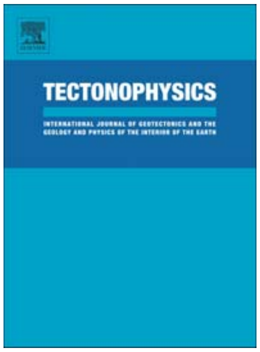

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# A Triassic to Cretaceous Sundaland–Pacific subduction margin in West Sarawak, Borneo

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## Abstract

Metamorphic rocks in West Sarawak are poorly exposed and studied. They were previously assumed to be pre-Carboniferous basement but had never been dated. New $^{40}$Ar/$^{39}$Ar ages from white mica in quartz-mica schists reveal metamorphism between c. 216 to 220 Ma. The metamorphic rocks are associated with Triassic acid and basic igneous rocks, which indicate widespread magmatism. New U-Pb dating of zircons from the Jagoi Granodiorite indicate Triassic magmatism at c. 208 Ma and c. 240 Ma. U-Pb dating of zircons from volcaniclastic sediments of the Sadong and Kuching Formations confirm contemporaneous volcanism. The magmatic activity is interpreted to represent a Triassic subduction margin in westernmost West Sarawak with sediments deposited in a forearc basin derived from the magmatic arc at the Sundaland–Pacific margin. West Sarawak and NW Kalimantan are underlain by continental crust that was already part of Sundaland or accreted to Sundaland in the Triassic.

One metabasite sample, also previously assumed to be pre-Carboniferous basement, yielded Early Cretaceous $^{40}$Ar/$^{39}$Ar ages. They are interpreted to indicate resumption of subduction which led to deposition of volcaniclastic sediments and widespread magmatism. U-Pb ages from detrital zircons in the Cretaceous Pedawan Formation are similar to those from the Schwaner granites of NW Kalimantan, and the Pedawan Formation is interpreted as part of a Cretaceous forearc basin containing material eroded from a magmatic arc that extended from Vietnam to west Borneo. The youngest U-Pb ages from zircons in a tuff layer from the uppermost part of the Pedawan Formation indicate volcanic activity continued until c. 86 to 88 Ma when subduction terminated.

*Keywords: $^{40}$Ar/$^{39}$Ar dating; U-Pb LA-ICP-MS geochronology; detrital zircon; accretionary margin; Kuching Zone; Sarawak*

## 1. Introduction

Borneo is part of Sundaland and records a complex tectonic history due to collisions in the Mesozoic and Cenozoic. Early reconstructions placed all of Borneo in the Sunda region from the Paleozoic/Early Mesozoic (Gatinsky et al., 1984; Metcalfe 1988) or from the Late Mesozoic onwards (Ben-Avraham, 1973). Van Bemmelen (1949) and Haile (1974) inferred a Paleozoic basement underneath SW Borneo and this basement was interpreted later (e.g. Gatinsky et al., 1984; Metcalfe, 1988) to indicate that Borneo was part of the SE Asia core and Cathaysia from the Paleozoic. More recently Borneo has been interpreted as composed of various fragments that were accreted to Sundaland and derived either from Gondwana or Cathaysia (e.g. Metcalfe and Irving, 1990; Metcalfe, 2009; Hall et al., 2009; Hall, 2012).

Until recently, the metamorphic rocks in SW Borneo and the Kuching Zone (Haile, 1974) of Sarawak were undated but were considered to be Paleozoic basement (van Bemmelen, 1949; Tate, 1991; Tate and Hon, 1991). This supposed age was the basis for correlation of SW Borneo and Sarawak and suggested a Cathaysian origin for both. The Kuching Zone has been interpreted (Fig. 1a) to include a Cathaysian terrane (Semitau) bounded by suture zones (e.g. Metcalfe, 2006, 2009; Zahirovic et al., 2014) or as a wide suture zone (Hall and Sevastjanova, 2012). However, south of the Kuching Zone the SW Borneo block is now interpreted as a Gondwana block that was added to Sundaland in the Cretaceous (Hall et al., 2009; Metcalfe, 2009; Hall, 2012). Furthermore, Davies (2013) and Davies et al. (2014) reported Cretaceous ages for the Pinoh Metamorphics of the Schwaner Mountains in SW Borneo. The changing interpretations of SW Borneo, and Cretaceous ages of the Pinoh Metamorphics, raise questions about correlations of metamorphic rocks from West Sarawak to SW Borneo, and whether the Kuching Zone was attached to SW Borneo or Sundaland or was a separate terrane.

The study area is located in West Sarawak in the Kuching Zone. When this study began there were no radiometric ages reported from metamorphic and many sedimentary rocks in West Sarawak. This study reports new results based on field investigations, $^{40}$Ar/$^{39}$Ar geochronology of metamorphic rocks and U-Pb dating of detrital zircons from sedimentary rocks and one igneous pluton. A new interpretation of the Mesozoic tectonic evolution of West Sarawak (Kuching Zone) is proposed.

## 2. Geological background

The Kuching Zone (Haile, 1974) in West Borneo comprises the southern part of Sarawak (West Sarawak) and extends into west and central Kalimantan (Fig. 1b). The zone includes sedimentary rocks ranging in age from Paleozoic to Mesozoic, and metamorphic rocks. These are overlain by largely undeformed Upper Cretaceous to Cenozoic sediments, and bounded in the north by the Lupar Line and to the south are the Pinoh Metamorphics and the Schwaner granites.

In the Kuching Zone thick Upper Cretaceous to Cenozoic fluvial or marginal marine sediments (Haile, 1957; Liechti et al., 1960; Wolfenden and Haile, 1963; Wilford and Kho, 1965; Haile, 1974; Tan, 1979) overlie a heterogeneous crust with fossils of Paleozoic and Early Mesozoic age, including a Cathaysian fauna and flora from the Permian onwards (Kon`no, 1972; Beauvais and Fontaine, 1990; Vachard, 1990). The Lupar Line separates the Kuching Zone from the Sibu Zone (Central Sarawak) to the north and has been interpreted as a suture (e.g. Hutchison, 1996, 2005; Tan, 1979) and as a major strike-slip fault (Haile, 1974; Gower, 1990; Hall, 2012). The Sibu Zone is composed of deep marine sediments, but no basement rocks have been found (Kirk, 1957; Liechti et al., 1960; Wolfenden, 1960; Haile, 1974). South of the Kuching Zone, SW Borneo or the SW Borneo Basement (Haile, 1974) is composed of Cretaceous granites (Haile et al., 1977; Williams et al., 1988; Bladon et al., 1989) intruded into metamorphic rocks which were assumed to be Paleozoic (Zeijlmans van Emmichoven, 1939; van Bemmelen, 1949; Pieters et al., 1987). Haile (1973) describes the SW Borneo Basement as “little-known zone with a complex Paleozoic and Early Mesozoic history of repeated sedimentation, orogeny, volcanism and intrusion.”

Metamorphic rocks in the Kuching Zone were assigned to the Tuang Formation and the Kerait Schist and interpreted as Carboniferous or older basement (Pimm, 1965; Tate and Hon, 1991). The metamorphic rocks were assumed to be older than unmetamorphosed Devonian to Carbo-Permian limestones and calcareous sediments such as the Terbat Limestone Formation of Sarawak or Telen River sediments of Kalimantan (Rutten, 1940; Cummings, 1962; Pimm, 1965; Wilford and Kho, 1965; Sanderson, 1966; Metcalfe, 1985; Vachard, 1990; Sugiaman and Andria, 1999) although no contacts have ever been reported from West Sarawak or nearby Kalimantan. The supposed Paleozoic schists have led many authors to interpret a pre-Carboniferous metamorphic basement beneath the whole of West Sarawak (e.g. Zeijlmans van Emmichoven, 1939; van Bemmelen, 1949; Pieters and Supriatna, 1990; Hutchison, 2005; Metcalfe, 2009) which extended into Kalimantan based on correlation (e.g. Tate and Hon, 1991) with the similarly undated Pinoh Metamorphics of Kalimantan, also assumed to be Paleozoic (Zeijlmans van Emmichoven, 1939; van Bemmelen, 1949). These metamorphic rocks have been interpreted as the oldest rocks exposed in Borneo (Tate and Hon, 1991). However, recently the Pinoh Metamorphics were dated as Early Cretaceous (Davies, 2013; Davies et al., 2014). Exposures of younger metamorphic rocks of Late Mesozoic age in West Sarawak have been assigned to various formations (Lubok Antu Melange, Serabang, Sejingkat and Sebangan Formation) with uncertain protoliths and origin and have been interpreted to be related to a Cretaceous to Cenozoic accretionary setting (e.g. Tan, 1979, 1982, 1993; Hutchison, 2005).

The occurrence of various undated metamorphic rocks and their interpretation as basement, and the Cathaysian fauna in Upper Paleozoic and Lower Mesozoic sedimentary rocks, led to interpretations that the Kuching Zone is a separate terrane, named Semitau (e.g. Metcalfe and Irving, 1990; Metcalfe, 2002, 2009; Zahirovic et al., 2014) or was part of/similar to the basement of the SW Borneo block (e.g. Metcalfe, 2002, 2006; Hall, 2002). The Semitau block as defined by e.g. Metcalfe and Irving (1990) includes only part of the Kuching Zone, bounded by the Lubok Antu Melange (named the Kapuas Complex in Kalimantan) in the north and the Boyan Melange in the south (Fig. 1b). However, the mapping of Supriatna et al. (1993) and Pieters et al. (1993) demonstrated that Jurassic and possibly Triassic sediments outcrop southwest of the Boyan Melange and therefore the definition of the Semitau block is rather unclear. Collision in the Late Cretaceous with another terrane called the Luconia-Dangerous Grounds block (Hall et al., 2009; Hall, 2012) or collision of a Semitau block with SW Borneo in the Late Eocene (Hutchison, 1996; 2005; Zahirovic et al., 2014) was assumed to be related to southward-directed subduction below West Borneo (e.g. Williams et al., 1988).

## 3. Stratigraphy

The geological map of the units discussed in this study (Fig. 2) is based on geological maps compiled for West Sarawak by Liechti et al. (1960) and Heng (1992) modified by new field observations made in this study. The following section summarises previous stratigraphic ideas and outlines differences based on the new observations.

### *3.1. Metamorphic rocks*

Some metamorphic rocks in Sarawak have been assigned to separate metamorphic formations named the Kerait Schist and the Tuang Formation (Pimm, 1965; Tate and Hon, 1991), and others included in various formations of Cretaceous (and possibly Late Jurassic) age named the Sejingkat, Serabang and Sebangan Formations and the Lubok Antu Melange (Wolfenden and Haile, 1963; Tan, 1979, 1982, 1993; Hutchison, 2005).

#### *3.1.1. Kerait Schist and Tuang Formation*

The Kerait Schist is poorly exposed and outcrops only in the Kerait valley (Pimm, 1965) where it forms small isolated exposures with no observable contacts. In contrast to the undeformed Upper Carboniferous to Permian Terbat Formation (Cummings, 1962; Pimm, 1965; Wilford and Kho, 1965; Sanderson, 1966; Metcalfe, 1985; Vachard, 1990) c. 30 km to the west, the Kerait Schist is metamorphosed and strongly deformed and Pimm (1965) concluded it was older.

The Tuang Formation is found in the area southeast of Kuching and near Sungai Tuang. Tate and Hon (1991) reported the Tuang Formation is distributed over an area of approximately 80 km² and included phyllites, pelitic and basic schists, metasandstones, pelitic hornfels and silicified volcanics and chert. However, they also included exposures north of Kuching assigned in this study to the Triassic sedimentary rocks (see below). No contacts were reported by Tate and Hon (1991). They reported that the age of the Tuang Formation was thought to be pre-Carboniferous based on an unpublished report of a ”dubious fossil tentaculid”. They also stated that “In west Sarawak, the oldest rocks are the Tuang and Kerait Schist Formation” and this statement appears to be based on the inference that deformed metamorphic rocks must be older than undeformed dated sedimentary rocks.

Today the Kerait Schist and the Tuang Formation are found in small inliers and exposures. In this study the Kerait Schist was examined in the only current exposure in the northern part of the Kerait valley. The Tuang Formation is observable only in small isolated exposures which have no contacts with other rocks. Housing development and expansion of the airport in southern Kuching may have significantly reduced the area of exposure. The Tuang Formation was examined at various locations in south Kuching and in the Sungai Tuang area. Rock types in both formations include mylonites, phyllites and low-grade quartz-mica schists, and as discussed below they are of similar age. Therefore, the two formations are here grouped together and named the West Sarawak Metamorphics.

#### *3.1.2. Upper Mesozoic metamorphic rocks*

Metamorphic rocks are found in the Serabang, Sejingkat and Sebangan Formations (Wolfenden and Haile, 1963) that resemble melanges (Hamilton, 1979; Tan, 1993; Hutchison, 2005), and in the Lubok Antu Melange (Tan, 1978; Tan, 1979) named the Kapuas Complex in Kalimantan (Williams et al., 1988) thought to be of Late Jurassic to Cretaceous age. Because of similarities in lithology and the interpreted Late Jurassic to Cretaceous age they are discussed together in this paper.

The interpreted ages of the melanges are based on fossils. Radiolaria from recrystallised cherts were identified as Upper Jurassic to Lower Cretaceous (Wolfenden and Haile, 1963; Tan, 1978; Tumanda et al., 1993; Basir and Aziman, 1996; Basir, 1996, 2000). Tan (1979) also reported Upper Cretaceous foraminifera from the Lubok Antu Melange. Tan (1979, 1982) included the undeformed calcareous Middle Eocene Engkilili Formation in the Lubok Antu Melange. However, Haile (1996) disputed this, based on lithological and deformation differences, and excluded the Engkilili Formation from the Lubok Antu Melange.

Metamorphic rocks include locally mylonitized and brecciated shale, slate, recrystallized chert and meta-chert, quartzite and pelitic hornfels associated with greenstone, meta-gabbro, meta-basalt and amphibolite, sheared phyllite, schist, and metagreywacke, associated with microdiorite, serpentinite and andesite in a pelitic matrix (Wolfenden and Haile, 1963; Tan, 1978, 1993). None of the metamorphic rocks have been dated.

In NW Kalimantan, close to the Sarawak border, a second melange belt is exposed and named the Boyan Melange (Williams et al., 1986). Williams et al. (1989) considered the Boyan Melange as Late Cretaceous. The relation of Boyan Melange and the melanges in West Sarawak are uncertain.

In this study metamorphic rocks from the Sejingkat Formation at Tanjung Bako, the Serabang Formation in the Biawak area and around the Pueh intrusion, and the Lubok Antu Melange in the Lupar valley were examined. A greenstone fault block (TB10, Jalan Datu Stephen Yong) described in Tate and Hon (1991) as Tuang Formation, is regarded as part of the Upper Mesozoic metamorphic rocks based on the findings in this study. As discussed further below it differs petrographically and in age from the West Sarawak Metamorphics.

