by-layer deposition (Talling *et al*., 2012). Low angle bedding, plane beds and concave upwards bed forms suggest upper flow regime conditions in the submarine channel system. Amalgamated sandstone beds suggest removal of fine-grained material of the turbidity flow by erosion of each flow, resulting in sand-to-sand contacts. The general absence of mud intraclasts in sandstones indicates their transport farther downstream. Basal lags are related to bedload transport of higher energy flows. Scattered clasts in coarse-grained sandstone are likely related to rapid loss of velocity of the high density flow, which results in a mix of clasts in the sandy matrix. The white fine-grained tuffaceous sandstone bed is likely a relic of the upper part of a flow, which has been eroded into by the overlying sandstone. The tuffaceous character indicates contemporaneous volcanism.

Clast-rich, poorly sorted sandstones (facies ii)

Clast-rich sandstone beds are composed of light to dark grey, argillaceous, fine to medium-grained, very poorly sorted, quartz-rich sandstone containing abundant coal, shale and sandstone clasts ‘floating’ in the sandstone matrix (Figures 6G & 7A). Bed thickness is generally up to 20 cm, although one pronounced bed in section TG-1 reaches 40 cm in thickness. Clasts are typically sub-angular, more rarely subrounded, and are scattered in the beds, creating the impression of ‘floating’ in the sandstone matrix (Figure 6G & 7B). Shale and coaly clasts are most abundant, and exhibit different shapes (Figure 7B). White clay clasts, likely tuffaceous clasts, were observed in low abundance (Figure 7B). Sandstone clasts are elongated and some of the larger clasts consist of poorly sorted, graded sandstone (Figures 6G & 7A). Sandstone clasts show evidence of internal deformation and soft-sediment folding (Figure 7C). No apparent grading is visible in the clast-rich beds. The bases to these beds frequently scour into the underlying shale facies.

The clast-rich sandstone facies is interpreted to represent debrites deposited by cohesive debris flows which moved downslope as a coherent mass (Lowe, 1982; Hodgson, 2009; Talling *et al*., 2012). Deposition occurred through freezing of the flows *en masse* (Talling *et al*., 2004; Shanmugam, 2006), which formed the structureless, poorly sorted, non-graded sandstone beds. Coal, shale and sandstone clasts may have been derived by erosion and reworking from underlying beds (Johansson & Stow, 1995) or from where the debris flow initiated (Jackson & Johnson, 2009; Zavala & Arcuri, 2016). Coarser clasts that show a large grain size variation compared to the surrounding succession (exotic composition) indicate non-local derivation, characteristic of debrites (Haughton *et al*., 2003; Zavala & Arcuri, 2016). Clast-rich intervals that consist of non-exotic clasts may be the result of post-depositional liquefaction and foundering of overlying material, water escape (dewatering), or sediment loading (Talling *et al*., 2004).

Thin-bedded, graded sandstone (facies iii)

The thin-bedded, graded sandstone facies comprises Bouma units T_a, T_b and T_c, and consist of grey to whitish, dominantly fine-grained quartzose sandstone (Bouma unit T_a) with horizontal laminae (Bouma unit T_b) and, towards the top of beds, current ripples (Bouma unit T_c) (Figures 7D & 7E). Sorting is moderate to poor. Individual grains are usually angular to sub-angular and enclosed in a muddy matrix, although the sandstones are grain-supported. The base of the beds is always sharp with a planar erosive contact and frequent low-amplitude scours. Rip-up mud clasts are common in the lower parts of the beds (Figure 7F). The beds are normal graded, i.e., fining-upwards, with bed thickness ranging from 1 cm to a maximum of 20 cm, and are typically sheet-like with uniform thickness (Figure 7E) but include multiple planar erosion surfaces, indicating amalgamation packages. Sandstone beds tend to stack on top of each other without finer material preserved between (Figure 7D), and bed thickness remaining the same throughout the sequence. Folded quartz veins and quartz boudins are typical, whilst thin extensional quartz-veining is developed perpendicular to the sandstone bedding (Figure 7F), indicating low grade metamorphism.

The horizontal laminated sandstone (T_b) within this lithofacies is composed of white to grey, fine- to medium-grained, moderately well sorted, quartzose sandstone. Bed thickness ranges from 2 to 10 cm. Internal structures consist of very fine (mm thick) well-defined planar horizontal laminations which are sometimes wavy (Figure 7D). With grain size ranging from sand to mud, T_b is also a heterolithic unit. The fine horizontal laminations are composed of dark siltstone and mudstone layers, often carbonaceous. This facies is associated with the graded sandstone (T_a), but rarely also observed with sharp basal contact to laminated shale

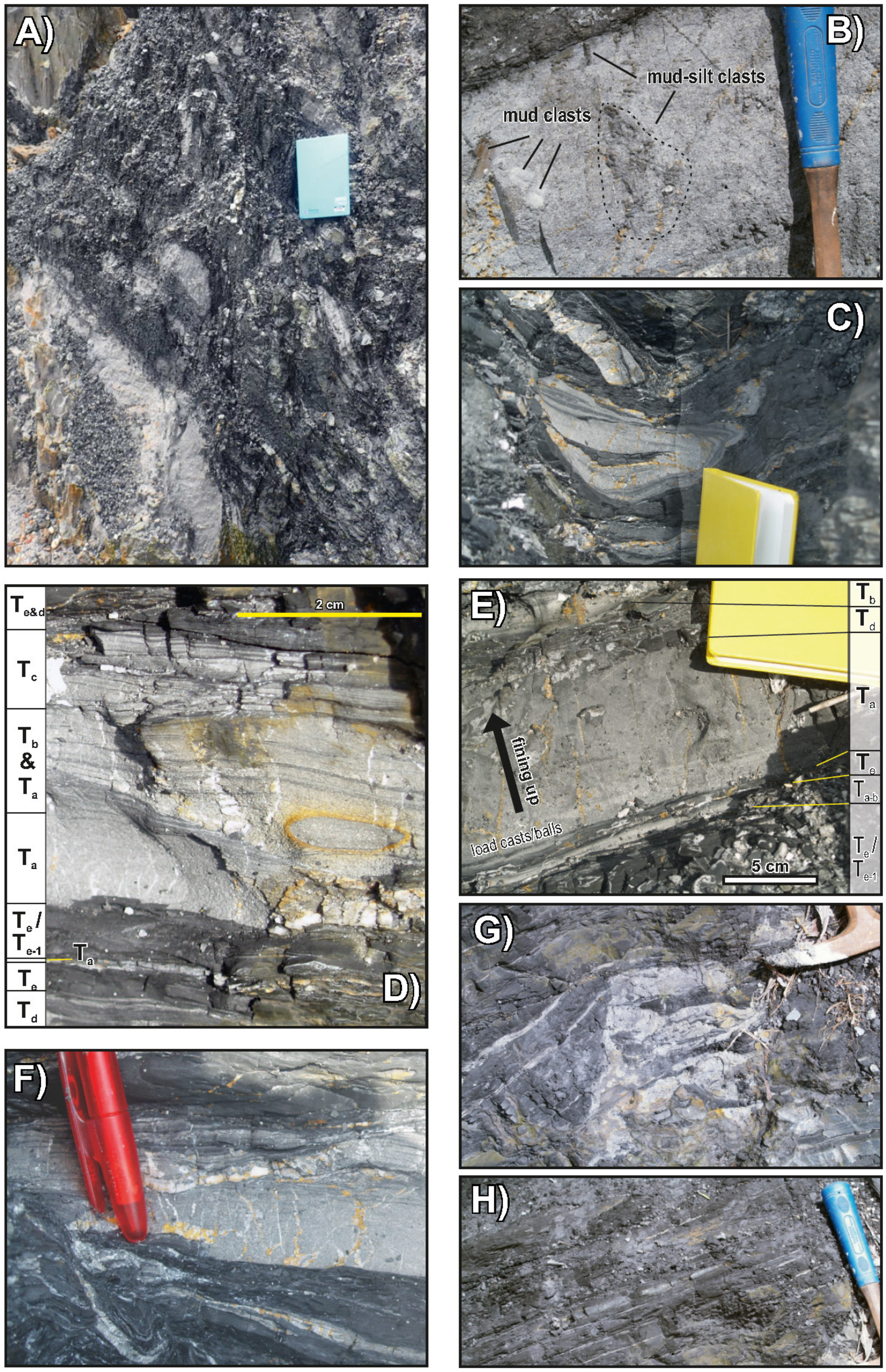

Figure 7: Photographs of typical sedimentary structures of the Kuching Formation. A) Sandstone and coal fragments in a debris flow deposit. B) Clast-rich sandstone with mud-rich matrix. Sandstone is ungraded and sharply overlain and underlain by shale. Clasts are subangular to subrounded. White mud clasts may represent tuffaceous material. C) Folded sandy intra-clasts (composed of T_a and T_b) in shale-dominated sequence. Two generations of quartz veins are visible. An older generation of vein has yellowish-orange stain while a younger one is clean and white. D) Well-preserved Bouma sequences with large floating sandstone clast in T_b (yellow stained rim) and planar laminations in a fine-grained sandstone. The middle section contains multiple flows of T_a and T_b. E) Typical 10 cm thick fine-grained sandstone with graded bedding (mainly T_a) and a sharp base. Load casts are developed in the underlying mud (lower left corner). The image shows three incomplete Bouma cycle. F) Graded sandstone with mud clasts overlain by laminated sandstone. Abundant quartz veins are visible, which can show early stages of folding and boudins. Yellow staining (presumably limonitic) on some veins and segregations. G) Laminated mudstone-siltstone alternation (T_d and T_e) truncated and disrupted by a younger sandy matrix that appears to have intruded into the sequence. H) Horizontal laminated silt-mudstone alternation (T_d). Silt laminations are laterally not persistent.