### *3.2. Triassic sedimentary rocks*

Sedimentary rocks in the Sadong valley were assigned to the Sadong Formation (Liechti et al., 1960; Wilford and Kho, 1965). Lithologies include mudstones, siltstones, sandstones, shales, conglomerates, meta-sediments, thin limestone beds, marl and coal (Wilford and Kho, 1965). Tuffaceous sandy mud layers and volcanic rock fragments are commonly interbedded throughout the succession (Wilford and Kho, 1965), and record contemporaneous volcaniclastic input. The Sadong Formation was interpreted to represent an estuarine to neritic deposit (Liechti et al., 1960) with periodically brackish water influence (Wilford and Kho, 1965). The age of deposition is interpreted to be Carnian to Norian (Late Triassic) from a small assemblage of plant material, named the Krusin flora, with Cathaysian affinity (Kon`no, 1972) and from fossil bivalves within the succession (Liechti et al., 1960; Wilford and Kho, 1965). In this study the Sadong Formation was examined in road-sections south of the Kerait valley, where mainly inclined sandstone and shale alternations with interbedded thin coal layers are exposed.

Similar rocks observed in this study north of Kuching were previously included by Tate and Hon (1991) and Tan (1993) in the Tuang Formation. These rocks are here named Kuching Formation and include all sedimentary to meta-sedimentary rocks exposed along Sungai Sarawak north of the city of Kuching. The Kuching Formation comprises an alternation of graded sandstones, siltstones and mudstones interpreted as a marine turbidite succession. It is possibly a deeper marine lateral equivalent of the shallow marine Sadong Formation. Folding and a very low-grade greenschist facies overprint are observed locally in both formations.

### *3.3. Triassic volcanic rocks*

Andesites and basalts of the Serian Volcanic Formation form a mountain range in West Sarawak and NW Kalimantan (Pimm, 1965). The formation is reported to interfinger with the Triassic sedimentary rocks (Wilford and Kho, 1965) and is therefore concluded to be Triassic. Basir et al. (1996) identified Early Jurassic radiolaria in a tuff sequence near Kampung Piching, subsequently named the Binong Bed. Basir and Uyop (1999) included the Binong Bed in the Serian Volcanic Formation. The volcanic rocks in West Sarawak indicate magmatic activity from the Triassic to Early Jurassic. Possible time equivalents of the Serian Volcanic Formation in NW Kalimantan are the undated Sekadau Volcanics (Rusmana et al., 1993) and the undated Jambu Volcanics (Supriatna et al., 1993).

In this study the Serian Volcanic Formation was examined in a small active quarry south of Kuching. The dominant rock type is andesite. The rocks are affected by metamorphism and could be classified as metabasites. The contact with the Tuang Formation (West Sarawak Metamorphics) appears to be faulted but is not exposed.

### *3.4. Jagoi Granodiorite - Triassic granitoids*

Triassic granitoids are exposed in northwest and central Kalimantan in the Embuoi and Busang Complexes and at the border of Sarawak there is the Jagoi Granodiorite. In Kalimantan, K-Ar ages from the Embuoi Complex and the Busang Complex range from 201 to 263 Ma (Williams et al., 1988; Bladon et al., 1989; Supriatna et al., 1993, Pieters et al., 1993). Williams et al. (1988) also reported one sample with an age of 320 ± 3 Ma. Williams et al. (1988) subsequently named the area of Triassic granitoids the NW Kalimantan domain. Recent U-Pb zircon data from a metatonalite in west Kalimantan dated as 233 ± 3 Ma (Setiawan et al., 2013), in combination with the NW Kalimantan ages, indicates a significant Triassic igneous province.

The Jagoi intrusion in Sarawak is part of a small mountain range at the border with Kalimantan close to the town of Serikin and includes the peaks of Gunung Jagoi and Gunung Kisam. Previous dating yielded ages ranging from Cretaceous to Triassic. These included a whole rock K-Ar age of 89.3 ± 3.6 Ma (JICA, 1985), a K-Ar age of 112 Ma from a hornblende-bearing xenolith (Bignell, 1972), and K-Ar hornblende ages of 123 ± 15 Ma, 192 ± 10 Ma (JICA, 1985) and 195 ± 2 Ma (Bladon et al., 1989). This wide age range shows some uncertainty about the timing of the magmatic activity in the Jagoi intrusion. The Jagoi Granodiorite is reported to be the basement for the Upper Jurassic Bau Limestone Formation and the Upper Jurassic to Cretaceous Pedawan Formation (Ting, 1992). JICA

(1985) reported local alteration of the Jagoi Granodiorite, resulting in silicification, sericitization and chloritization.

In this study the Jagoi Granodiorite was sampled at one location for petrographic and geochemical analyses, and age dating.

### *3.5. Upper Jurassic to Cretaceous sedimentary rocks*

Upper Jurassic to Lower Cretaceous calcareous sediments and limestones were assigned to the Kedadom Formation and the Bau Limestone Formation in West Sarawak (Wilford and Kho, 1965; Bayliss, 1966; Yanagida and Lau, 1978; Ishibashi, 1982; Beauvais and Fontaine, 1990) and have a Cathaysian affinity from the Kimmeridgian onwards (Beauvais and Fontaine, 1990). In Kalimantan, limestones of the Brandung Formation with a Cathaysian affinity were deposited in a shallow marine reef environment in the Callovian (Schairer and Zeiss, 1992).

The clastic uppermost Jurassic to Cretaceous Pedawan Formation overlies the Jurassic to Lower Cretaceous calcareous formations (Wilford and Kho, 1965; Muller, 1968; Nuraiteng and Kushairi, 1987, Morley, 1998). The Pedawan Formation contains contemporaneous volcanic material (Wilford and Kho, 1965; Supriatna et al., 1993) and indicates a switch from a calcareous shallow marine environment to a clastic-dominated deeper marine depositional environment. The Pedawan Formation was examined in various outcrops around the town of Bau and the west of Kuching. It comprises alternations of graded sandstones, laminated sandstones and mudstones, deposited as turbidites with interbedded limestones and thin tuff or dacite layers, suggesting contemporaneous magmatism.

## **4. Sampling and methodology**

### *4.1. Sampling*

The Tuang Formation (TB4, TB249) and the Kerait Schist (TB35) (West Sarawak Metamorphics), the Sadong (712, 713a_b), Kuching (TB12, TB250a), Pedawan (STB07a, STB34, STB61a, STB62, STB68a_b, TB109) and Serian Volcanic (TB6) Formations, the Jagoi intrusion (TB114), and Upper Mesozoic metamorphic rocks of the Serabang and Sejingkat Formations (TB66a_c, TB67, TB68a_b, TB74, TB79, TB86, TB162) and the greenstone TB10 were sampled in this study for petrographic and geochemical analysis, and dating. Fig. 3 displays the sample locations and the distribution of metamorphic and igneous target lithologies. Fresh rocks with minimal alteration were sampled from outcrops or nearby float. White micas from three metamorphic samples for $^{40}Ar/^{39}Ar$ dating and zircons from seven sedimentary/igneous samples for U-Th-Pb dating were separated.

### *4.2. Sample preparation*

Sample preparation was carried out at Royal Holloway University of London. The samples were crushed to gravel-sized chips using a jaw crusher and the more friable (meta-) sedimentary samples by pestle and mortar. A 63-250 µm fraction was separated, which was used for geochronology analysis.

White mica was separated using standard heavy liquid lithium heteropolytungstate (LST) at a density of 2.75 g/cm³ and a FRANTZ magnetic barrier separator. The white mica separates were handpicked under a binocular microscope to achieve the required purity of >99% for the final separates that were analysed at The Australian National University (ANU).

Zircon was separated by using standard heavy liquids sodium polytungstate (SPT) and lithium heteropolytungstate (LST) at a density of 2.89 g/cm³ and a FRANTZ magnetic barrier separator. Additional heavy liquid separation was performed with di-iodomethane (DIM) at 3.3 g/cm³ to maximise the purity of the zircon separates. The zircon separates were hand-picked or poured and mounted in epoxy resin blocks. These resin blocks were polished to expose mid-grain sections. Zircons were imaged in transmitted light and with cathodoluminescence secondary electron microscope (CL-SEM) for selecting the analysis spot for each grain and to detect cracks and inclusions, and zoning of zircons prior the analysis. CL-SEM of the igneous sample (TB114) was obtained only after the LA-ICP-MS analysis.

### *4.3. Geochronology*

#### *4.3.1. $^{40}$Ar/$^{39}$Ar dating*

$^{40}$Ar/$^{39}$Ar dating of white micas was performed for samples TB10, TB35 and TB249 at the Australian National University. The white mica aliquots were analysed using the using in vacuo step-heating method in a resistance furnace attached to a VG1200 mass spectrometer (Forster and Lister, 2010, 2014; Forster et al., 2015). The internal laboratory biotite standard GA-1550 (98.5 ± 0.8 Ma; Spell and McDougall, 2003) was used as the flux monitor for the samples. 22-23 heating steps were performed on each sample, with a minimum difference of +30˚C between successive heating steps. A final heating step at 1450˚C ensured all gas was released from the sample.

The data were reduced using Noble software in accordance with the correction factors and J-factors. Correction factors were calculated from the analyses of $CaF_2$ and K-glass, and J-factors were calculated from analysis of the flux monitors. Standard values recommended by the IUGS subcommission on geochronology for $^{40}$K abundances and decay constants were used (Steiger and Jäger, 1977). The decay factor of $^{40}$K ($\lambda^{40}$K) for all age calculations was set at $5.5430e^{-10}$ $yr^{-1}$. Data interpretation was carried out using the programme eArgon written by G. S. Lister. Results tables for each step heating experiment are presented in Supplementary Table 1.

### *4.3.2. LA-ICP-MS U-Th-Pb dating*

LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) dating of zircons from 7 samples was performed at Birkbeck College, University of London. Zircon U-Pb dating was performed on a New Wave NWR 193 (213 for a single sample) nm laser ablation system coupled to an Agilent 7700 quadrupole-based plasma mass spectrometer (ICP–MS) with a two-cell sample chamber. A spot size of 25 µm for the NWR 193 nm and of 30 µm for the NWR 213 nm system was used. The Plešovice zircon standard (337.13 ± 0.37 Ma; Sláma et al., 2008) and a NIST 612 silicate glass bead (Pearce et al., 1997) were used to correct for instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U.

Data reduction software GLITTER (Griffin et al., 2008) was used. The data were corrected using the common lead correction method by Andersen (2002), which is used as a $^{204}$Pb common lead-independent procedure.

### *4.4. U-Pb age data reduction*

For grains older than 1000 Ma, the age obtained from the $^{207}$Pb/$^{206}$Pb ratio is given and for grains younger than 1000 Ma, that from the $^{238}$U/$^{206}$Pb ratio is given, because $^{207}$Pb cannot be measured with sufficient precision in these samples resulting in large analytical errors (Nemchin and Cawood, 2005). Ages greater 1000 Ma were considered to be concordant if the difference between the $^{207}$Pb/$^{206}$Pb and $^{206}$Pb/$^{238}$U age is 10% or less and ages smaller 1000 Ma were considered to be concordant if the difference between the $^{207}$Pb/$^{235}$U and $^{206}$Pb/$^{238}$U age is 10% or less.

Isoplot 4.11 (Ludwig, 2003) was used for graphical illustration of conventional Concordia plots (Wetherill, 1956) and Tera-Wasserburg Concordia diagrams (Tera and Wasserburg, 1972). Concordia and Tera-Wasserburg plots were used to identify individual peaks or visually assess outliers (due to e.g. lead loss, inheritance and common lead) within the population which were excluded from the weighted mean age calculation. The weighted mean age was calculated for the igneous samples TB114 and for the pyroclastic sample STB68b from the significant youngest population. Age histograms with probability for the rocks were created with Isoplot 4.11 (Ludwig, 2003). Age histograms and probability density plots for (meta-) sedimentary rocks were created using an R script written by I. Sevastjanova. Results tables are presented in Supplementary Tables 2 for each sample.

### *4.5. Geochemistry*

#### *4.5.1. SEM white mica geochemistry*

Micas used for the $^{40}Ar/^{39}Ar$ dating (TB10, TB35, TB241) were first analysed with a HITACHI S3000 scanning electron microscope (SEM) at Royal Holloway University of London. Chemical analyses were conducted with Aztec energy-dispersive X-ray detection system (EDS) by Oxford Instruments using an acceleration of 20 kV and 76 µA. The mica classification presented in this study follows the classification scheme of Tischendorf et al. (2004). Representative mica data is presented in Supplementary Table 3.

#### *4.5.2. XRF geochemistry*

Samples were processed with a jaw crusher and a tungsten-carbide mill at Royal Holloway University of London. Fusion discs and powder pellets were analysed for major and trace elements with a 2010 PANalytical Axios sequential X-ray fluorescence (XRF) spectrometer with 4kW Rh-anode X-ray tube. Analysed samples include the Serian Volcanic Formation (TB6) and the Jagoi Granodiorite (TB114). XRF data tables are presented in the Supplementary Table 4.1 and normative calculations are in Supplementary Table 4.2.

## **5. Petrography**

### *5.1. Metamorphic rocks*

#### *5.1.1. West Sarawak Metamorphics*

Quartz-mica schists (TB4, TB35 and TB249) of the West Sarawak Metamorphics are strongly foliated low-grade mylonites. Fig. 4a and b are outcrop photographs of the quartz-mica schists. A foliation defined by fine grained white mica, polycrystalline quartz and an opaque phase (Fig. 4c and d) is crenulated by later stage deformation.

The compositions of the white micas are rather restricted; homogeneous grains show no significant changes throughout sample or any zoning. Analyses of white micas of samples TB35 and TB249 are plotted on Fig. 5 and Supplementary Fig. 1.

Sample TB249 contains white mica with Si content from 3.28 to 3.33 a.p.f.u. Mg# numbers range from 0.61 to 0.67. Almost all observed white micas have a very minor paragonite content (Na/(Na + K) from 0.021 to 0.068. Following the classification scheme of Tischendorf et al. (2004) the white mica of sample TB249 plots along the muscovite-phengite boundary (Fig. 5).

White mica of sample TB35 has a similar composition to sample TB249. The compositions show slight variations, but grains are generally homogeneous. Si content ranges from 3.26 to 3.47 a.p.f.u. Coarser white mica grains within the foliation bands usually have slightly higher Si values compared to finer grained white micas. The Mg# numbers range from 0.76 to 0.84 and are slightly higher than the white mica of sample TB249. The paragonite component ranges up to 0.051.  According to the classification scheme of Tischendorf et al. (2004), the white mica in sample TB35 can be classified as muscovite (Fig. 5).

### *5.1.2. Upper Mesozoic metamorphic rocks*

Sample TB10 is a chlorite-albite-(orthoclase)-quartz-mica schist (Fig. 4e and f). Fresh, clean white mica was carefully obtained from cleavage surfaces. The dominant mica is fine-grained phengite. The sample has various domains where chlorite is more abundant than mica. Brittle deformation associated with abundant quartz and feldspar veining is common within the sample. Fine grained clinozoisite and epidote were observed. Polycrystalline quartz and albite bands are common. Occasionally alkali feldspar is present in these bands. White micas have similar Si values to the other two samples and range from 3.29 to 3.35 a.p.f.u. However, the micas have high $FeO_{tot}$ and higher MgO and $K_2O$. The Mg# number is lower due to the high Fe content, ranging from 0.47 to 0.56. The paragonite component ranges up to 0.035. According to the classification scheme of Tischendorf et al. (2004), the white mica in sample TB10 can be classified as phengite (Fig. 5 and Supplementary Fig. 1).

Samples from the Serabang Formation include various undated meta-sediments. TB86 is a hornfelsed folded meta-sediment. The hornfels is composed of monocrystalline quartz, lithic fragments, chert, polycrystalline quartz and rare microcline. It resembles a quartz-rich but texturally immature sediment which has been locally folded and has been affected by a contact metamorphic overprint related to the younger Pueh intrusion. Grain size variations define layers which resemble the original sedimentary structure of the rock. Extension cracks are filled with quartz and quartz segregations are observed.

Associated with these meta-sediments are silicified brecciated fault rocks (cataclasites), quartzites and recrystallized cherts from the Serabang and Sejingkat Formations. The quartzites are entirely composed of monocrystalline quartz and domains of microcrystalline quartz. Grain boundary migration is common and indicates recrystallization of quartz. The microcrystalline quartz domains are separated by a mesh of quartz veins. Coarser quartz is affected by static recrystallization and grain size reduction is common. Within the samples are dark, near isotropic domains which are heavily brecciated (Fig. 4g). Abundant circular areas of fibrous chalcedony are present (Fig. 4h) and more fibrous chalcedony is present in finer grained domains. Extension cracks in various directions are filled with polycrystalline quartz. Monocrystalline or polycrystalline quartz is present in coarser crack fillings which usually form a quartz vein mesh. The mesh is interpreted to resemble the original structure of the protolith. The microcrystalline quartz domains are probably pseudomorphs after olivine or serpentinised olivine. The unusual structures of the samples suggest that the quartzites of the Serabang and Sejingkat Formations are silicified serpentinites. Similar silicified serpentinite has been reported from many areas including the Semail nappe of Oman (Stanger, 1985), the United Arab Emirates (Lacinska and Styles, 2013) and the Stalemate Fracture Zone in the NW Pacific (Silantyev et al., 2012). Magnetite occurs along cracks as commonly found in serpentinised olivine. Angular opaque crystals are magnetite, rutile and pyrite. No chromite was found.

### *5.2. Triassic sedimentary rocks*

Five samples from the Sadong and Kuching Formations were analysed in thin section. Three of the five samples were dated (see below). All samples are classified as lithic greywackes in the QFL diagram (Supplementary Fig. 2) (Pettijohn et al., 1987). The samples are composed mainly of monocrystalline quartz, polycrystalline quartz and lithic fragments, with subordinate volcanic quartz and chert (Supplementary Table 5). The samples lack feldspar or feldspar is below 1 %. Lithic fragments including metamorphic, volcanic and sedimentary rocks indicate a wide variety of source rocks. Cherts indicate a source of deep marine sedimentary rocks.

### *5.3. Serian Volcanic Formation*

One sample of the Serian Volcanic Formation (TB6) is an andesite which is the dominant rock type in the Serian Volcanic Formation. It is fine grained with plagioclase needles and quartz in a dark ground mass. Chlorite and epidote replace plagioclase and pyroxene. The sample has coarse grained plagioclase-pyroxene xenoliths (Fig. 6a) and well-rounded polycrystalline quartz xenoliths (Fig. 6b). Late stage deformation produced extensional fractures filled by polycrystalline quartz or chlorite.

### *5.4. Jagoi Granodiorite*

The Jagoi Granodiorite sample TB114, an amphibole granodiorite, is composed mainly of plagioclase, alkali feldspar, quartz, biotite and amphibole. Plagioclase and alkali feldspar are affected by sericitic alteration and saussuritization. Biotite is usually chloritised (Fig. 6c). Epidote, clinozoisite and chlorite replace amphiboles. An opaque phase occurs usually with amphibole or biotite. Fine grained titanite is present within the chloritised biotite. The Jagoi Granodiorite has a coarse grained phaneritic texture. There are no indications of shearing, mineral alignment or metamorphic overprint. Plagioclase forms large euhedral crystals with polysynthetic twinning, which are commonly zoned

(Fig. 6d). Alkali feldspar occurs usually as zoned euhedral to subhedral crystals. Biotite shows undulose extinction indicating minor deformation. Quartz occurs commonly as monocrystalline grains with non-undulose to slightly undulose extinction. Amphibole occurs as subhedral to anhedral crystals which may be twinned (Fig. 6e and f).

### *5.5. Pedawan Formation*

Five representative clastic samples of the Pedawan Formation were selected. Four samples are classified as lithic greywackes and a single sample as a lithic arenite (Supplementary Fig. 2) (Pettijohn et al., 1987). They are mainly composed of feldspar, lithic fragments and monocrystalline quartz with subordinate polycrystalline quartz and chert (Supplementary Table 5). Feldspar is predominantly plagioclase. Lithic fragments are mainly volcanic and minor sedimentary.

Two of the lithic greywacke samples are composed mainly of volcanic lithic fragments and volcanic quartz. Both samples are almost devoid of feldspar. The very fine grained character, the whitish appearance and the composition indicate a pyroclastic origin for the two samples.

A micritic packstone (STB61a) from the upper part of the Pedawan Formation, interbedded with the clastic sediments, has Turonian foraminifera and the fossil assemblage indicates an inner neritic environment of deposition (Table 1).

## 6. Analytical results

### *6.1. XRF geochemistry – results*

#### *6.1.1. Serian Volcanic Formation*

The metabasite of the Serian Volcanic Formation is a high-K calc-alkaline andesite based on the $K_2O$-$SiO_2$ diagram (Peccerillo and Taylor, 1976) and an andesite in the QAPF diagram (Streckeisen, 1974). In the tectonic discrimination diagrams of Schandl and Gorton (2002) it is classified as an active continental margin or oceanic arc rock. Crustal influence is confirmed in the normalised spider-diagrams by the enrichment of large ion lithophile elements (LILEs) such as Cs, Rb and Ba, a positive Pb peak and a negative Nb trough (Fig. 7). The high field strength elements (HFSE), such as Yb and Y, are slightly higher than the N-MORB values. A subduction-related origin is interpreted for the Serian Volcanic Formation, possibly in an island arc.

#### *6.1.2. Jagoi Granodiorite*

Sample TB114 is classified as granodiorite in the QAPF diagram (Streckeisen, 1974), which is the dominant lithology of the Jagoi intrusion. It is an I-type granite according to the classification of Chappell and White (2001) with a calc-alkaline character in the AFM (Irvine and Baragar, 1971) and in the $K_2O$-$SiO_2$ diagram (Peccerillo and Taylor, 1976). It has a high $Na_2O$ value (>3.2 wt%), A/CNK<1.1 and <1% normative corundum. The ASI (aluminium saturation index) value is 1.02 and the sample is therefore classified as peraluminous (Frost et al., 2001). It has an Fe*-number of 0.77 and is classified as magnesian. The MALI (modified alkali-lime index) value is 3.1 at 70.4% $SiO_2$, classifying this as calcic (Frost et al., 2001). It can be described as a magnesian calcic peraluminous granitoid using the Frost et al. (2001) classification, similar to island arc plutons, plagiogranites and plutons associated with Cordilleran batholiths. The sample plots into the volcanic arc granite (VAG) field in the tectonic discrimination diagrams of Pearce et al. (1984) with trace element values and ratios (Y, Nb, Yb, Ta and Rb) indicating a volcanic arc-related origin. Crustal influence is confirmed in the normalised spider-diagrams by the enrichment of LILEs, with prominent troughs in Nb, La, Ce, P and Ti, and a positive Pb and K peaks (Fig. 7). HFSEs are below the N-MORB values and indicate depletion. A subduction-related origin for the Jagoi Granodiorite is interpreted from the geochemistry.

## *6.2. $^{40}Ar/^{39}Ar$ mica geochronology*

Three metamorphic samples were dated by the $^{40}Ar/^{39}Ar$ method. Two of these have a Triassic age (TB35, TB249) and are named the West Sarawak Metamorphics in this study, while a single sample revealed Cretaceous ages (TB10). Sample TB249 is a quartz-mica schist previously mapped as Tuang Formation (Tate and Hon, 1991). Sample TB35 is a strongly foliated low-grade mylonitic quartz-mica schist from the Kerait Schist (Pimm, 1965). TB10 is a chlorite-albite-(orthoclase)-quartz-mica schist sampled from an isolated outcrop in SW Kuching previously assigned to the Tuang Formation (Tate and Hon, 1991). The analytical data for the step heating procedure are presented in Supplementary Table 1 for each sample.

### *6.2.1. West Sarawak Metamorphics*

**TB249**

The sample was analysed in 22 heating steps. The apparent age plot (Fig. 8a) shows a relatively simple Triassic age plateau with a potential Cretaceous overprint. The age spectrum shows minimal argon loss in the first 5 steps (450 – 630˚C), rising rapidly to a well-defined plateau at 216.8 ± 1.2 Ma calculated from steps 6 – 11 and 13 (marked green). For better visual presentation, only the heating steps 2-18 are displayed in the apparent age plot. The orange coloured step (step 12) is considered an outlier and is excluded from the age calculation. The initial steps are affected by calcium contamination and may not show reliable ages.

**TB35**

The sample was analysed in 23 heating steps. The apparent age plot indicates a Triassic metamorphic event with a thermal event in the Cretaceous and/or Cenozoic (Fig. 8b). The Triassic plateau is calculated at 219.6 ± 3 Ma from steps 9-12 (marked in green) from a slightly disrupted plateau. Only the first 16 steps of the analysis are displayed in the apparent age plot. All steps after 16 are above 99.7 % argon released and can be disregarded. The age spectrum initially shows argon loss in the first 8 steps (450 – 700˚C). These steps may be affected by younger low grade metamorphic events but also show significant chlorine contamination. The upper limit is recorded in step 10 at approximately 222 Ma (marked in orange).

### *6.2.2. Upper Mesozoic metamorphic rocks – sample TB10*

The sample was analysed in 23 heating steps. The apparent age plot indicates metamorphism in the Cretaceous, and a possible thermal event in the Cenozoic (Fig. 8c). The age spectrum rises asymptotically from c. 23 Ma towards an upper limit of c. 143 Ma in the first 9 heating steps (450 – 780˚C). Then it drops in the next 4 steps to a lower limit of 118.5 ± 1 Ma calculated from steps 14 and 15 (marked in orange), before it rises again to the same upper limit in step 18. The upper limit is defined by steps 10, 11 and 18 (marked in green), and gives an apparent age of 143 ± 2.2 Ma. For better visual presentation, only the heating steps 2-19 are displayed in the apparent age plot. The observed age spectrum usually suggests mixing of age populations potentially from two different phases. However, phengite compositions analysed are very restricted and indicate that the complicated age spectrum is derived from a single phase which records various metamorphic events in the Cretaceous.

## *6.3. U-Th-Pb zircon geochronology*

### *6.3.1. Triassic sedimentary rocks*

Zircons from two samples (712, 713b) of the sedimentary Sadong Formation were analysed. A total of 272 concordant U-Pb ages were obtained from 259 zircons (Fig. 9a and b). The data for the two samples are presented in Supplementary Tables 2.1 and 2.2. All zircons analysed were between 70 and 200 µm in length. The two samples analysed have very similar zircon age distributions, consisting in total of 64 Phanerozoic, 203 Proterozoic and 5 Archean ages, and show very similar dominant age peaks. There is a wide peak in the Permian-Triassic and a narrow major peak at around 1.8 Ga (Paleoproterozoic). Permian-Triassic ages range from 205 to 290 Ma with a major peak at 240 to 270 Ma. There are minor differences between the two samples for older Phanerozoic zircons. A small number of Carboniferous and Devonian ages were obtained from sample 712, and a few Silurian ages from sample 713b. Both samples have a few Ordovician ages. The major

Proterozoic age peak at 1.8 Ga is accompanied by a small number of scattered Paleoproterozoic and Archean ages, ranging from 1.7 Ga to 2.8 Ga with a small peak at around 2.4 Ga. The oldest age recorded in the Sadong Formation is Neoarchean at 2732 ± 10 Ma in sample 713b. The youngest age is 212 ± 2 Ma (Norian, Late Triassic) in sample 713b and 205 ± 2 Ma (Rhaetian, Late Triassic) in sample 712. Both grains are interpreted to be affected by potential lead-loss and the second youngest grains of each sample (231 ± 3 Ma, 225 ± 2 Ma) are interpreted to give a reliable magmatic age. The Proterozoic and Archean zircons are mainly rounded, indicating multiple reworking, and are generally pinkish in colour. The Permo-Triassic and Carboniferous zircons are subrounded to euhedral, suggesting first cycle to moderately recycled input, and are commonly colourless.

A lithic greywacke sample (TB250a) was analysed from the Kuching Formation. A total of 129 concordant U-Pb ages were obtained from 121 zircons (Fig. 9c). The data table for the sample is presented in the Supplementary Table 2.3. All zircon grains are between 70 and 200 µm. The zircon populations are similar to the Sadong Formation, consisting of 30 Phanerozoic, 92 Proterozoic and 7 Archean and dominant age peaks in the Permian-Triassic and in the Proterozoic at 1.8 Ga. Permo-Triassic ages range from 221 to 284 Ma with a major peak at 240 to 245 Ma. There is a minor zircon age population in the Carboniferous to Devonian. The major Proterozoic age peak at 1.8 Ga is accompanied by a small number of widely distributed Paleoproterozoic and Archean ages, ranging from 1.5 Ga to 3.4 Ga. The oldest age recorded in the Kuching Formation is Paleoarchean at 3436 ± 11 Ma, which is one of the oldest U-Pb zircon ages reported from Borneo. The youngest age is Norian (Late Triassic) at 221 ± 3 Ma. The Phanerozoic zircons are commonly euhedral and subrounded with slightly elongated form and indicate a first cycle to moderately recycled sediment, and are commonly colourless. They have generally concentric or sector zoning which record magmatic growth (Fig. 8d). The Precambrian zircons are dominated by rounded and subrounded grains which are interpreted to indicate multiple recycling and are generally pinkish in colour or the ages are related xenocryst cores.