(facies iv). The top of a graded sandstone bed is, in places, formed by poorly developed rippled sandstone (Figure 7D).

Rippled sandstone (T_c) is a heterolithic unit composed of white to grey, fine grained quartzose sandstone interbedded with thin shale laminations. Bed thickness ranges from 1 to 4 cm. Internal structures include poorly preserved asymmetrical current ripples, climbing ripples and convolute laminations. The base of the rippled sandstone is usually a gradual transition from the horizontal laminated sandstone (T_b), but locally sharp erosive contacts were also observed. The top is sharp contact to the overlying shale-siltstone laminations (facies iv) (Figure 7D). The T_c Bouma unit is relatively rare in the studied sections, and T_a and T_b are often directly followed by shale-siltstone alternations (facies iv). Soft-sediment deformation, e.g., slump folding and convolute bedding, is commonly observed within heterolithic units (T_b, T_c and facies iv) with high mud content (Figure 7G).

Sandstones with overall normal-grading and moderate to poor sorting are indicative of rapid deposition from waning current flows, whilst the markedly erosive bases, parallel laminations and convex-upwards bedding are suggestive of upper flow regime conditions. Normal grading supports the suggestion of deposition from a waning flow associated with grain size segregation (Bouma, 1962; Lowe, 1982; Talling *et al*., 2012). The presence of scoured bases and mud rip-up clasts indicates reworking of the interbedded mudstone lithofacies. Horizontal laminated sandstone is generated by grain separation in the upper flow regime (Bouma, 1962). Planar laminations generated at high velocities are usually well-defined with current lineations on bedding surfaces (Bridge, 1978). Climbing ripple lamination in a turbidite is a result of suspended-load fallout due to changes in flow boundary conditions in areas of flow non-uniformity with a narrow grain-size range (Jobe *et al*., 2012). Convolute lamination is interpreted to be formed during or after deposition as a result of local liquefaction on a slope or where there is a shear on the material in combination with overlying mud-rich deposits that cap the convolutions (Gladstone *et al*., 2018). Compositionally mature, but texturally immature indicates a proximal quartzose source. The facies is interpreted to represent a partial Bouma T_a-T_b-T_c sequence deposited by distal non-cohesive dilute turbidity currents (Bouma, 1962; Lowe, 1982).

Laminated siltstone and shale (facies iv)

Many of the Kuching Formation outcrops are dominated by mud-rich sequences that are characterised by repeated alternations of grey coloured, fine-grained sandstone and siltstone with shale (Figures 7G, 8A & 8B). Alternations are developed on a millimetre to centimetre scale. Bed thicknesses vary from 0.5 to 10 cm. Fine sand- to silt layers usually show well-developed horizontal laminations or poorly-developed ripple lamination. The finer silt and sands intercalations are discontinuous (Figure 7G). The thicker siltstone intervals often show grading and ripple cross-lamination. The laminated shale lithofacies consists of dark to dark grey, laminated shale (Figure 8C) which also grades to silt. At outcrop these have a structureless appearance, which may be a result of surface outcrop weathering. Slumped shale and sandstone are common, forming sandstone clasts in slumped shale intervals (Figures 8A-D).

The development of laminated silt-mud is not well understood. Lowe (1988) suggested they form by the waning of dilute currents in which ripples cannot form because of insufficient time to settle, or lack of sufficient sand supply. The classical Bouma T_e sequence was expanded by Piper (1978) into T_{e-1} laminated mudstone, T_{e-2} graded mudstone, and T_{e-3} massive mudstone. In the studied sections, only very rarely is a massive mudstone (T_{e-3}) observed; the dominant lithology being laminated shale (T_{e-1}) with some grading into siltstone (T_{e-2}). Laminated muds are typically better developed in more proximal settings (Piper, 1978; McCave & Jones, 1988; Jones *et al*., 1992; Talling *et al*., 2012). The fine-grained laminae within mudstone is inferred to be the result of incremental floc settling leading to segregation of silt and clay material (Kuenen, 1965; Kneller & McCaffrey, 2003; McAnally *et al*., 2007) during waning flows (Stow & Bowen, 1978) although the process is currently not well understood (Talling *et al*., 2012). Graded mudstone is formed by segregation settling (Talling *et al*., 2012). The massive mudstone represents deposition by settling from suspension during continuous background sedimentation (Bouma, 1962; Talling *et al*., 2012). Slumping follows deposition on a slope or destabilisation due to saturation, which results in collapse of structures. Thicker mudstone-siltstone alternations represent the typical Bouma division T_d (Bouma, 1962). Both lithofacies show a transition in the observed outcrops.

Sedimentary environments

The Kuching Formation succession represents a sequence of stacked turbidites typified by incomplete Bouma sequences, with stacked, erosive channel sandstone bodies deposited under upper flow regime waning flows. The individual lithofacies constitute four facies associations comprising (i) thick-bedded, massive coarse-grained sandstone, (ii) clast-rich, poorly sorted, coarse-grained sandstones, (iii) thin bedded, graded sandstone and (iv) laminated shales/siltstones. These are interpreted to represent (i) sub-marine channels associated with (ii) slope debrites, (iii) distal marine turbidites deposited on a deep water lobe and (iv) settling from suspension between turbidity flows. Soft-sediment deformation and slumping are present throughout the succession and implies rapid deposition on a slope (Figures 8A-D).

Turbidity currents are flows that decrease in velocity through time and distance, therefore a decrease in grain size with distance is observed (Stow, 1994). Lower parts of the Bouma sequence are only present in proximal parts of the flow. Distal parts are dominated by finer grained