### 6.3.2. Jagoi Granodiorite

Sample TB114 from the Jagoi Granodiorite was dated. A total of 108 concordant U-Pb ages were obtained from 104 zircon grains. The data for the sample is presented in the Supplementary Table 2.4. All zircon grains are between 80 and 150 µm in length and dominated by elongated zircons with concentric (oscillatory) zoning. CL from zircons is usually very dark, indicating high U-Th ratios. Cores are rare and are related to inherited ages. Some zircons have greyish homogeneous rims. The zircon population is composed of mainly Late Triassic zircons with very few Jurassic and Middle Triassic zircons. The Tera-Wasserburg diagram (Fig. 10a) indicates common lead in the discordant analyses.

A weighted mean age of 208.3 ± 0.9 (MSWD = 4.6) is calculated for the Jagoi Granodiorite from an age range between 200 to 217 Ma (Fig. 10c). Inherited ages are around c. 240 Ma (Fig. 10b).

Several apparently concordant and near concordant Jurassic, and discordant Cretaceous ages, ranging from 82 to 200 Ma, suggest a younger thermal event, potentially in the Late Cretaceous (Fig. 10a). Concordant ages of 163 and 182 Ma are related to rims or overprinted cores. The relatively high MSWD indicates a post-intrusive overprint and inheritance. CL images with analytical spots for assorted zircons are displayed in Fig. 10d.

### *6.3.3. Pedawan Formation*

U-Pb zircon ages of the Pedawan Formation were acquired from sedimentary samples STB07a and STB34, and the pyroclastic sample STB68b.

Sample STB34 is a lithic arenite. A total of 70 concordant U-Pb ages were obtained from 80 zircons. The data table is presented in the Supplementary Table 2.5. All zircon grains are between 63 and 250 µm. The zircons include 60 Phanerozoic, 9 Proterozoic and 1 Archean age (Fig. 11a). Most prominent peaks include the Early Cretaceous, the Late Jurassic and the Permian-Triassic. The Early Cretaceous population has a major peak between 110 and 120 Ma. The Middle Mesozoic peak ranges from Early Cretaceous to Middle Jurassic between 130 to 170 Ma with a major peak at 150 to 160 Ma. The Permian-Triassic has two peaks, the younger between 220 to 240 Ma and a second between 250 to 260 Ma. A small number of ages are in the early Paleozoic (Carboniferous and Ordovician). Proterozoic ages are composed of Neoproterozoic, ranging of 700 Ma to 800 Ma, and Paleoproterozoic, ranging from 1.6 Ga to 2.1 Ga. The oldest age recorded in sample STB34 is Neoarchean at 2502 ± 34 Ma. The youngest age is 102 ± 1 Ma (Albian, Early Cretaceous). The Mesozoic zircons are commonly euhedral to subrounded and indicate a first cycle to moderately recycled origin. There are several dark rims of Cretaceous age which indicate a metamorphic event at this time. Permian zircons are generally subrounded to rounded and suggest moderately recycled grains. The Proterozoic zircons are mainly rounded and indicate multiple recycling. The Archean age is found in a xenocryst core.

Sample STB07a is a lithic greywacke. A total of 78 concordant U-Pb ages were obtained from 106 zircons. The data are presented in Supplementary Table 2.6. All zircon grains are between 63 and 200 µm. The zircon age populations consist of 56 Phanerozoic and 22 Proterozoic ages (Fig. 11b). Most prominent peaks are Late and Early Cretaceous, Late Jurassic, Permian-Triassic and around 1.8 Ga to 1.9 Ga. The Cretaceous peaks include subpeaks at 85 to 100 Ma and at 120 to 130 Ma. Jurassic ages range from the Jurassic-Cretaceous boundary at 140 to 150 Ma, the most dominant age peak of the sample, to 180 Ma. The whole Triassic and the Late Permian is represented in the sample ages ranging from 200 to 260 Ma. Minor populations are Early Permian, Devonian and Proterozoic up to 1.8 to 1.9 Ga. The oldest age recorded in sample STB07a is 1874 ± 15 Ma (Paleoproterozoic). The youngest age is 86 ± 1 Ma (Santonian, Late Cretaceous). The Mesozoic dominated by subrounded to euhedral zircons, indicating mostly moderately recycled material with minor first-cycle material. The Proterozoic is mainly composed of rounded zircon grains which indicate multiple recycling.

Sample STB68b is a pyroclastic deposit sampled at Gunung Singai. A total of 101 concordant U-Pb ages were obtained from 121 zircons. The data table is presented in the Supplementary Table 2.7. All zircon grains are between 63 and 200 µm. All U-Pb ages obtained are Mesozoic. The sample is composed of mainly Cretaceous zircons with a few Jurassic zircons (Fig. 12a). The Cretaceous has a major peak at 90 to 100 Ma which forms more than 50% of the zircon age population (Fig. 12b). The Lower Cretaceous to Upper Jurassic zircon population ranges from 140 to 175 Ma. The oldest age recorded in sample STB68b is 173 ± 2 Ma (Middle Jurassic). The youngest age is 87 ± 1 Ma (Coniacian, Late Cretaceous). The variability of Cretaceous zircon ages indicates that the sample was not sourced by a single magmatic pulse and zircon growth may have occurred during a long period of time. Jurassic ages suggest inherited detrital sources. The weighted mean age calculation of the Cretaceous population results in 95.6 ± 0.6 Ma (MSWD = 2.9) (Fig. 12b). In view of the interpreted long period of zircon crystallisation and inheritance, only the youngest population was used to identify the timing of eruption (Fig. 12c). The weighted mean age calculation of the youngest population consisting of five grains gives an age of 88.5 ± 1.5 Ma (MSWD = 1.3). CL images with analytical spots for assorted zircons are displayed in Fig. 12d.

## 7. Discussion

Table 2 summarises the age data obtained by U-(Th)-Pb zircon dating and by the $^{40}Ar/^{39}Ar$ white mica dating. The following paragraph discusses the tectonic implications for West Sarawak and adjacent areas from the age, provenance and geochemical results. Fig. 13 displays the results of the U-Pb zircon and $^{40}Ar/^{39}Ar$ white mica age dating and their tectonic significance.

### *7.1. Triassic magmatism*

Triassic magmatism in West Sarawak is recorded by the Serian Volcanic Formation, the Jagoi Granodiorite and the volcaniclastic sediments of the Kuching and Sadong Formations. These are interpreted to be the subduction products of a volcanic arc at the margin of Sundaland. A subduction-related origin of the Jagoi Granodiorite is indicated by the geochemistry.

An I-type amphibole granodiorite (TB114) of the Jagoi Granodiorite was dated. Zircon U-Pb dating yielded an age of 208.3 ± 0.9 (Late Triassic) and an inherited age of c. 240 Ma. The inherited age is interpreted as the first magmatic phase and the younger age is interpreted as a second magmatic phase with some recrystallization of older zircons. A similar interpretation was given by Supriatna et al. (1993) for K-Ar ages of the Triassic Embuoi complex in NW Kalimantan with initial crystallisation at 230-263 Ma and later recrystallization at 201-214 Ma. The Jagoi Granodiorite was affected by later thermal events which resulted in lead-loss in zircons and ages ranging from Early Jurassic to Late Cretaceous. A Cretaceous thermal overprint could account for the wide range of K-Ar ages for the Jagoi Granodiorite reported by various previous authors (Bignell, 1972; JICA, 1985; Bladon et al., 1989).

No age dating was carried out on andesitic rocks of the Serian Volcanic Formation, but a Triassic age is inferred by Pimm (1965) and Wilford and Kho (1965) from the interfingering with the Triassic Sadong Formation. A subduction-related origin is interpreted from geochemical data for sample TB6.

Triassic volcaniclastic sediments are assigned to the Sadong Formation and newly-defined Kuching Formation. The two formations have very similar characteristics and are interpreted to be lateral equivalents deposited in different parts of an arc basin. The Sadong Formation is a shallow marine to estuarine deposit (Liechti et al., 1960; Wilford and Kho, 1965) and the Kuching Formation is a deep marine turbidite. U-Pb zircon dating provides a maximum depositional age (MDA). The MDA of the Sadong Formation is c. 225 to 240 Ma (Carnian to Ladinian) and the MDA of the Kuching Formation is 221 Ma (Norian) to c. 230 Ma (Carnian). Within the Sadong Formation are two grains that are slightly younger; they were interpreted to be affected by lead-loss and excluded from the MDA determination. Since the Sadong Formation is locally metamorphosed it is possible that some zircons were partly reset by this metamorphism. The Norian to Ladinian MDA is consistent with the previous published paleontological ages of Late Carnian (Kon`no, 1972) and Norian (Liechti et al., 1960; Wilford and Kho, 1965) for the Sadong Formation. The Sadong Formation has a Cathaysian flora (Kon'no, 1972) which indicates deposition at low latitudes.

The Triassic ages of the Jagoi Granodiorite in West Sarawak and plutonic rocks in NW Kalimantan indicate widespread magmatism in a plutonic province in NW Kalimantan and West Sarawak. The Triassic volcanic and volcaniclastic rocks indicate widespread volcanic activity in the same region. The volcanic arc is interpreted to have been built on older continental basement. The zircon age peak at c. 1.8 Ga in the Triassic sedimentary rocks indicates recycling of older material. Paleoproterozoic zircons of c. 1.8 Ga in the region are known from the Malay Peninsula (Sevastjanova et al., 2011) and from Indochina (Thailand/Laos) (Carter and Moss, 1999; Burrett et al, 2014; Arboit et al., 2016). Plutons of Paleoproterozoic age at c. 1.8 Ga are known from the Cathaysia block in SE China (Liu et al., 2009; Chen et al., 2016). It is therefore concluded that the western part of NW Kalimantan and West Sarawak (western part of the Kuching Zone) was a Cathaysian fragment that was part of, or was accreted to, Sundaland in the Triassic.

### *7.2. Triassic metamorphism*

Prior this study no dating had been carried out on the metamorphic rocks in Sarawak. They were previously assumed to be Permian/Carboniferous or older and to represent old basement (Pimm, 1965; Tate and Hon, 1991; Hutchison, 2005). The results of this study require revision of this assumption.

Three metamorphic rocks were dated with the $^{40}$Ar/$^{39}$Ar method in this study. Two samples yielded Triassic ages. The samples are strongly foliated low grade mylonites with abundant quartz veins and quartz segregations. Their compositions indicate a quartz-rich fine-grained protolith, potentially volcaniclastic sediments. White mica from TB35 (Kerait Schist) and TB249 (Tuang Formation) were dated as c. 216 to 220 Ma. Because of the similarity in character and ages of the rocks from the two formations it is proposed to drop the previous assignment to separate formations, which is based only on geographical location, and introduce the term West Sarawak Metamorphics to include all isolated exposures of metamorphic rocks from this area.

The volcaniclastic Sadong and Kuching Formations locally show low-grade metamorphism and are interpreted as the unmetamorphosed and very low grade equivalents of the West Sarawak Metamorphics. Abundant quartz veins and quartz segregations within the Kuching Formation indicate a slightly higher degree of metamorphism compared to the Sadong Formation. The metamorphism might be related to burial depth or deformation.

The Triassic ages of the metamorphic rocks are interpreted to record metamorphism associated with the Sundaland volcanic arc.

### *7.3. Triassic arc setting*

There are two possible scenarios. A Triassic subduction margin could be the southern continuation of west-directed Paleo-Pacific subduction along the eastern margin of South China and Indochina (Fig. 14a) associated with the Indosinian orogeny, as shown by e.g. Carter and Clift (2008). Extensive Permian to Triassic magmatism in Vietnam is reported by e.g. Faure and Fontaine (1969), Lasserre et al. (1974), Lepvrier et al. (2004), Pham et al. (2008), Liu et al. (2012), Vladimirov et al. (2012), Ishihara and Orihashi (2014), Hieu et al. (2015) and Halpin et al. (2016). Similar magmatic activity is reported from SE China by Shao et al. (1995), Yu et al. (2010), Deng et al. (2012), and Mao et al. (2013), and from Hainan Island by Li et al. (2006) and Jiang et al. (2015). Gatinsky et al. (1984) and Hutchison (1989) suggested west-directed subduction could be traced southwards from the Kontum Massif in eastern Vietnam. Kudrass et al. (1986) reported Triassic sediments similar to the Sadong Formation from South China Sea (Reed Bank area) dredge samples.

Alternatively, Triassic magmatism and metamorphism could be the result of east-directed subduction of the Paleo- or Meso-Tethys. Permian-Triassic magmatism is recorded in the Malay Peninsula (e.g. Bignell and Snelling 1977; Liew and Page, 1985; Darbyshire, 1988; Cobbing et al., 1992; Searle et al., 2012) and has been attributed to east-directed subduction of the Paleo-Tethys and accretion during the collision of Sibumasu with the Sukhothai island arc and East Malaya (e.g. Hutchison, 1989; Metcalfe, 2006; Sevastjanova et al., 2011; Searle et al., 2012).

Pimm (1967) however, demonstrated geochemical differences between the Serian Volcanic Formation and subduction-related rocks in the Malay Peninsula. The subduction of the Paleo-Tethys was also completed by the Late Triassic (Sevastjanova et al., 2011; Metcalfe, 2013). There are no Late Triassic metamorphic rocks reported from the Malay Peninsula (East Malaya) and metamorphic rocks associated with the Sibumasu-Sukhothai island arc-East Malaya collision occur only in Sibumasu (see review in Morley et al., 2013). The position of the Serian Volcanic Formation would favour a west-directed subduction zone as the distance to the Paleo-/Meso-Tethys subduction zone would have been much greater than to the Paleo-Pacific subduction zone.

### *7.4. Jurassic stable platform*

There are no Early and Middle Jurassic records in West Sarawak. A non-magmatic interval in the region is interpreted from drilling in the South China Sea to show subduction pulses rather than continuous long-lived subduction throughout the Jurassic and Cretaceous (Xu et al., 2016). Sedimentation in West Sarawak in the Late Jurassic is recorded by the Bau Limestone Formation and the Kedadom Formation (e.g. Bayliss, 1966). This limestone reef complex seems to be on top of the Triassic sedimentary, metamorphic and igneous rocks. Schairer and Zeiss (1992) reported Middle Jurassic ammonites from the Brandung Formation, the NW Kalimantan equivalent of the Bau Limestone Formation, suggesting an earlier beginning of reef facies in that region. The Brandung Formation is close to Triassic rocks of the Balaisebut Group and the Embuoi Complex (Supriatna et al., 1993) which suggests a similar setting of Jurassic reef facies on top of Triassic and older accretionary rocks. This suggests that by the Middle Jurassic parts of NW Kalimantan formed a stable carbonate platform which extended in the Late Jurassic into present-day West Sarawak.

### *7.5. Late Jurassic – Early Cretaceous deep marine setting*

A significant change occurred before the beginning of the Cretaceous. Deep marine Late Jurassic to Early Cretaceous sedimentation is reported from parts of the Serabang Formation (Wolfenden and Haile, 1963; Basir and Aziman, 1996) northwest of the carbonate platform. In the Late Jurassic to Early Cretaceous (Muller, 1968; Morley, 1998; Basir and Uyop, 1999) the carbonate platform was rapidly subsiding and clastic open marine sedimentation of the Pedawan Formation was established.

### 7.6. Cretaceous magmatism

Cretaceous magmatism is evident in the Cretaceous volcaniclastic Pedawan Formation (Wilford and Kho, 1965; Muller, 1968; Nuraiteng and Kushairi, 1987, Morley, 1998), which incorporates layers and beds of pyroclastic deposits. Upper Jurassic fossils were reported from only one location (Basir and Uyop, 1999) and an extension of the Pedawan Formation into the Jurassic is uncertain. U-Pb dating of zircons from the Pedawan Formation in this study revealed dominant Cretaceous and Jurassic age peaks and abundant Paleozoic and Proterozoic zircons. The MDA of the analysed sedimentary samples ranges from 86 to 102 Ma. This age is consistent with the palynological age assigned by Morley (1998) to the youngest part of the Pedawan Formation. The pyroclastic sample (STB68b) dated in this study has a calculated weighted mean age of 88.5 ± 1.5 Ma which is interpreted as the age of eruption. Foraminifera in one sample indicate a similar/slightly older Turonian (92.8-91.3 Ma) age of deposition.

Abundant Upper Jurassic to Lower Cretaceous zircons are interpreted as subduction-related and derived from a nearby arc. Upper Cretaceous zircons of the Pedawan Formation may have been sourced by the Schwaner Mountain arc of SW Borneo. The wide age range of Paleozoic and Proterozoic zircons indicates additional sources compared to the Triassic volcaniclastics. These zircons may be related to the arrival of the SW Borneo block, providing a new source area, or could have been derived from the Malay Peninsula or SE Vietnam.

The Pedawan Formation is interpreted as a forearc basin fill in a long-lived subduction zone. The termination of arc-related sedimentation in the Coniacian or Santonian is interpreted to mark the end of subduction below West Sarawak and SW Borneo.

### 7.7. Cretaceous metamorphism

Metamorphic rocks are known from the Serabang Formation, Sejingkat Formation, Sebangan Formation and the Lubok Antu Melange are all melanges which contain Cretaceous sediments and in West Sarawak are interpreted to be Cretaceous.

TB10 is a metamorphic rock previously assigned to the Tuang Formation (Tate and Hon, 1991) which was assumed to be Carboniferous or older. Dating in this study with the $^{40}Ar/^{39}Ar$ method yielded a much younger age. White micas in the sample TB10 yielded an Early Cretaceous metamorphic age. It is concluded that this schist is likely a fragment in a melange similar to fragments observed in the Serabang, Sebangan and Sejingkat Formations. The Cretaceous metamorphism is interpreted to be associated with the Cretaceous subduction zone.

The Boyan Melange in NW Kalimantan is dated as Late Cretaceous (Williams et al., 1989) and may be an extension of the Lubok Antu Melange-Kapuas Complex to the south. If so, this would indicate a large area underlain by accretionary material and not two separate accretionary belts. The dated schist sample is slightly older than the age interpreted (Williams et al., 1989; Basir, 1996) for the Kapuas Complex-Lubok Antu Melange and Boyan Melange and suggests accretion onto the Sundaland margin in the Early Cretaceous. The age of the Lubok Antu Melange is still debated. Tan (1979, 1982) included the undeformed Middle Eocene calcareous Engkilili Formation in the melange, but undeformed sediments of similar or greater age reported north and south of the Lubok Antu Melange (Haile, 1957; Wolfenden, 1960; Tan, 1979) suggest an older age for the melange. Haile (1996) disputed the inclusion of the Engkilili Formation in the melange and if the Engkilili Formation is excluded the available age data (Tan, 1979, 1982; Basir, 1996) suggest a Late Jurassic to Cretaceous age for the melange.

The ocean associated with this Cretaceous accretionary margin was named the Danau Sea by Haile (1994) and is considered in this study to be part of the Paleo-Pacific subduction. Remnants of this Cretaceous accretionary margin are found within the Serabang Formation (Wolfenden and Haile, 1963), Lubok Antu Melange (Tan, 1979; Tan, 1982; Basir, 1996) and in the Boyan Melange (Williams et al., 1989). The Sibu Zone may be underlain by similar accreted material. This would suggest a very wide zone of accreted material from eastern West Sarawak to Central Sarawak.

### *7.8. Cretaceous arc setting*

Cretaceous magmatism in the region was reported from the Schwaner Mountains in SW Borneo based on dating by the K-Ar method (e.g. Haile et al., 1977; Williams et al., 1988) and by U-Pb zircon dating (van Hattum et al., 2013; Davies, 2013; Davies et al., 2014). Pulses of Late Jurassic to Cretaceous magmatism from the South China Sea are reported by Xu et al. (2016). Extensive Cretaceous magmatism is known from the Da Lat Zone in SE Vietnam from U-Pb ages (Nguyen et al., 2004; Shellnutt et al., 2013). Minor Cretaceous plutons are also reported from the Malay Peninsula (e.g. Searle et al., 2012). Taylor and Hayes (1983) interpreted a wide Cretaceous subduction margin in eastern China and Vietnam. A similar Andean arc from SE China to Borneo was also suggested by e.g. Charvet et al. (1994), Clements et al. (2011) and Pubellier and Morley (2014). Yan et al. (2010) reconstructed the arc from Taiwan to SE Vietnam. No magmatism is recorded in West Sarawak in the Late Jurassic to Early Cretaceous. However, metamorphism at this time is indicated by schist sample TB10 (this study) and the Serabang Formation (Wolfenden and Haile, 1963). It is concluded that there was an Andean arc from SE China to Borneo in the Cretaceous, subducting the Paleo-Pacific in a similar setting as in the Triassic.

SW Borneo was suggested to have been the Banda block rifted from the Australian margin in the Late Jurassic (Hall et al., 2009; Hall, 2012) leaving the Banda embayment (Spakman and Hall, 2010; Hall and Spakman, 2015). SW Borneo has a completely different stratigraphic and magmatic history from now adjacent parts of Sundaland but there is still only limited evidence for an Australian origin. Alluvial diamonds reported from southern Borneo resemble diamonds from NW Australia (Taylor et al., 1990) and were interpreted by White et al. (2016) to be derived from the Australian margin of Gondwana.

The SW Borneo block is interpreted to have docked with Sundaland in the Early Cretaceous (Hall et al., 2009; Hall, 2012) but the exact timing of the arrival is still uncertain. The shift from shallow marine carbonate sedimentation to volcaniclastic sediments of the Pedawan Formation in the Early Cretaceous may mark the arrival of SW Borneo. Age data in SE Vietnam (Nguyen et al., 2004; Shellnutt et al., 2013) and in the Schwaner Mountains (Haile et al., 1977; Williams et al., 1988; van Hattum et al., 2013; Davies, 2013; Davies et al., 2014) indicate a magmatic arc from c. 120 Ma in eastern Sundaland (Fig. 14b) which remained active until c. 90-80 Ma (Clements et al., 2011; Hall, 2012).

The wide accretionary zone related to Late Jurassic to Early Cretaceous subduction and to the Schwaner Mountain arc in the early Late Cretaceous would indicate a trench relatively distant from the magmatic arc. This suggests a flat slab subduction model. Flat slab subduction along the eastern SE China margin has been suggested for the Mesozoic (e.g. Li and Li, 2007; Li et al., 2007) and in northeast China in the Cenozoic (e.g. Tang et al., 2014).

Early in the Cretaceous small fragments of continental crust were accreted from Cathaysia. Cretaceous metabasites in the South China Sea were reported from dredge samples by Kudrass et al. (1986) and a Late Mesozoic accretionary zone has been interpreted by Zhou et al. (2008).

### *7.9. Younger metamorphic episodes from the $^{40}$Ar/$^{39}$Ar dating*

The three metamorphic samples record a complex thermal history. All three samples show $^{40}$Ar/$^{39}$Ar ages in the initial steps of the step-heating method which are significantly younger than the inferred Mesozoic ages of metamorphism (Fig. 13). The amount of radiogenic Ar indicates that these ages are not a consequence of contamination and are therefore not artefacts. However, these first steps need to be interpreted cautiously as chlorine and calcium values are high and the ages may not be very precise.

The initial heating steps for Triassic samples TB35 and TB249 indicate a Cretaceous overprint. The age of this event is coincident with the metamorphic age of sample TB10 and is interpreted as indication of a widespread Cretaceous metamorphic event.

Triassic sample TB35 and Cretaceous sample TB10 record a potential Oligocene metamorphic event. The age of c. 25 to 30 Ma is coincident with $^{40}Ar/^{39}Ar$ ages reported by Davies (2013) from the Pinoh Metamorphics and with apatite fission track ages in igneous rocks reported by Moss et al. (1998). The age is interpreted to indicate a widespread shearing event in Borneo at c. 25 Ma, potentially related to the Lupar Line trend and counter-clockwise rotation (Schmidtke et al., 1990; Fuller et al., 1999) of Borneo. Early Miocene volcanics (Sintang Suite) in West Sarawak and NW Kalimantan (Hutchison, 2005) are not deformed or sheared and indicate termination of shearing before their emplacement.

### *7.10. Origin of the Kuching Zone*

Borneo is composed of several fragments which were accreted from the Triassic onwards and form a heterogeneous crust in central Borneo. It is interpreted that by the Late Cretaceous, Borneo was composed of several different tectonic components that included SW Borneo, NW Sulawesi, E Java–W Sulawesi, Triassic Sundaland, and the Mesozoic accretionary complex (previously partially assigned to a Luconia-Dangerous Grounds block by Hall, 2012) as shown in Fig. 15. The Argo (E Java–W Sulawesi) and Inner Banda blocks (NW Sulawesi and E Sabah) include parts of eastern Borneo and rifted from the Australian margin of Gondwana in the Late Jurassic (Hall, 2012; Hennig et al., 2016). SW Borneo comprises the block that was derived from the Australian margin in the Late Jurassic to Early Cretaceous and today includes the Schwaner Mountains and the region south of them. Essentially it comprises the area named by Haile (1974) the West Borneo Basement. Triassic Sundaland encompasses the area of Triassic granitoids, metamorphic and sedimentary rocks that form the basement to the Middle to Upper Jurassic carbonate platform of NW Kalimantan and West Sarawak (western Kuching Zone) and were part of Cathaysia from the Permian onwards. The Mesozoic accretionary complex is located in the northern and eastern part of West Sarawak and underlies most of the eastern part of the Kuching Zone and potentially the whole Sibu Zone. It includes Cathaysian fragments that were accreted between the Triassic and the Cretaceous derived from the South China continental margin. The Busang Complex and the Telen River sediments are probably such fragments. The Kuching Zone is therefore underlain by the Triassic Sundaland margin and the Mesozoic accretionary complex that formed along the Paleo-Pacific subduction zone between the Triassic and Late Cretaceous (Fig. 14).

There must be a suture in western Borneo between Triassic Sundaland and SW Borneo. The northern margin of Triassic Sundaland is marked by the Triassic Serian Volcanic Formation, which represents the Triassic volcanic arc and may locate the position of the suture between Triassic Sundaland and the Mesozoic accretionary complex. The Lupar Line is not considered to represent a suture and is merely a younger strike-slip fault that exposes part of the melanges in Kalimantan and West Sarawak.

## 8. Conclusions

Metamorphic rocks, which were previously thought to represent pre-Carboniferous basement, have been dated as Late Triassic and are named the West Sarawak Metamorphics. These metamorphics do not represent old basement. They indicate collision and metamorphism associated with a Triassic accretionary margin in eastern Sundaland, potentially part of the Indosinian orogen. U-Pb zircon ages from the Jagoi Granodiorite reveal a complex history. Early magmatism occurred around 240 Ma and a later magmatic episode associated with recrystallisation has been dated as c. 208 Ma. Triassic volcaniclastics (Sadong and Kuching Formations) were sourced by a contemporaneous Triassic volcanic arc built on continental crust as indicated by reworking of Paleoproterozoic crust (with zircon ages of c. 1.8 Ga). Their MDA is dated as c. 221 to 230 Ma. They are interpreted as the forearc basin fill at the eastern Sundaland margin where there was west-directed subduction of the Paleo-Pacific. The Triassic part of Borneo (western part of the Kuching Zone) is not considered to be a separate Semitau block, but is interpreted to belong to the Mesozoic eastern Sundaland margin.

One other metamorphic rock, also previously thought to be pre-Mesozoic basement, have been dated as Early Cretaceous and are associated with the Serabang, Sebangan and Sejingkat Formations, all melanges, which indicate accretion during the Late Jurassic to Cretaceous and are part of a zone of Cretaceous accretionary material. This accretionary zone is associated either with a new subduction zone which initiated in the Cretaceous or with resumption of subduction, as indicated by the Cretaceous volcaniclastics of the Pedawan Formation and the magmatic rocks of the Schwaner Mountains.

The data obtained in this study are interpreted to indicate a long-lived subduction margin in eastern Sundaland from the Triassic to the Late Cretaceous. Within this west-directed subduction margin, several fragments of Cathaysia, and basic and metabasic rocks, were accreted to the continental core of Sundaland. The Cathaysia fragments were derived from South China to the north/northeast. The results of this study cause us to doubt the existence of a separate ‘Semitau block’. The metamorphic rocks show an Oligocene overprint which may be related to a major widespread shearing event in Borneo due to counter-clockwise rotation.

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**Figure captions**

(Size preferred below each caption)

Fig. 1: a) Principal continental blocks of SE Asia showing the interpreted Semitau and SW Borneo (SWB) blocks (modified after Metcalfe, 2013). Sibumasu and Indochina-East Malaya formed Early Mesozoic Sundaland. b) Tectonic provinces of NW Borneo (modified after Haile, 1974). The black box shows the research area in the Kuching Zone (West Sarawak).

(1.5 column size)

Fig. 2: Mesozoic stratigraphy map of West Sarawak (modified after Liechti et al., 1960; Heng, 1992). The map includes our own field observations. West Sarawak and NW Kalimantan form the Kuching Zone. Central Sarawak is the Sibu Zone. (T. = Tanjung/headland, G. = Gunung/mountain).