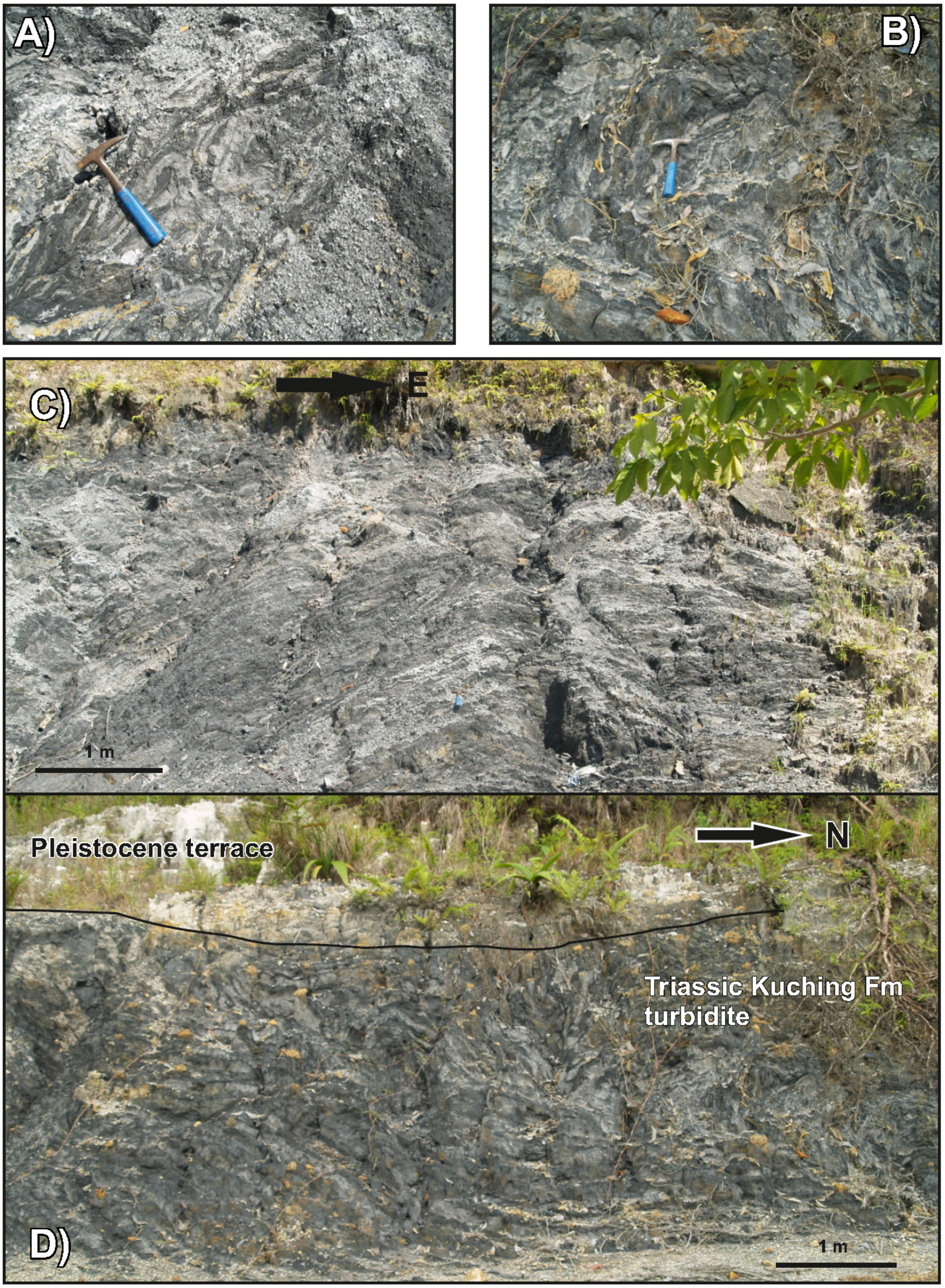

Figure 8: Examples of convolute bedding and slump folds. A) and B) Diffuse convolute bedding of thin layered graded sand-/siltstone and shale alternations. C) and D) Slump folds in typical weathered grey sandstone-shale alternations of the Kuching Formation overlain by Pleistocene to Holocene river terrace conglomerates and sands in Petra Jaya (northern Kuching). Location: Kampung Bintawa Tengah - Jalan Kampong Pulo Ulu (C), Jalan Foreign Diplomatik Mission (D).

units, while the coarser units are not present. Incomplete Bouma sequences are likely a product of dilute and low-density turbidity currents, while complete sequences record transition from high density to low density turbidity current (Bouma, 1962; Lowe, 1982; Kuswandaru *et al*., 2019). The complete, thicker sequences could indicate deposition in a more proximal regime or deposition in a submarine canyon/channel system, particularly the case for the coarser grained, sandstone-dominated sequence in section TG-1 (Figure 5). The overall thin-bedded character of the turbidites in most of the Kuching Formation suggest deposition off the lobe axis or within the lobe fringe rather than outer fan or basin floor. Mutti (1977) interpreted thin-bedded turbidites to be deposited along the channel margin. Submarine feeder channels are only likely present in section TG-1, which is consistent with deposition off the axis for most of the sections. Due to limited exposure, it is not possible to map out individual lobes or identify a complete fan system. Intercalated debrites (Figures 6G & 7A-B) indicate periodically high influx or remobilisation of clastic material (Haughton *et al*., 2003; Amy & Talling, 2006; Hodgson, 2009). Coarser sandstone deposits in location TG-1 suggests relics of the main channel system. Abundant quartz veins and segregations, as well as folding of veins (Figure 7F) indicate a low-grade metamorphic overprint. The apparent lack of trace fossils either indicates a stressed environment or poor preservation due to remobilisation of material. The lack of fossils could be a result of unfavourable conditions due to high sediment input. Sand injections may indicate post-depositional liquefaction (e.g., Kawakami & Kawamura, 2002), and exhibit sharp, irregular boundaries with the enclosing finer grained shale-siltstone alternations or sandstone intervals. The Kuching Formation turbidites with their overall fine-bedded structure are distinctively different from the adjacent Cretaceous Pedawan Formation turbidites (Breitfeld *et al*., 2017; Mazumder *et al*., 2021; Samsudin *et al*., 2021) or the Palaeogene Belaga Formation turbidites of the Sibu Zone (Bakar *et al*., 2007; Kuswandaru *et al*., 2019) where thicker amalgamated sandstone beds are much more common.

A characteristic feature of the Kuching Formation turbidite system is the presence of dark-coloured, highly carbonaceous shale intervals, lignite fragments, transported coal lenses and accumulations of transported coal fragments to form thin seams. The abundance of such coaly material indicates proximity of the Kuching Formation turbidites to a swampy coastal floodplain which supplied coal fragments to the shelf. The contemporaneous inner neritic-estuarine Sadong Formation is known to be rich in carbonaceous shales, silicified woody material, plant material and coal seams deposited in swampy environments (Liechti *et al*., 1960; Pimm, 1965; Wilford & Kho, 1965; Kon'no, 1972), supporting the interpretation of a close spatial and temporal relationship between the Sadong and Kuching formations.

WEST SARAWAK METAMORPHICS (TUANG FORMATION AND KERAIT SCHIST)

The metamorphic rocks of the Tuang Formation and the Kerait Schist were combined by Breitfeld *et al*. (2017) into the West Sarawak Metamorphics. The Kerait Schist was described in detail in Pimm (1965) and the Tuang Formation in Tate & Hon (1991) and Tan (1993). The Tuang Formation forms a more or less well-defined belt from the Kim Hin ceramics area south of Kuching to the type locality in the Kuap area southeast of Kuching where Sungai Tuang is located (Figure 2). Outcrops are sparse along road sections and most of the area is lowland either covered by vegetation or development areas. The Kerait Schist occurs in isolated inliers within the Sadong Formation in southern West Sarawak, where its type locality the Kerait valley is located. On the map it appears that the Kerait Schist localities are the southern continuation of the Tuang Formation belt (Figure 2).

The typical lithology is a foliated quartz-mica schist or mylonite (Figures 9A-B), with accessory minerals chlorite, graphite, iron oxides, tremolite and prehnite. Pimm (1965) also reported some feldspar. Folded quartz veins (Figures 9C-D), segregations and quartz boudins (Figures 9E-F) are common. Tate & Hon (1991) also reported basic schists, pelitic hornfels, silicified volcanics and chert within the Tuang Formation. The metamorphic rocks have an orange to red colour (Figure 9G), sometimes purple, when weathered. Graphite-rich or more basic varieties weather into a dark black soil (Figure 9H). Fresh outcrops (Figures 9D-E) are very rare and were only found in the Kim Hin ceramics area during fieldwork in 2012. No contacts to other formations are known and it can be assumed that the belt is fault-bounded. The contact to the Kuching Formation appears to be a fault, and in the Kuap area the formation is separated by a fault from the Serian Volcanic Formation.

Although their protolith age cannot be determined due to lack of zircons, they can confidently be placed into the Triassic. Breitfeld *et al*. (2017) interpreted a fine-grained volcaniclastic protolith, similar to the Upper Triassic Kuching and the Sadong formations. The Late Triassic white mica Ar/Ar cooling ages (Figure 10) record metamorphism immediately after deposition of the Sadong and Kuching formations, and Breitfeld *et al*. (2017) interpreted their formation in a Triassic accretionary setting associated with the Palaeo-Pacific subduction. The formation likely represents metamorphosed equivalents of the Sadong and Kuching formations.

DISCUSSION

Stratigraphic relations of the various Triassic rocks in West Sarawak

The turbidites and associated deep water shales of the Kuching Formation have almost no preserved stratigraphic contacts with other formations. In northern Kuching (Petra Jaya district, Figure 4), they are overlain by Plio-Pleistocene fluvial