(double column size)

Fig. 3: Sample locations and map of metamorphic rocks and the Triassic Jagoi intrusion in West Sarawak (modified after Liechti et al., 1960; Heng, 1992). Samples in italics and brackets were not dated; all other samples were dated with U-Pb zircon, $^{40}$Ar/$^{39}$Ar white mica or micropalaeontology. Note: Mesozoic sediments and the Triassic Serian Volcanic Formation are not shown.

(double column size)

Fig. 4: Metamorphic rocks in West Sarawak. a) Folded quartz-mica schists (TB249). b) Phyllitic and folded quartz-mica schist (TB35). c) and d) Thin section photomicrographs of white mica foliation bands in plane and crossed polarized light (TB249). e) and f) Thin section photomicrographs of the Cretaceous schist showing chlorite and epidote/clinozoisite alteration in plane and crossed polarized light (TB10). g) Offset of various extension cracks in opaque porphyroblast in plane polarized light (TB66a). h) Radial fibrous chalcedony and extension cracks in crossed polarized lights (TB68b). (Ms = muscovite, Op = opaque phase, Qp = polycrystalline quartz, Ab = albite, Phg = phengite, Ep = epidote, Clz = clinozoisite, Chl = chlorite).

(1.5 column size)

Fig. 5: Classification of the analysed micas in the mgli-feal diagram (mgli = Mg – Li; feal = $Fe_{tot}$ + Mn + Ti + $^{VI}$Al) of Tischendorf et al. (2004). Shaded area indicates solid-solution series. White micas of the West Sarawak Metamorphics are classified as muscovite/phengite, white mica of the Upper Cretaceous metamorphic rocks as phengite.

(single column size)

Fig. 6: Thin section photomicrographs of the Serian Volcanic Formation (TB6) and the Jagoi Granodiorite (TB114). a) Plagioclase-pyroxene xenolith crossed polarized light (Serian Volcanic Formation, TB6). b) Polycrystalline quartz xenoliths crossed polarized light (Serian Volcanic Formation, TB6). c) Biotite with chloritization and basal section (Jagoi Granodiorite, TB114). d) Euhedral oscillatory zoned plagioclase affected by alteration (Jagoi Granodiorite, TB114). e) and f) Amphibole twinnings in plane and crossed polarized light (Jagoi Granodiorite, TB114). (Pyx = pyroxene, Plg = plagioclase, Qp = polycrystalline quartz, Am = amphibole (hornblende), Bt = biotite, Chl = chlorite.)

(1.5 column size)

Fig. 7: N-MORB normalised spider-diagram for the Triassic igneous rocks: Serian Volcanic Formation (TB6) and the Jagoi Granodiorite (TB114) indicating enrichment in LILE interpreted as subduction-related. N-MORB normalisation values from Sun and McDonough (1989).

(single column size)

Fig. 8: Apparent age plots from the $^{40}$Ar/$^{39}$Ar step heating experiments. a) Sample TB249 shows a plateau with ~70% of gas release at ~217 Ma. b) Sample TB35 shows an asymptote at ~220 Ma with Ar loss in the initial steps. c) Sample TB10 shows an upper age limit of 143 Ma and a lower age limit of 119 Ma, as well as Ar loss in the initial steps and mixing between the limits.

(1.5 column size)

Fig. 9: U-Pb zircon age histograms with probability density plot of detrital samples from Sadong Formation a) 712 and b) 713b, and Kuching Formation c) TB250a showing two major age peaks in the Permian-Triassic and in the Proterozoic at 1.8 Ga. The Permian-Triassic age peak is associated with a fresh magmatic source and the 1.8 Ga peak indicates recycling of Sundaland crust. Histograms for each sample use a bin size of 10 Ma for Phanerozoic ages and 50 Ma for Precambrian ages. d) Catholuminescence (CL) image of zircons with analysis spots (yellow circles) of sample TB250a. Spot sizes are c. 25 µm. Spot numbers of Triassic samples are listed in Supplementary Tables 2.1 to 2.3.

(1.5 column size)

Fig. 10: U-Pb zircon ages for sample TB114 of the Jagoi Granodiorite. a) Tera-Wasserburg plot showing a significant Late Triassic zircon population with inheritance of a very small Middle Triassic population. Ages affected by lead-loss and common lead range from the Jurassic to the Cretaceous. b) Zircon age population histogram with probability density of all concordant ages. Outliers are coloured in grey. Jurassic ages are from lead-loss affected grains. c) Weighted mean age calculation

gives an age of 208.3 ± 0.9 Ma. Blue marks are excluded outliers. d) CL image of zircons with analysis spots (yellow circles). Spot sizes are c. 30 µm. Spot numbers are listed in Supplementary Table 2.4.

(1.5 column size)

Fig. 11: U-Pb zircon age histograms with probability density plot of detrital samples a) STB34 and b) STB07a of the Pedawan Formation showing several age populations ranging from Cretaceous to Proterozoic which indicate a wide range of sources. The dominant Late Jurassic and Cretaceous peaks indicate intensive magmatism. Histograms for each sample use a bin size of 10 Ma for Phanerozoic ages and 50 Ma for Precambrian ages. Spot numbers are listed in Supplementary Table 2.5 and 2.6.

(1.5 column size)

Fig. 12: U-Pb zircon ages for pyroclastic sample STB68b of the Pedawan Formation. a) Concordia plot showing a significant Late Cretaceous zircon population. b) Zircon age population histogram with probability density plot of all concordant ages. Inherited ages range from Early Cretaceous to Middle Jurassic. Inlet figure shows weighted mean age calculation for the Late Cretaceous population. c) Weighted mean age calculation for youngest population gives an age of 88.5 ± 1.5 Ma. d) CL image of zircons with analysis spots (yellow circles). Spot sizes are c. 25 µm. Spot numbers are listed in Supplementary Table 2.7.

(1.5 column size)

Fig. 13: Summary of magmatic and metamorphic ages from the accretionary margin in West Sarawak and NW Kalimantan. Data from the Schwaner Mountains of the SW Borneo block from Haile et al. (1977), Williams et al. (1988), van Hattum et al. (2013) and Davies et al. (2014). Data from SE Vietnam from Nguyen et al. (2004) and Shellnutt et al. (2013).

(1.5 column size)

Fig. 14: Tectonic reconstruction for West Sarawak and central Kalimantan in the Mesozoic (modified from Hall, 2012). a) Late Triassic subduction of the Paleo-Pacific. The volcanic arc in Triassic Sundaland (West Sarawak) is formed by the Serian Volcanic Formation and the Jagoi Granodiorite with deposition of the volcaniclastic Kuching and Sadong Formations in the forearc basin. b) Early Late Cretaceous subduction of the Paleo-Pacific. The Schwaner Mountains form the volcanic arc in SW Borneo and the volcaniclastic Pedawan Formation is deposited in the forearc basin. (SPG – Songpan Ganzi accretionary complex, SWB - Southwest Borneo, TS – Triassic Sundaland of Borneo/western part of the Kuching Zone, NWS - Northwest Sulawesi, EJWS - East Java-West Sulawesi).

(1.5 column size)

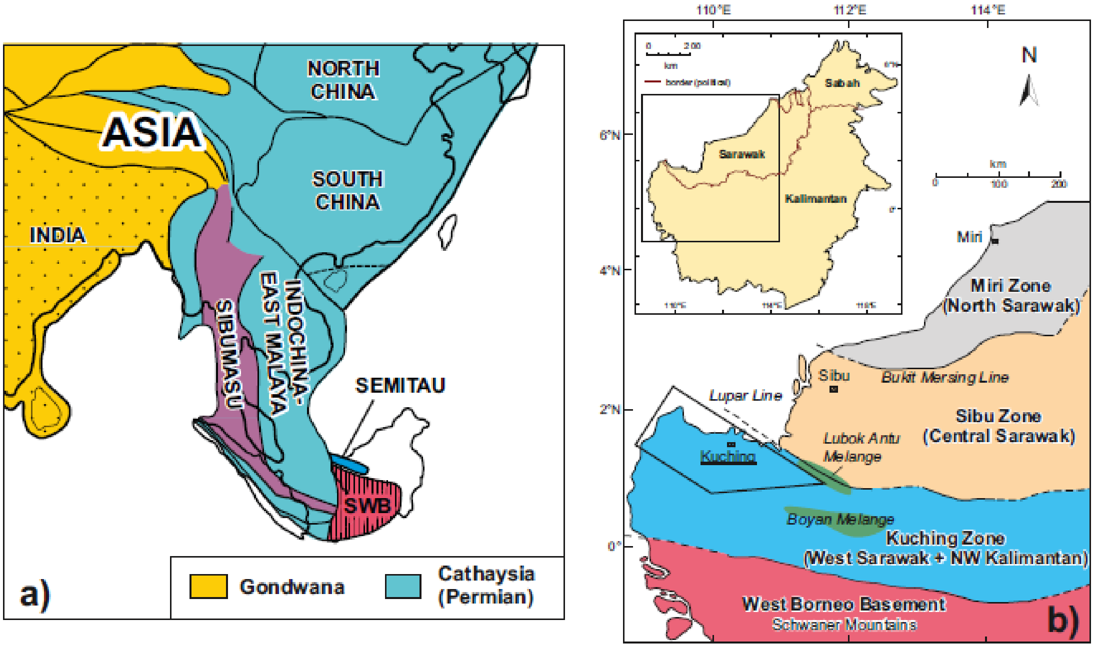
Fig. 15: Tectonic provinces of Borneo (basement map). (SWB - Southwest Borneo, TS - Triassic Sundaland of Borneo/western part of the Kuching Zone, NWS - Northwest Sulawesi and E Sabah, EJWS - East Java-West Sulawesi).

(1.5 column size)

**Table captions**

Table 1: Summary of the identified fossil assemblage of sample STB61a of the upper part of the Pedawan Formation (classification scheme by BouDagher-Fadel, 2013).

Table 2: Summary of radiometric ages obtained in this study. (1σ error for U-Pb; 2σ error for $^{40}$Ar/$^{39}$Ar).



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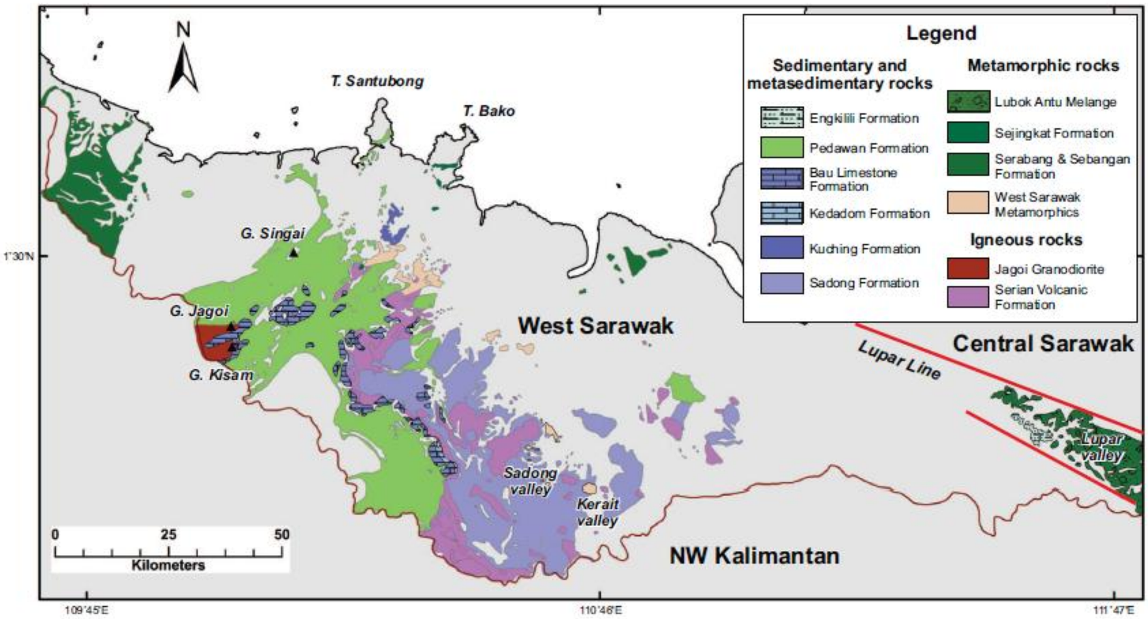

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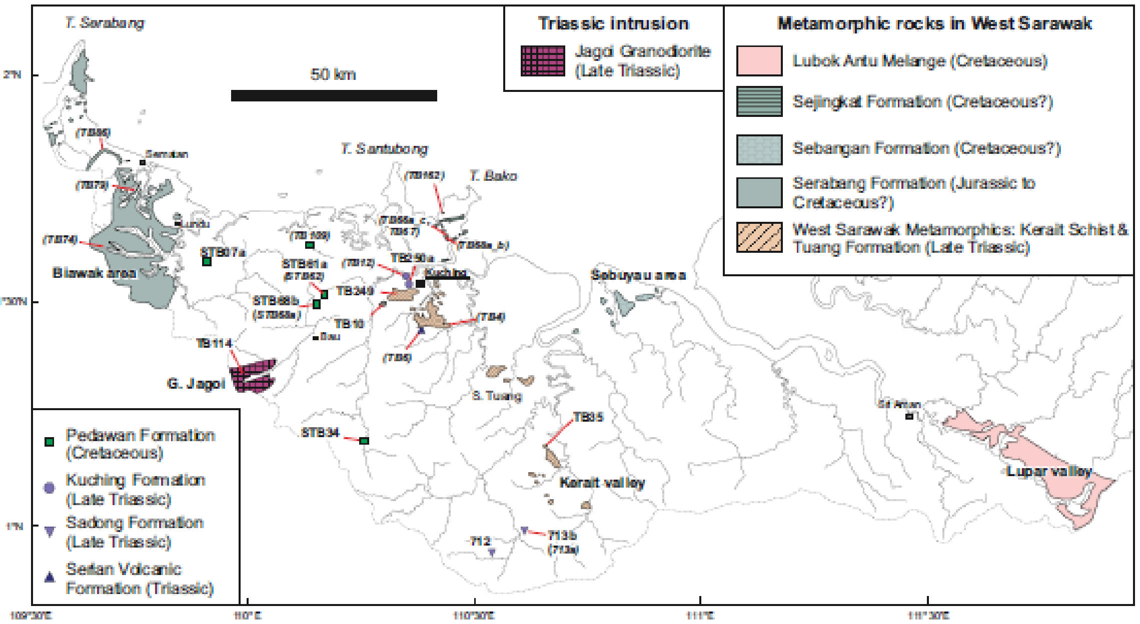


**Fig. 3:** Sample locations and map of metamorphic rocks and the Triassic Jagoi intrusion in West Sarawak (modified after Liechti et al., 1960; Heng, 1992). Samples in italics and brackets were not dated; all other samples were dated with U-Pb zircon, $^{40}Ar/^{39}Ar$ white mica or micropalaeontology. Note: Mesozoic sediments and the Triassic Serian Volcanic Formation are not shown.