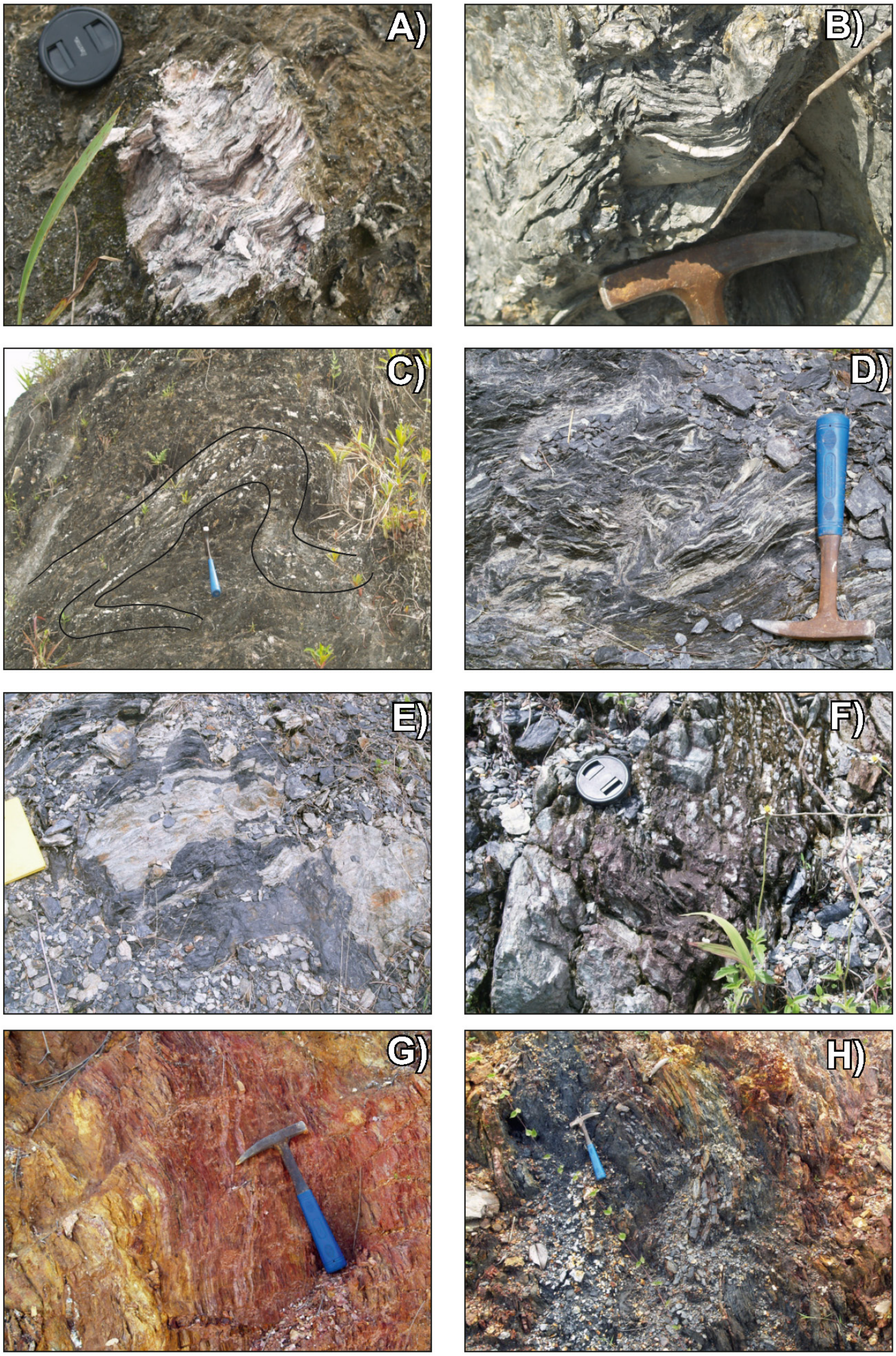

Figure 9: Field photographs of the West Sarawak Metamorphics. A) Mylonitic quartz-mica schist from the Kerait Valley. B) Phyllitic quartz-mica schist from the Sungai Tuang/Kuap area. C) Deeply weathered chevron-type folds of quartz veins in the Kerait Valley. D) Ptygmatic-type folding of quartz layers (Kim Hin ceramics area south of Kuching). E) and F) Examples of boudinaged quartz clasts. G) Typical orange-red-coloured alteration of the schists in the Sungai Tuang/Kuap area. H) Dark-coloured weathering of clay-graphite-mica layers in the Sungai Tuang/Kuap area.

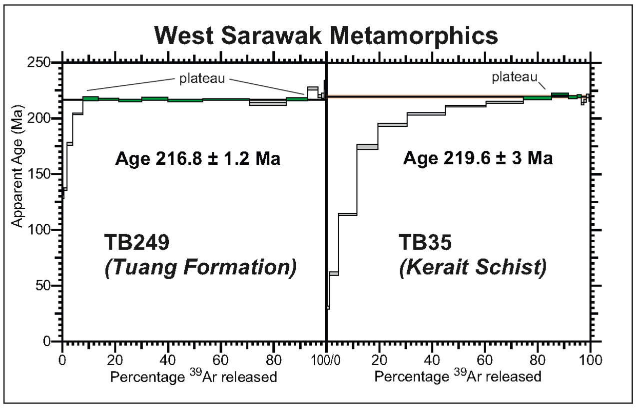

Figure 10: Upper Triassic Ar-Ar step heating ages for white mica of the West Sarawak Metamorphic samples (modified from Breitfeld *et al*., 2017). Green bars mark the heating steps used for plateau ages, and grey bars mark outlier and steps affected by argon loss.

sedimentary rocks with a prominent angular unconformity (Figure 8D; Tan, 1993; Breitfeld, 2021). The Upper Jurassic to Cretaceous Pedawan Formation is either in fault contact or alternatively resting unconformably on top of the Kuching Formation (Tan, 1993) and marks the only other observed stratigraphic contact of the Kuching Formation. In southern Kuching the contact to the West Sarawak Metamorphics (metamorphic rocks of the Tuang Formation) is sharp with no transition in metamorphic grade visible. Therefore, the boundary could be a W-E striking fault, but this has not been seen so far. The absence of stratigraphic context and fossils in the turbidite succession led to a previously unsure age classification (e.g., Tate & Hon, 1991), until Breitfeld *et al.* (2017) obtained abundant Triassic detrital zircons from the strata (Figure 11) and was able to demonstrate a correlation to the deposits of the Sadong Formation.

Similarly to the Kuching Formation, stratigraphic context of other pre-Cretaceous formations is also poorly exposed (e.g., Liechti *et al*., 1960). The West Sarawak Metamorphics are believed to be overlain unconformably or in fault-contact with the Sadong, Serian Volcanic and Pedawan formations (Tan, 1993), and the Sadong Formation may rest unconformably on, or is in fault contact with, the Carboniferous-Permian Terbat Formation (Pimm, 1965). Contacts to overlying formations are generally assumed to be unconformities (e.g., Pimm, 1965), with Wilford & Kho (1965) noted faults obscuring relationships between the different formations. Due to poor exposure and faulting none of the contacts have been seen in outcrop. As Triassic shallow marine (Sadong Formation), turbiditic (Kuching Formation) and metamorphic rocks (West Sarawak Metamorphics) all occur spatially close together, it is concluded that contacts between the Triassic rocks are most likely fault-related and a substantial amount of thrusting and displacement must have taken place.

The Sadong Formation represents brackish, shallow water environments that changed periodically and included both non-marine and marine conditions indicated by the occurrence of crinoid fragments and ammonite fossils. Liechti *et al*. (1960) and Wilford & Kho (1965) interpreted deposition in an estuarine to neritic environment. The Sadong Formation is typically intensely weathered, steeply dipping and folded, and locally includes very low-grade metamorphic rocks. The thickness of the Sadong Formation is estimated to be between c. 2200 to 3000 m (Pimm, 1965; Wilford & Kho, 1965), although due to incomplete exposures and partly steeply dipping beds the thickness could exceed the assumed figure. The Kuching Formation represents turbidites and associated debrites deposited on the continental slope as more distal equivalent to the Sadong Formation (Breitfeld *et al*., 2017). Exposures in Kuching city suggest most of the turbidite sequence were deposited off the lobe axis with only a few sections including feeder/submarine channels, principally section TG-1. No estimates of the thickness can be given due to the restricted and isolated exposures.

Detrital zircon U-Pb ages of the Kuching Formation are almost identical to the Sadong Formation samples (Figure 11A). The youngest zircon populations in the two formations are Carnian to Norian age, comparable to the Upper Triassic depositional age of the Sadong Formation assigned by Liechti *et al* (1960) based on the presence of bivalves (e.g., *Monotis* sp., *Halobia* sp., *Daonella* sp.) and the Krusin floral assemblage (Kon'no, 1972). The Permo-Triassic detrital zircons within the two formations indicate igneous activity immediately preceding deposition. Upper Triassic zircons indicate contemporaneous volcanic activity, although numbers are too low to obtain a robust maximum depositional age (e.g., Dickinson & Gehrels, 2009; Tucker *et al*., 2013; Coutts *et al*., 2019) for the three individual samples. However, using the Maximum Likelihood Age (MLA) method to obtain a Maximum Depositional Age (MDA) (Vermeesch, 2021) for the combined three samples, assuming contemporaneous deposition as indicated by the youngest zircons, provides a Carnian MLA estimate of 230.7 ± 1.1 Ma (Figure 12A). Zhou *et al.* (2023) presented zircon U-Pb data for another sample from the Kuching Formation, where the youngest cluster yields a slightly older MLA age of 244 ± 2 Ma (Figure 12B). Therefore, deposition of the Kuching Formation may have been taken place between the Anisian and Carnian.

The West Sarawak Metamorphics consist of metamorphosed volcaniclastic sedimentary rocks (Breitfeld *et*

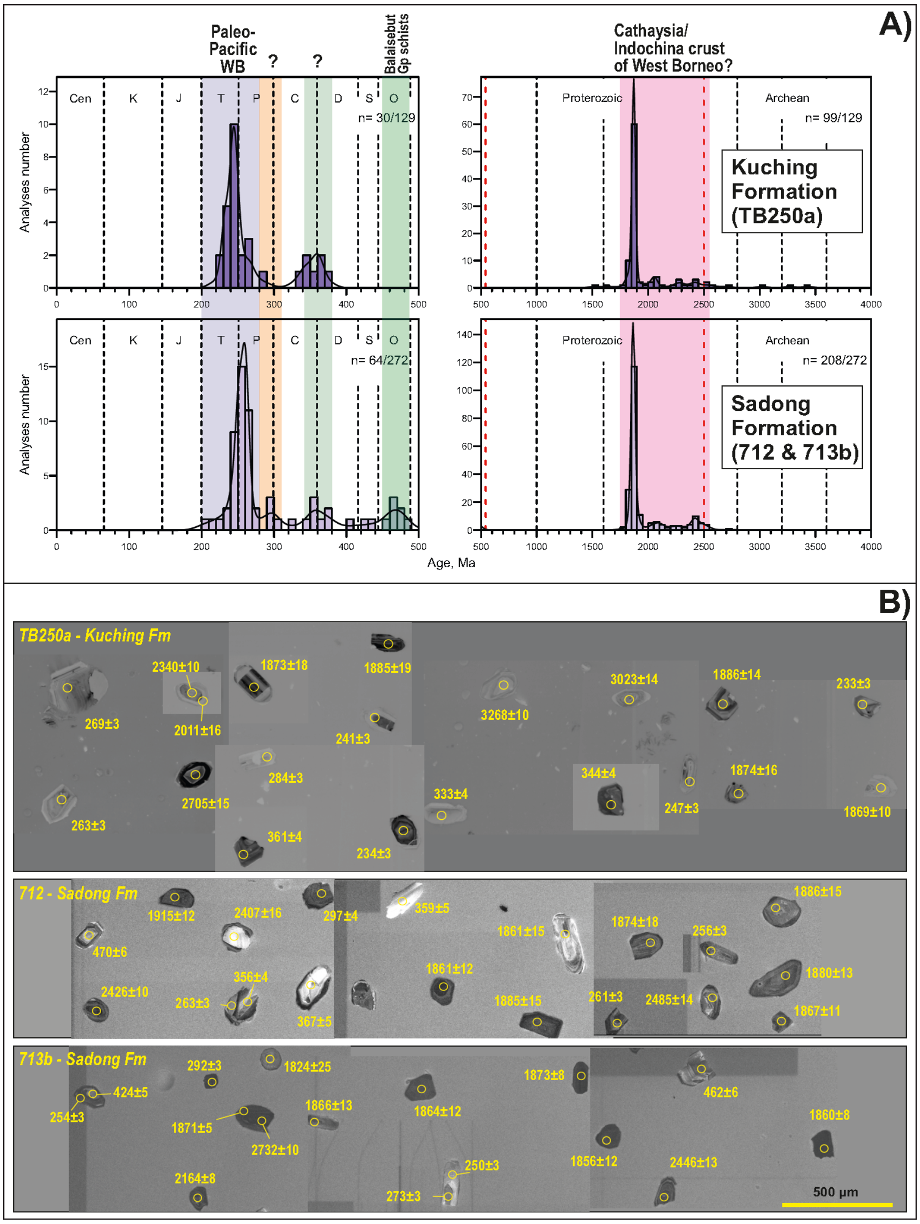

Figure 11: A) Detrital zircon U-Pb age histograms with kernel density curves for the Sadong and Kuching formations, showing almost identical age distribution (from data in Breitfeld *et al.*, 2017). Coloured areas mark potential sources. Histogram bin width 10 Ma for ages <500 Ma and 50 Ma for ages>500Ma. Kernel density bandwidth 5 for ages < 500 Ma and 15 > 500 Ma. Plots created in IsoplotR (Vermeesch, 2018) and an internal R-based script. B) Assorted CL images from zircons of the Sadong and Kuching formations with characteristic ages (from Supplementary material of Breitfeld, 2015; Breitfeld *et al.*, 2017).

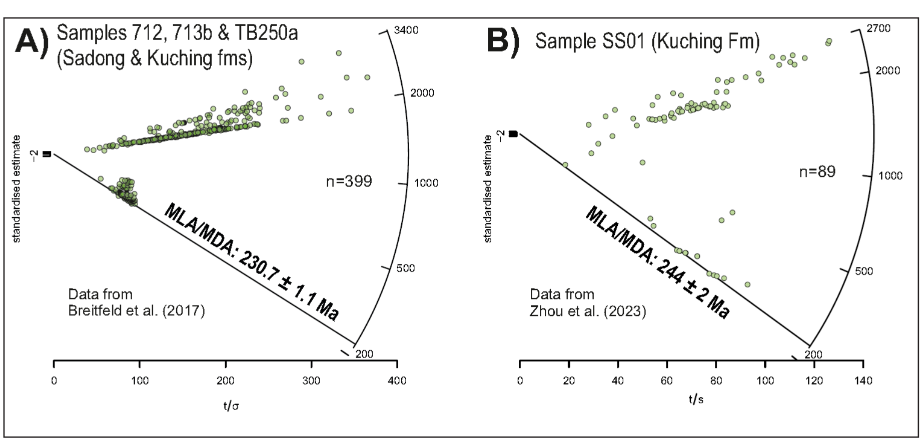

Figure 12: Calculation of the maximum likelihood age (MLA) as maximum depositional age (MDA) estimate (based on the method of Vermeesch, 2021). A) the combined data of the Sadong and Kuching formations (data from Breitfeld *et al.*, 2017), giving a Late Triassic Carnian age for the youngest zircon age population. The two youngest zircons have been excluded as their age is younger as the depositional age, and likely affected by lead-loss. B) Sample SS01 from the Kuching Formation (data from Zhou *et al.*, 2023) yields an older Anisian MLA.

al., 2017). In parts they represent metamorphosed turbidites (Tate & Hon, 1991; Tan, 1993; Breitfeld *et al*., 2017), but a shallow marine protolith is equally possible. Therefore, they are likely to consist of metamorphosed equivalents of both the Kuching and Sadong formations. A thickness of c. 600 m was assumed by Hon (in Tan, 1993) for the Tuang Formation in the Kuap area (Sungai Tuang) with no estimates given for the Kerait Schist. As the metamorphic rocks are strongly folded, faulted, partly overturned and poorly exposed, no thickness of the complete sequence can be given.

The prominent andesite mountains mapped as Serian Volcanic Formation, previously thought to be Triassic, are probably mostly Cretaceous (Wang, Y. *et al*., 2021b). Contacts of the volcanics with the Triassic rocks need further study. Fault-controlled contacts would be expected, but if the mafic volcanics are indeed 'interfingering' as suggested by Pimm (1965) and Wilford & Kho (1965), it is possible that lava flows and near-surface igneous bodies within the Triassic sedimentary and metamorphic rocks indicate that the Triassic units were already at or near the surface in the Late Cretaceous. Subsequent subsidence related to Cenozoic extensional and strike-slip basin development buried the Triassic rocks. Permo-Triassic granitoids (Jagoi Granodiorite, Embuoi Complex) in West Borneo that also include one sample from the 'Serian Volcanic Formation' (Wang, Y. *et al*., 2021a) represent the relics of the arc system responsible for deposition of the Triassic volcaniclastic rocks.