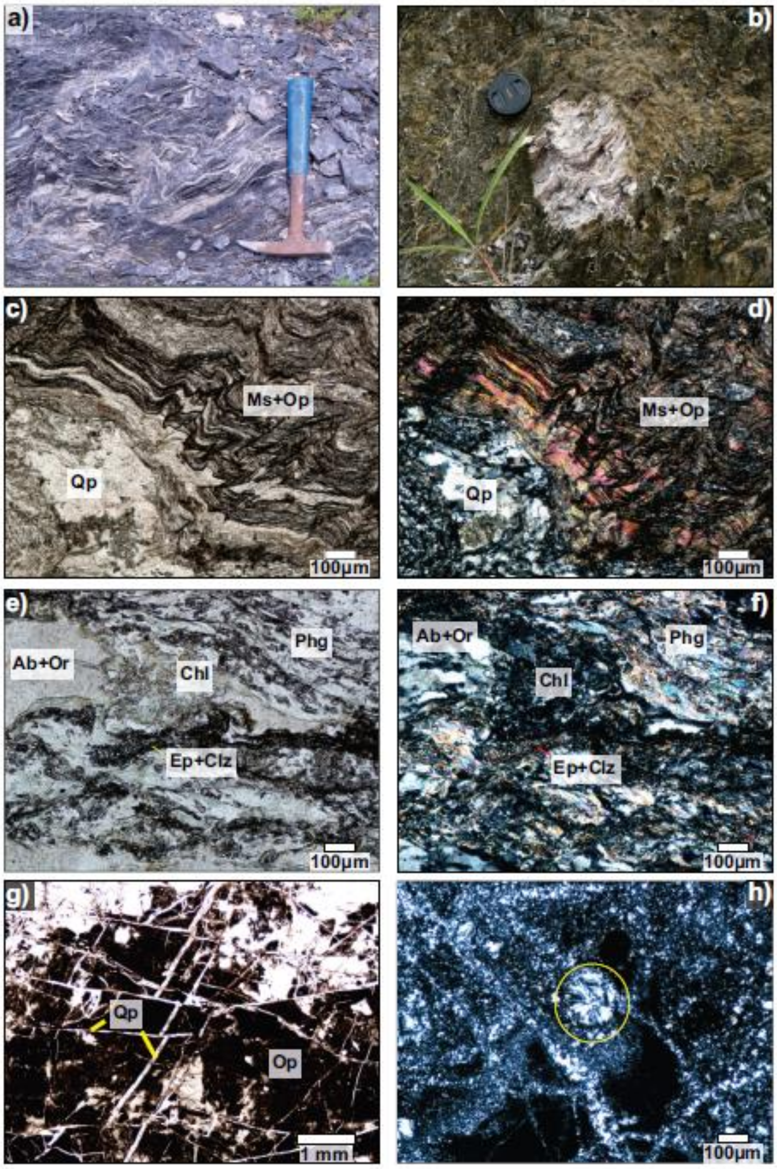


**Fig. 4:** Metamorphic rocks in West Sarawak. a) Folded quartz-mica schists (TB249). b) Phyllitic and folded quartz-mica schist (TB35). c) and d) Thin section photomicrographs of white mica foliation bands in plane and crossed polarized light (TB249). e) and f) Thin section photomicrographs of the Cretaceous schist showing chlorite and epidote/clinozoisite alteration in plane and crossed polarized light (TB10). g) Offset of various extension cracks in opaque porphyroblast in plane polarized light (TB66a). h) Radial fibrous chalcedony and extension cracks in crossed polarized lights (TB68b). (Ms = muscovite, Op = opaque phase, Qp = polycrystalline quartz, Ab = albite, Phg = phengite, Ep = epidote, Clz = clinozoisite, Chl = chlorite).

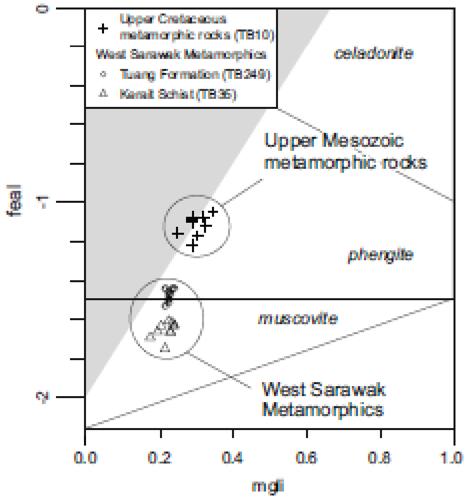


**Fig. 5:** Classification of the analysed micas in the mgli-feal diagram (mgli = Mg – Li; feal = $Fe_{tot}$ + Mn + Ti + $^{VI}Al$) of Tischendorf et al. (2004). Shaded area indicates solid-solution series. White micas of the West Sarawak Metamorphics are classified as muscovite/phengite, white mica of the Upper Cretaceous metamorphic rocks as phengite.

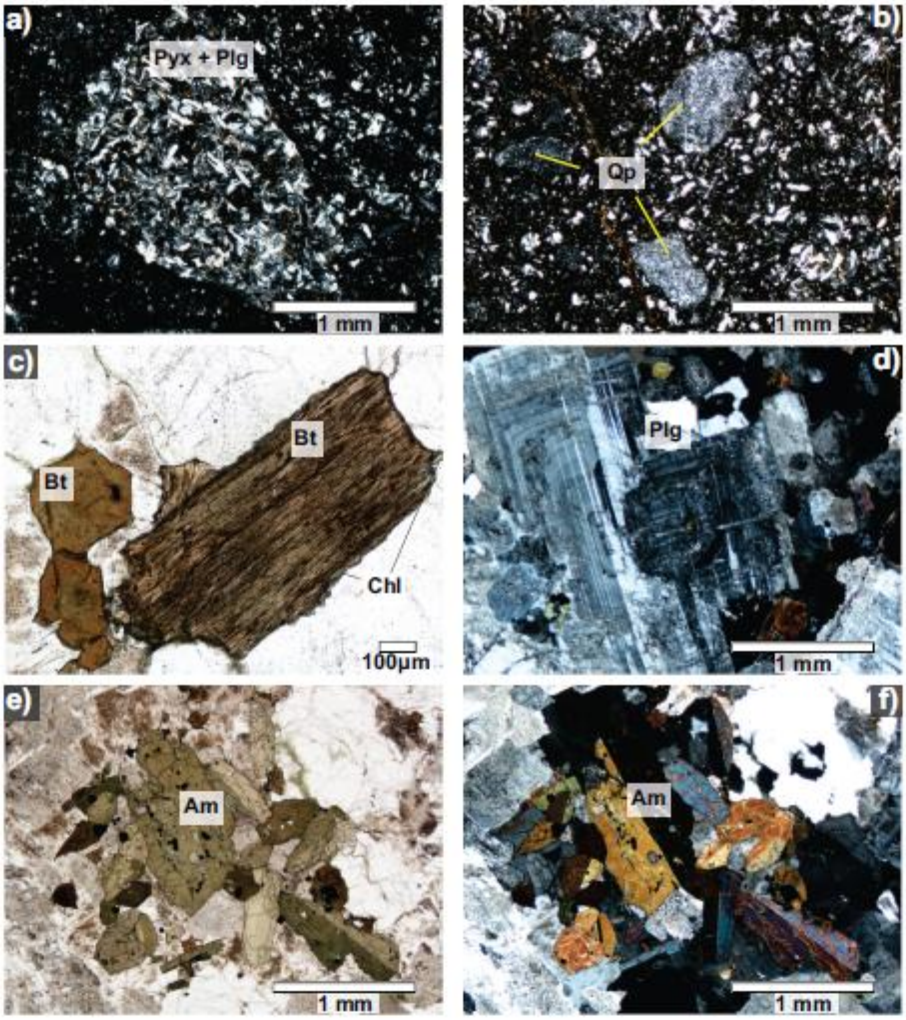


**Fig. 6:** Thin section photomicrographs of the Serian Volcanic Formation (TB6) and the Jagoi Granodiorite (TB114). a) Plagioclase-pyroxene xenolith crossed polarized light (Serian Volcanic Formation, TB6). b) Polycrystalline quartz xenoliths crossed polarized light (Serian Volcanic Formation, TB6). c) Biotite with chloritization and basal section (Jagoi Granodiorite, TB114). d) Euhedral oscillatory zoned plagioclase affected by alteration (Jagoi Granodiorite, TB114). e) and f) Amphibole twinnings in plane and crossed polarized light (Jagoi Granodiorite, TB114). (Pyx = pyroxene, Plg = plagioclase, Qp = polycrystalline quartz, Am = amphibole (hornblende), Bt = biotite, Chl = chlorite.)

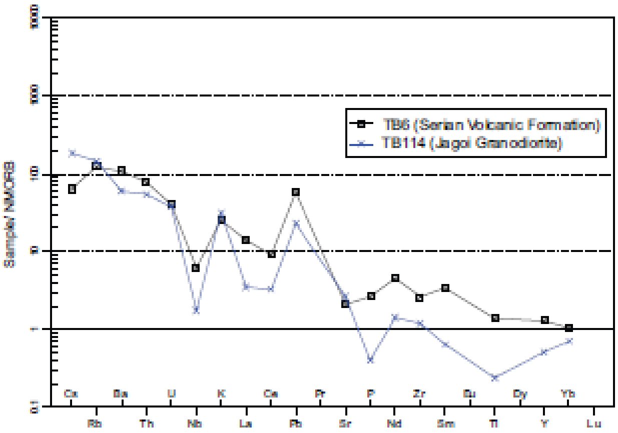


**Fig. 7:** N-MORB normalised spider-diagram for the Triassic igneous rocks: Serian Volcanic Formation (TB6) and the Jagoi Granodiorite (TB114) indicating enrichment in LILE interpreted as subduction-related. N-MORB normalisation values from Sun and McDonough (1989).

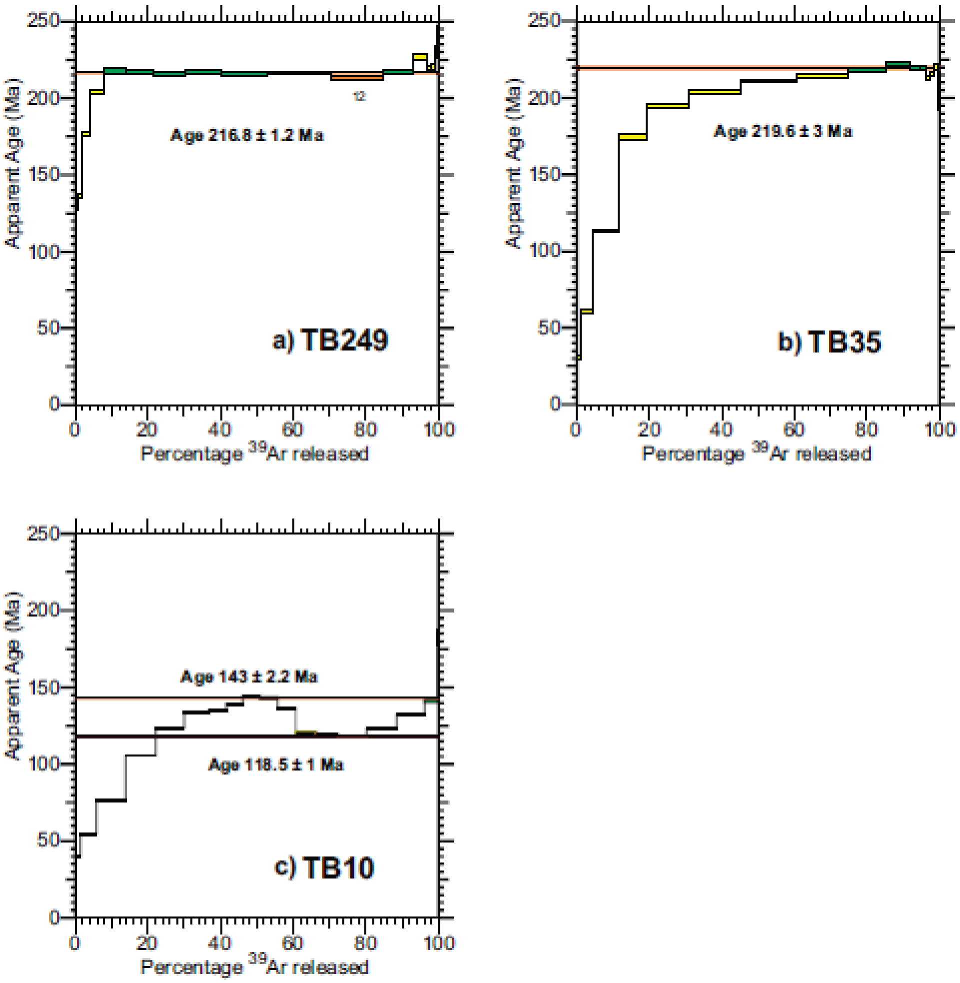


**Fig. 8:** Apparent age plots from the $^{40}$Ar/$^{39}$Ar step heating experiments. a) Sample TB249 shows a plateau with ~70% of gas release at ~217 Ma. b) Sample TB35 shows an asymptote at ~220 Ma with Ar loss in the initial steps. c) Sample TB10 shows an upper age limit of 143 Ma and a lower age limit of 119 Ma, as well as Ar loss in the initial steps and mixing between the limits.