Provenance of the Triassic volcaniclastic rocks and insights into the basement of West Borneo

The Sadong-Kuching depositional system was developed along an active Andean-type margin, where the Palaeo-Pacific was subducted westwards beneath the eastern margin of Sundaland (Breitfeld *et al*., 2017; Hennig, J. *et al*., 2017). The sediment is characterised by a high quartz content and various lithic fragments. Feldspar is almost absent, which is likely the result of break-down due to tropical weathering conditions, but some feldspar has been reported by e.g., Liechti *et al*. (1960), Wilford & Kho (1965) and Tan (1993). Detrital zircons reported by Breitfeld *et al*. (2017) and Zhou *et al*. (2023) indicate two main source regions contributed to the sediment, which can give insights into the crustal composition of West Borneo. The majority of detrital zircons are skewed to the range from 1.8 Ga to 1.9 Ga with a long tail of older ages extending up to 2.5 Ga (Figure 13), typical of Cathaysian basement of SE China (Xu, X. *et al*., 2005; Liu, R. *et al*., 2009; Xia *et al*., 2012; Chen & Xing, 2013; Chen *et al*., 2016). This Proterozoic to Archean age signature is widely distributed in sedimentary rocks of Indochina (Carter & Moss, 1999; Clift *et al*., 2006; Burrett *et al*., 2014; Hara *et al*., 2017; Hennig, J. *et al*., 2018; Breitfeld *et al*., 2022) and East Malaya (Sevastjanova *et al*., 2011; Basori *et al*., 2018; Dodd *et al*., 2019; Fyhn *et al*., 2019; Quek *et al*., 2021), indicating a similar basement for Indochina. Similar ages were reported from various sedimentary rocks in Borneo (Witts *et al*., 2012; van Hattum *et al*., 2013; Galin *et al*., 2017; Breitfeld & Hall, 2018; Hennig-Breitfeld *et al*., 2019; Breitfeld *et al*., 2020b; Burley *et al*., 2021; Zhao, Q. *et al*., 2021; Li, S. *et al*., 2022; Zhu, Z. *et al*., 2022). Breitfeld *et al*. (2017) and Hennig, J. *et al*. (2017) suggested that West Borneo was a continuation of the Cathaysian basement of SE China and Indochina. Within the Kontum Massif in Vietnam some of this basement is also exposed in Indochina (Hieu *et al*., 2015; Kawaguchi *et al*., 2021). The absence of any Meso- or Neo-Proterozoic ages in the reported samples is remarkable and suggests that the Cathaysian basement of West Borneo was, at least partly, directly exposed with drainage relatively restricted to the basement highs and their cover units. Zircon shapes are dominated by subrounded to rounded varieties (Figure 13), typical of multi-recycled sedimentary sources. There are, however, a few subangular to angular Palaeoproterozoic zircons (Figure 13), suggesting fresh first-

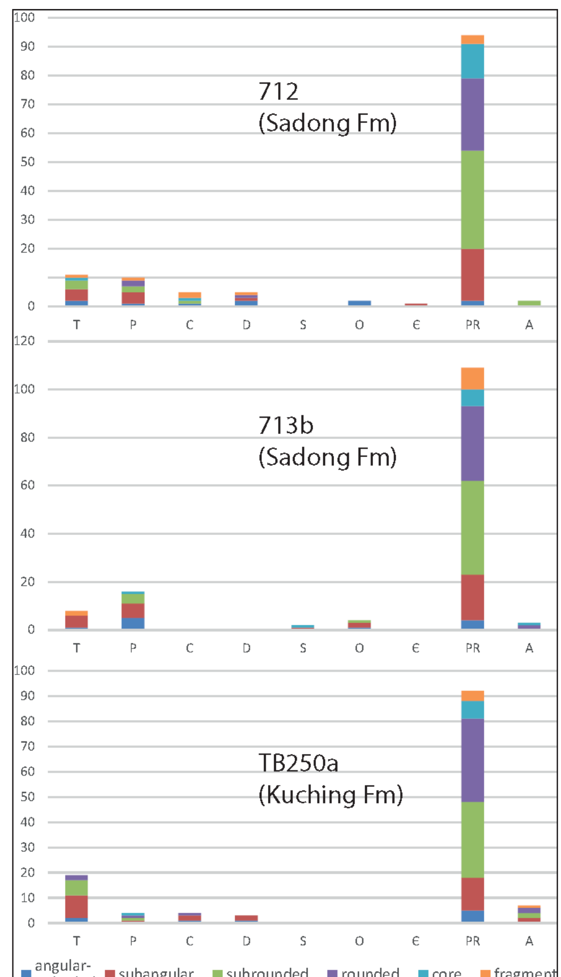

Figure 13: Grain shape histograms of the Sadong and Kuching samples (adapted from Breitfeld, 2015), revealing predominantly subangular Triassic zircons and subrounded to rounded Palaeoproterozoic varieties. (T-Triassic, P-Permian, C-Carboniferous, D-Devonian, S-Silurian, O-Ordovician, Є-Cambrian, PR-Palaeoproterozoic, A-Archean).

cycle or basement sources. Zircons with ages greater than 2 Ga can usually be found in zircon cores (Figure 13) with Palaeoproterozoic rims. Cathodoluminescence (CL) imagery (Breitfeld, 2015; Breitfeld *et al*., 2017) indicates that most Precambrian zircons are oscillatory zoned (Figure 11B), suggesting an igneous origin. It is concluded that during Triassic subduction, the main source for the Sadong-Kuching system was a partially uncovered basement mountain chain, consisting of 1.8 Ga (meta-) granitoids, with otherwise thick multi-recycled sedimentary cover units originally also derived from the Palaeoproterozoic basement. Based on geochemical data, Zhou *et al.* (2023) suggested recycling of an ancient craton as the main source, however, recycling of a Cathaysian terrane is probably a better terminology.

Permian-Triassic zircons cluster between c. 221 to 279 Ma and were partly derived by the active Palaeo-Pacific subduction margin. Relicts of Permo-Triassic plutons are widely distributed in West Borneo, including the Jagoi Granodiorite, the Embuoi Complex, a granite west of Sanggau, and the meta-granitoids of the North West Schwaner Zone (Figure 1). The Serian Volcanic Formation, originally thought to represent mafic volcanic material associated with Triassic subduction, are now dated as Cretaceous (Wang, Y. *et al*., 2021b). A granitoid within the formation is however dated as Late Permian (Wang, Y. *et al*., 2021a) correlative to the West Borneo granitoids, thus, indicating the need for further detailed mapping and age dating to understand the extent of Cretaceous and Permo-Triassic igneous rocks within the Serian Volcanic Formation. Based on the distribution of Permo-Triassic granitoids in West Borneo, the Sadong-Kuching depositional system was likely located a short distance from the uplifted highlands and volcanic arc (Figure 14A). Upper Triassic to middle Permian zircons are predominantly euhedral, angular (Figure 13), and oscillatory zoned varieties, with a few bright CL (Figure 11B) reflective grains and some subrounded grains. The textural maturity on most grains suggests first-cycle deposition from igneous basement, with a few grains showing more textural maturity which is likely a result of reworking in the Late Triassic.

The remaining detrital zircon ages are distributed across the Palaeozoic, forming three more or less well-developed small age clusters. The Sadong Formation samples show an age cluster in the Ordovician at around 460-480 Ma (Figure 11A), possibly corresponding to Ordovician schists within the Embuoi Complex (Zhu, J. *et al*., 2022), likely part of the Balaisebut Group. Similar ages are well-known from Indochina and SE China (e.g., Nagy *et al*., 2001; He, Z. *et al*., 2010; Wan *et al*., 2010; Xia *et al*., 2014; Jiang *et al*., 2015; Zhang, C.-L. *et al*., 2015; Wang, C. *et al*., 2015), and are interpreted to result from subduction along the Proto-Tethyan or Palaeo-Asian oceans at the northern margin of Eastern Gondwana (Zhang, C.-L. *et al*., 2015; Metcalfe, 2021; Wang, Y. *et al*., 2021c; Zhu, J. *et al*., 2022). Detrital Ordovician zircons in the samples are oscillatory zoned,

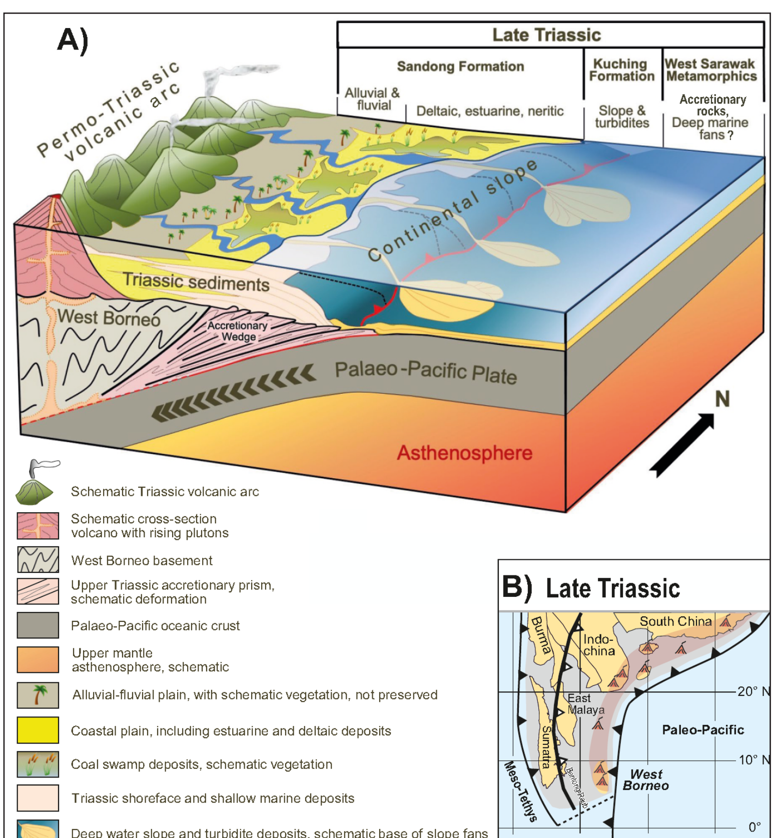

Figure 14: A) Schematic reconstruction of the Late Triassic in West Borneo, illustrating the depositional environments of the Sadong-Kuching forearc basin and the interpreted Palaeo-Pacific subduction (not to scale). B) Tectonic map reconstruction of the Palaeo-Pacific arc (red shaded area) from West Borneo in the south to southern China in the north (modified from Hennig, J. *et al*., 2017; Breitfeld *et al*., 2020a).

angular to subrounded and euhedral (Figures 11B & 13). A few are fragmented or show bright CL reflectance. An Ordovician core with an Upper Permian oscillatory zoned rim (Figure 11B) was observed in sample 713b (Sadong Formation). The texture of the zircons suggests fresh igneous sources with only minimal reworking, which could indicate a proximal West Borneo source.

The other two age clusters are in the Late Devonian-Early Carboniferous and in the Early Permian. With the exception of the 320 ± 3 Ma (K-Ar) fault block within the Boyan Melange (Williams *et al*., 1988; Bladon *et al*., 1989), no basement rocks of comparable age have been found in southern Borneo. Along the Indochina-South China boundary within the Song Ma and Ailaoshan suture zones, as well as on Hainan, Upper Devonian to Lower Carboniferous basic rocks, metabasites and plagiogranites were reported by Wang, X. *et al*. (2000), Li, X.-H. *et al*. (2002), Jian *et al*. (2008, 2009), V. Vượng *et al*. (2013), Lai *et al*. (2014), Zhang, R. *et al*. (2014) and He, H. *et al*. (2018). Carboniferous zircons are predominantly subhedral, angular to subrounded with oscillatory, patchy or convolute zoning (Figures 11B & 13), which may indicate igneous to metamorphic sources. Lower Permian basement is known from East Malaya (Oliver *et al*., 2014), Indochina (Waight *et al.*, 2021), and from the Indochina-South China suture zone (Hennig, D. *et al*., 2009; Lai *et al*., 2014; Halpin *et al*., 2016) associated with either Palaeo-Tethys, Palaeo-Pacific or Song Ma subductions. Lower Permian zircons are subhedral, angular to subrounded with oscillatory zoning or dark CL responses (Figures 11B & 13), which could suggest igneous to metamorphic sources and some reworking or recycling.

Extent and palaeogeography of the Permo-Triassic arc

The extent of this Permo-Triassic arc is widely debated in the literature. Several different models of subduction have been proposed. In principle there are three different tectonic models: i) Palaeo-Pacific subduction, ii) closure of Palaeo-Tethys between Indochina and Sibumasu, or iii) closure of the north-eastern branch of the Palaeo-Tethys (Song Ma ocean) between Indochina and South China.

Palaeo-Pacific subduction

The Triassic volcanic arc in West Borneo was interpreted as a southern continuation of westwards directed Palaeo-Pacific subduction along the eastern margin of Asia by Breitfeld *et al*. (2017) and Hennig, J. *et al*. (2017) (Figure 14B), which possibly initiated in the Permian and continued until the Late Cretaceous (e.g., Holloway, 1982; Wang, Q. *et al*., 2005; Li & Li, 2007; Knittel *et al*., 2010; Xu, C. *et al*., 2016, 2017; Breitfeld *et al*., 2020a; Hennig-Breitfeld *et al*., 2021; Batara & Xu, 2022; Wei *et al*., 2022; Xu, F., 2022). Kudrass *et al*. (1986) reported Triassic volcaniclastic siltstones from the Dangerous Grounds Reed Bank of the South China Sea that are similar to the Sadong Formation, and Xu, F. *et al*. (2022) and Wei *et al*. (2022) reported Upper Triassic basic volcanic rocks from the Mischief Reef/Meiji Reef (south of the Reed Bank) associated with Palaeo-Pacific subduction. Dacite with similar Late Triassic ages related to Palaeo-Pacific subduction are also reported by Miao *et al*. (2021) from the Dangerous Grounds block in the central South China Sea, indicating the remains of the Triassic Palaeo-Pacific volcanic arc system in the South China Sea. Hennig-Breitfeld *et al*. (2021) tentatively interpreted Triassic to Lower Jurassic volcaniclastic rocks from the Da Lat Zone in SE Vietnam and from the Nam Con Son Basin to be associated with the Palaeo-Pacific subduction as a northern continuation. The Sadong and Kuching formations would represent forearc basin fill sediments, and the West Sarawak Metamorphics would be associated with accretion (Figure 14A). Zhou *et al*. (2023) interpreted the Triassic Palaeo-Pacific subduction in West Borneo either as inactive or associated with limited magmatism only, based on geochemistry analysis of the Kuching and Sadong formations. The evidence outlined above suggests however active magmatism associated with subduction. Strong alteration of the Triassic successions, as observed, and the multi-recycling input of Cathaysia cover units might have diluted an active margin signal.

Permian to Triassic igneous and metamorphic rocks are also widely distributed in central-northern Vietnam, Hainan and South China (e.g., Nagy *et al*., 2001; Wang, Q. *et al*., 2005; Li, X.-H. *et al*., 2006; Liu, J. *et al*., 2012; Zi *et al*., 2012; Mao *et al*., 2013; Wang, Y. *et al*., 2013; Hieu *et al*., 2015; Halpin *et al*., 2016; Gao *et al*., 2017; Yan *et al*., 2017, Shen *et al*., 2018; He, H. *et al*., 2020; Xu, J. *et al*., 2020; Wang, Y. *et al*., 2021d) with ongoing discussion if they represent Palaeo-Tethys (Song Ma, Ailaoshan sections), Palaeo-Pacific, or both subductions. Xu, F. *et al*. (2022) demonstrated that Triassic volcanics in the South China Sea are related to westward subduction of the Palaeo-Pacific, thus indicating that Permian-Triassic igneous rocks in South China could at least be partly the northern continuation of the Palaeo-Pacific subduction from West Borneo. This Permo-Triassic Andean-type arc (Figure 14B) extends farther northwards into Taiwan (Yui *et al*., 2009), the Korea Peninsula (Kim *et al*., 2011; Choi *et al*., 2021) and Japan (Faure & Charvet, 1987; de Jong *et al*., 2009; Zhang, X. *et al*., 2019). Waight *et al*. (2021) also interpreted Permian granitoids in SW Vietnam-S Cambodia to be related to the Palaeo-Pacific. Knittel *et al*. (2010) identified Permian arc magmatism in the North Palawan Continental Terrane associated with the Palaeo-Pacific subduction.

Burton-Johnson *et al*. (2020) reported Triassic and Jurassic ages from granitoids in the Segama Valley in Sabah, NE Borneo and interpreted them also to be related to the Palaeo-Pacific arc as a southern continuation of West Borneo, which has rotated counter-clockwise c. 90° since the Cretaceous (Schmidtke *et al*., 1990; Fuller *et al*., 1999). This model would require most of Borneo already being assembled before the Triassic, and the Triassic arc would thus have to cross at least one Cretaceous suture zone (Lupar-Lubok Antu). Therefore, it is more likely that the igneous rocks in the Segama Valley are related to a basement fragment derived from South China (Wang, Y. *et al*., 2023), similar to Palawan, or alternatively, be part of the NW Sulawesi-E Sabah basement (Hennig, J. *et al*., 2016).

Closure of Palaeo-Tethys (main section)

The Triassic magmatism in Borneo has been interpreted by other workers to be associated with subduction of the Palaeo-Tethys oceanic crust. Wang, Y. *et al*. (2021a) advocated Triassic granitoids in West Borneo to be the southern and eastern continuation of the Malay Peninsula Tin Belt granitoids. In this scenario, the Sadong and Kuching formations would represent back-arc deposition. Permian to Triassic igneous rocks related to closure of Palaeo-Tethys are abundant in Sibumasu-East Malaya (Searle *et al*., 2012; Oliver *et al*., 2014), the Sukhothai Arc (Ueno *et al*., 2018), Chanthaburi terrane (Sone *et al*., 2012; Hara *et al*., 2018) and southern Cambodia (Waight *et al*., 2021), which have more or less similar ages to the Upper Permian to Upper Triassic granitoids in West Borneo. Associated turbiditic successions are the Semantan and Semanggol formations in Malay Peninsula, which both are likely related to a forearc or foredeep setting (e.g., Metcalfe, 2000; Hutchison & Tan, 2009; Madon, 2010; Sajid *et al*., 2020; Mohamed *et al*., 2022) and the Jurong Group of Singapore (Dodd *et al.,* 2019, 2020). Limited zircon U-Pb geochronology of Triassic sedimentary rocks from the Malay Peninsula indicates either more heterogeneous age spectra or spectra limited to Triassic age cluster (Sevastjanova *et al.,* 2011; Oliver *et al.,* 2014; Dodd *et al.,* 2019; Cui *et al.,* 2023). Back-arc extension associated with closure of the Palaeo-Tethys between Sibumasu and Indochina resulted in the formation of the Jinghong-Nan-Sa Kaeo Back-arc Basin behind the Sukhothai arc (e.g., Metcalfe, 2021 and references therein). The basin fill comprised turbidites and associated melanges of Permian to Triassic ages (Hara *et al.,* 2018). Limited detrital zircon ages reported by Hara *et al.* (2018) indicate a bimodal age distribution with Permo-Triassic and Palaeoproterozoic (1.8-1.9 Ga) age cluster, and scattered Palaeozoic ages. Although the age cluster are comparable to those of the Sadong and Kuching formations, the frequency of ages differ. Permo-Triassic ages are overwhelmingly dominant with only a few Palaeoproterozoic ages in the Sa Kaeo-Nan Back-arc Basin (Hara *et al.,* 2018). The clastic fill was interpreted to be sourced directly from back-arc basin basalts, as well as from the felsic volcanic rocks of the active Sukhothai Arc, and from the Indochina Block (Hara *et al.,* 2018). In contrast, the Sadong and Kuching formations are dominated by felsic material and sourced mainly by Indochina sedimentary cover and felsic active arc magmatic rocks (Breitfeld *et al.,* 2017; Zhou *et al.,* 2023). The close proximity to Permian-Upper Triassic I-type granitoids and the continuation of Upper Triassic volcanism into the Jurassic as seen in West Borneo (e.g., Hennig, J. *et al*., 2017; Wang, Y. *et al*., 2022a; Zhou *et al.*, 2023) is, however, more consistent with ongoing Palaeo-Pacific subduction setting rather than a Paleo-Tethys back-arc environment. The continuation of magmatism into the Jurassic is also reported from the Dangerous Grounds area in the South China Sea (Yan *et al*., 2010; Xu, C. *et al*., 2017; Yuan *et al*., 2018) and from SW Vietnam-S Cambodia (Waight *et al*., 2021). In contrast, collision of Sibumasu with East Malaya/Indochina and closure of Palaeo-Tethys was completed by the Late Triassic (Sone & Metcalfe, 2008; Metcalfe, 2013, 2017; Wang, Y. *et al*. 2013) and no Jurassic magmatism is reported from East Malaya. The Mid-Triassic S-type granite-magmatism of the North Thailand-West Malaya Main range, which is associated with tin mineralisation, is also absent from Borneo. Whereas the Permian-Triassic I-type magmatism of the East Malaya province is older than the majority of I-type granitoids in western Borneo.

Closure of Palaeo-Tethys (north-east section, Song Ma ocean)

Another possible Palaeo-Tethys interpretation is that the Permian-Triassic magmatism was associated with closure of the Song Ma ocean between Indochina and South China collision. Metcalfe (2013, 2017, 2021) interpreted the Semitau terrane (incorporating most parts of West Sarawak) to be derived from the South China-Indochina margin in the Cretaceous to Cenozoic, thus placing western Borneo close to the Indochina-South China boundary. Permo-Triassic rocks on the island of Hainan are generally interpreted to be related to closure of the northern Palaeo-Tethys section (Song Ma ocean) (He, H. *et al*., 2020; Zhou *et al*., 2020; Cao *et al*., 2022; Yin *et al*., 2022). Igneous and metamorphic rocks from the Kontum Massif in Central Vietnam of a similar Triassic age are also interpreted to be associated with the collision of Indochina with South China (Nagy *et al*., 2001; Hieu *et al*., 2015). The Palaeo-Tethys to Palaeo-Pacific association is, however, not clear. Zhou *et al*. (2020), for example, interpreted Permian to Lower Triassic igneous rocks on Hainan to be related to the Palaeo-Tethys, while Upper Triassic igneous rocks were interpreted to be associated with the Palaeo-Pacific subduction. Li & Li (2007) suggested onset of Palaeo-Pacific subduction beneath South China to be in the Middle Permian and interpreted the Permian igneous rocks of Hainan as Palaeo-Pacific subduction-related (Li *et al*., 2006). Additionally, Palawan, Mindaro and East Sabah fragments have been suggested to be derived from an area near south Hainan (Knittel *et al*., 2010; Suggate *et al*., 2014; Wang, Y. e*t al*., 2023), suggesting that a potential South China-derived West Borneo/Semitau was located much more to the south (e.g. Indochina). At last, Carter & Clift (2008) argued against an Indochina-South China collision and interpreted a reactivation of older faults driven by the accretion of Sibumasu.

As discussed by Breitfeld *et al*. (2017) and Hennig, J. *et al*. (2017), the stratigraphic record and distribution of pre-Cenozoic rocks in western Borneo is not consistent with an isolated Semitau/West Borneo block. Consequently, Hennig, J. *et al*. (2017) suggested that the West Borneo basement is a southern continuation of the Indochina basement which may have not been moved very far southwards during the Mesozoic and Cenozoic. Gatinsky & Hutchison (1986) and Hutchison (1989) identified the similarities of the Triassic in West Sarawak and eastern Vietnam, but concluded a much more southern position of western Borneo not in close proximity to eastern Vietnam (Hutchison, 2005). The proposed southern palaeogeographic position, continuation of magmatic activity into the Jurassic in West Borneo, and age similarities to igneous rocks in the SCS that have been interpreted to be related to the Palaeo-Pacific subduction are therefore more consistent with a Palaeo-Pacific subduction origin for the Triassic igneous and volcaniclastic rocks in West Sarawak and NW Kalimantan (West Borneo).

More research is needed to understand the complex relations of pre-Cretaceous rocks in southern Borneo, the tectonic development of the various terranes, and to distinguish Permian to Triassic magmatism and metamorphism associated with the various Palaeo-Tethys sections and the Palaeo-Pacific in East Asia.

CONCLUSIONS

It is recommended to use the term Kuching Formation for the Triassic sedimentary and meta-sedimentary slope deposits in the area of Kuching. A type section has yet to be assigned, due to poor exposure and housing development removing or covering outcrops. Jalan Foreign Diplomatic Road in Petra Jaya between TB17 and TG1 offers some of the best sections and is suggested as future possible type area. The Kuching Formation represents a Triassic turbidite and associated deep water shale sequence which is the deep marine equivalent of the shallow marine Sadong Formation. The succession mostly consists of thinly-bedded sandstones exhibiting partial Bouma sequences interbedded with occasional thin debrites. Two of the studied logged sections include much thicker sandstone packages, with one, TG-1, including coarse pebbly sandstones and basal lags. Most of the studied outcrops are sediments deposited either away from the lobe axis or from within the lobe fringe. Basinal plain deposits are represented by thicker shales between the turbidite deposits, but most of these are either not preserved or not exposed.

Detrital zircon ages for the Kuching Formation are very similar to those of the Sadong Formation and were predominantly derived from uplifted Cathaysian basement and its cover units, presumably from West Borneo. Permo-Triassic detrital zircons in the samples were derived from the Palaeo-Pacific subduction volcanic arc. Previously, the Kuching Formation succession was included within the metamorphic Tuang Formation and thought to be of Palaeozoic age.

The remaining part of the Tuang Formation, together with the Kerait Schist, are suggested to be renamed and combined into the West Sarawak Metamorphics (Breitfeld *et al*., 2017), with the term either used as a formation name or alternatively as a group name comprising the Kerait Formation and Tuang Formation. As type section, the original assigned lower part of the Kerait Valley (Pimm, 1965) and/ or Sg. Tuang in the Kuap area (Tate & Hon, 1991) could be used. During fieldwork the best exposure was found along the Q420 road near the Kim Hin ceramics factory. Lithologies consist mainly of low-grade metamorphic quartz-mica schists. The protolith was a fine-grained volcaniclastic sedimentary rock, likely the Sadong and Kuching formations. White mica Ar/Ar ages reveal an Upper Triassic cooling age, shortly after deposition of the Triassic sedimentary successions. It is concluded that parts of the Triassic sedimentary rocks were metamorphosed by shearing in the accretionary prism of the Palaeo-Pacific subduction. This could also include distal deep marine fans.

With recent advances in age dating and mapping, our understanding of the tectonic history of Borneo and stratigraphic relations have improved considerably. However, more research is needed to fully understand the Palaeozoic and Mesozoic development.

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AUTHORS CONTRIBUTION

HTB: Manuscript draft, visualisation, field work, data review, interpretation; SDB: Visualisation, editing and review, discussion and interpretation; TG: Field work, sedimentary logs, logistics; JHB: Field work, editing and review, discussion and interpretation; RR: Administration, coordination, review.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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