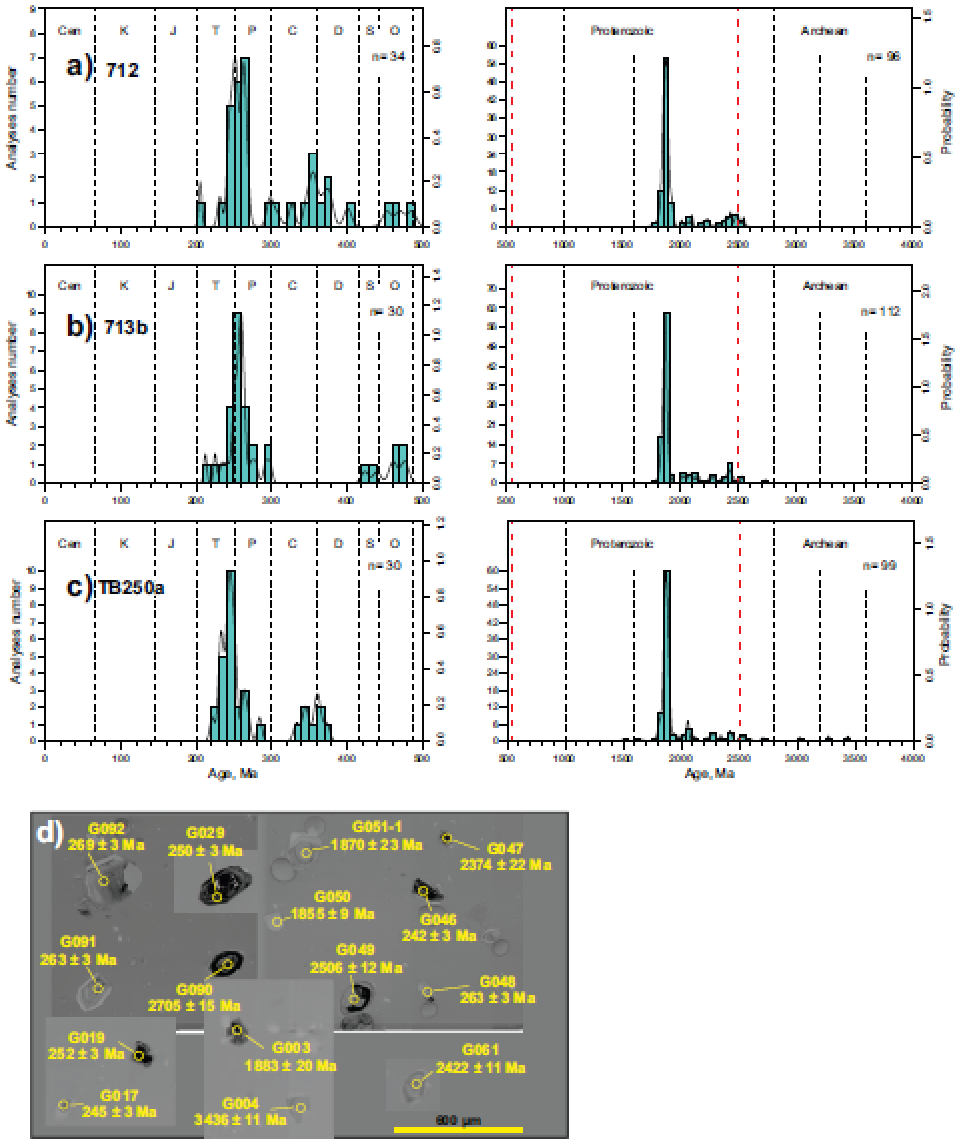


**Fig. 9:** U-Pb zircon age histograms with probability density plot of detrital samples from Sadong Formation a) 712 and b) 713b, and Kuching Formation c) TB250a showing two major age peaks in the Permian-Triassic and in the Proterozoic at 1.8 Ga. The Permian-Triassic age peak is associated with a fresh magmatic source and the 1.8 Ga peak indicates recycling of Sundaland crust. Histograms for each sample use a bin size of 10 Ma for Phanerozoic ages and 50 Ma for Precambrian ages. d) Catholuminescence (CL) image of zircons with analysis spots (yellow circles) of sample TB250a. Spot sizes are c. 25 µm. Spot numbers of Triassic samples are listed in Supplementary Tables 2.1 to 2.3.

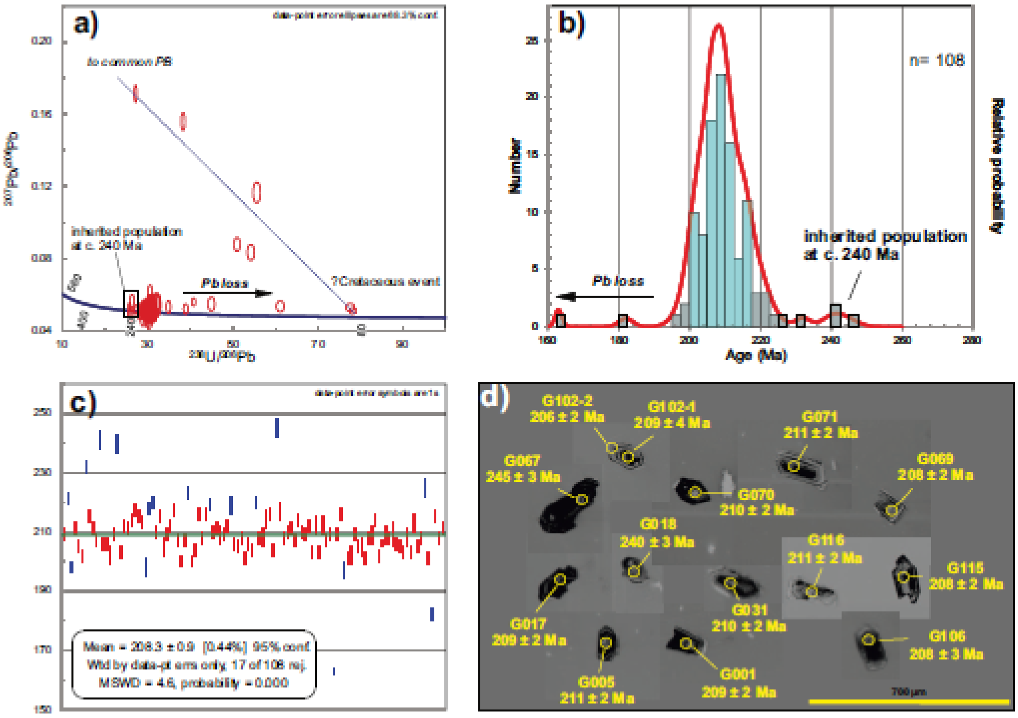


**Fig. 10:** U-Pb zircon ages for sample TB114 of the Jagoi Granodiorite. a) Tera-Wasserburg plot showing a significant Late Triassic zircon population with inheritance of a very small Middle Triassic population. Ages affected by lead-loss and common lead range from the Jurassic to the Cretaceous. b) Zircon age population histogram with probability density of all concordant ages. Outliers are coloured in grey. Jurassic ages are from lead-loss affected grains. c) Weighted mean age calculation gives an age of 208.3 ± 0.9 Ma. Blue marks are excluded outliers. d) CL image of zircons with analysis spots (yellow circles). Spot sizes are c. 30 µm. Spot numbers are listed in Supplementary Table 2.4.

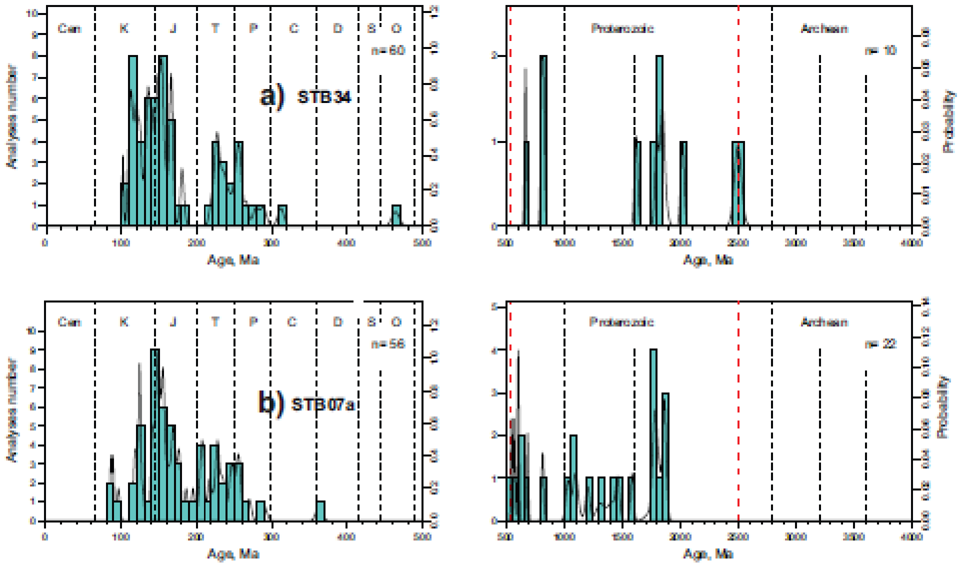


**Fig. 11:** U-Pb zircon age histograms with probability density plot of detrital samples a) STB34 and b) STB07a of the Pedawan Formation showing several age populations ranging from Cretaceous to Proterozoic which indicate a wide range of sources. The dominant Late Jurassic and Cretaceous peaks indicate intensive magmatism. Histograms for each sample use a bin size of 10 Ma for Phanerozoic ages and 50 Ma for Precambrian ages. Spot numbers are listed in Supplementary Table 2.5 and 2.6.

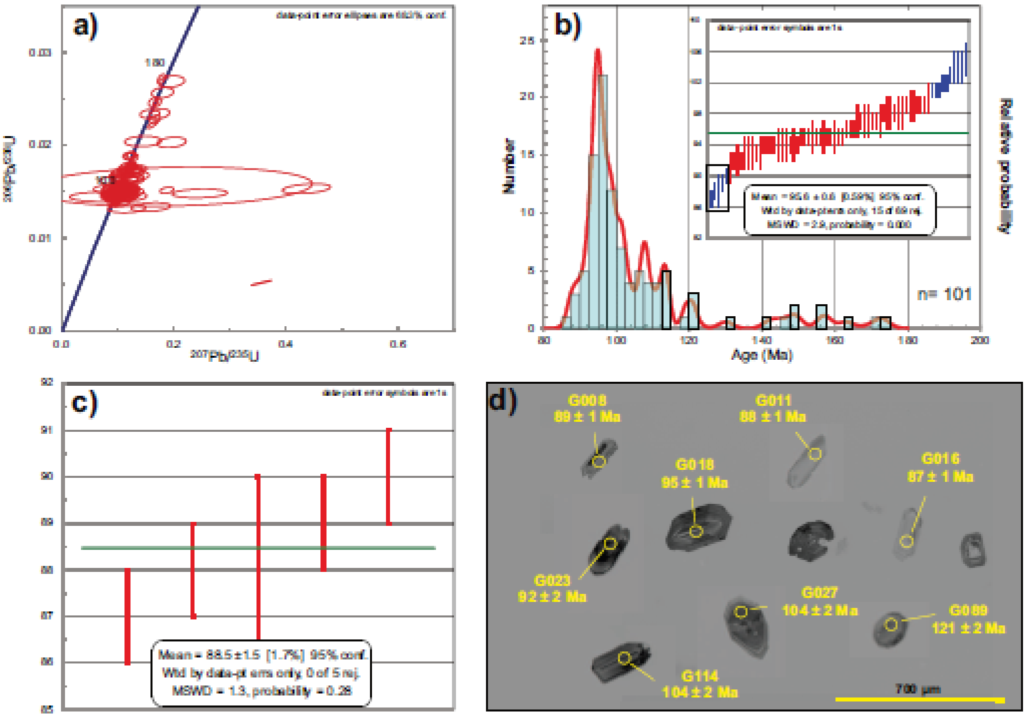


**Fig. 12:** U-Pb zircon ages for pyroclastic sample STB68b of the Pedawan Formation. a) Concordia plot showing a significant Late Cretaceous zircon population. b) Zircon age population histogram with probability density plot of all concordant ages. Inherited ages range from Early Cretaceous to Middle Jurassic. Inlet figure shows weighted mean age calculation for the Late Cretaceous population. c) Weighted mean age calculation for youngest population gives an age of 88.5 ± 1.5 Ma. d) CL image of zircons with analysis spots (yellow circles). Spot sizes are c. 25 µm. Spot numbers are listed in Supplementary Table 2.7.

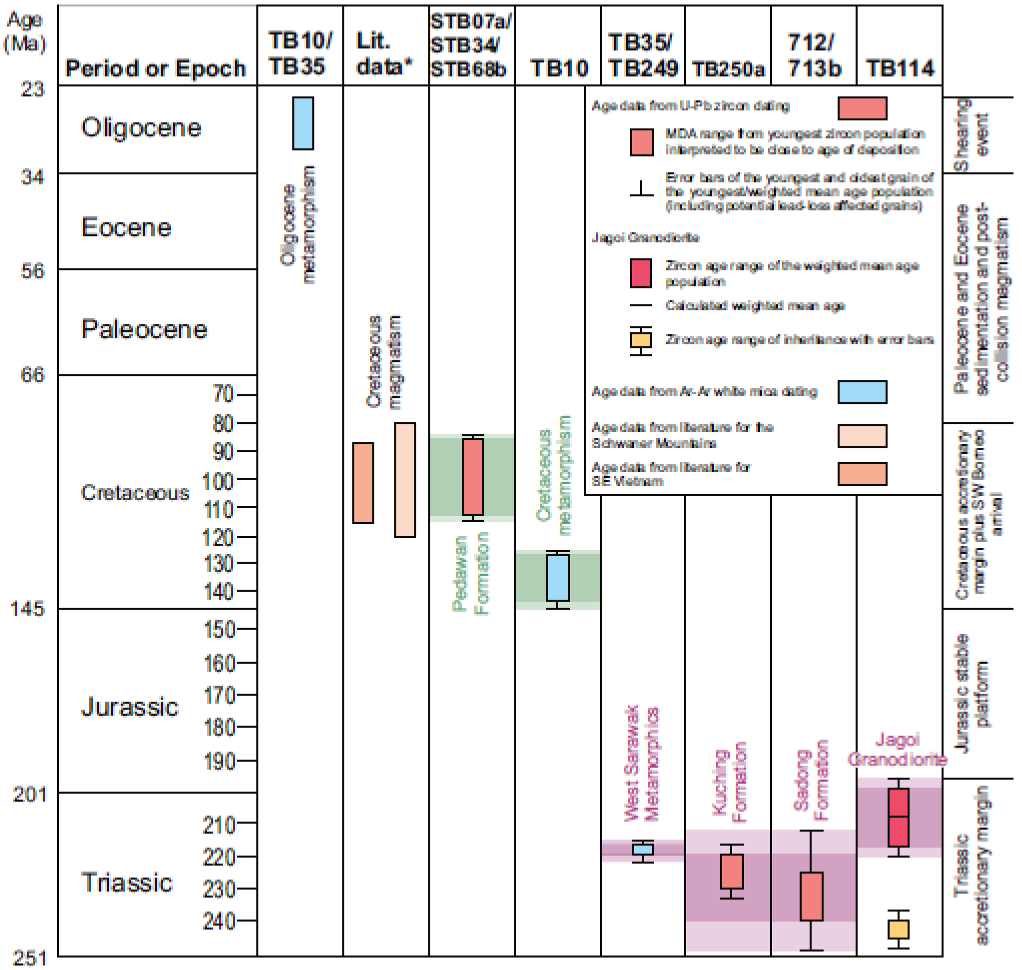


**Fig. 13**: Summary of magmatic and metamorphic ages from the accretionary margin in West Sarawak and NW Kalimantan. Data from the Schwaner Mountains of the SW Borneo block from Haile et al. (1977), Williams et al. (1988), van Hattum et al. (2013) and Davies et al. (2014). Data from SE Vietnam from Nguyen et al. (2004) and Shellnutt et al. (2013).

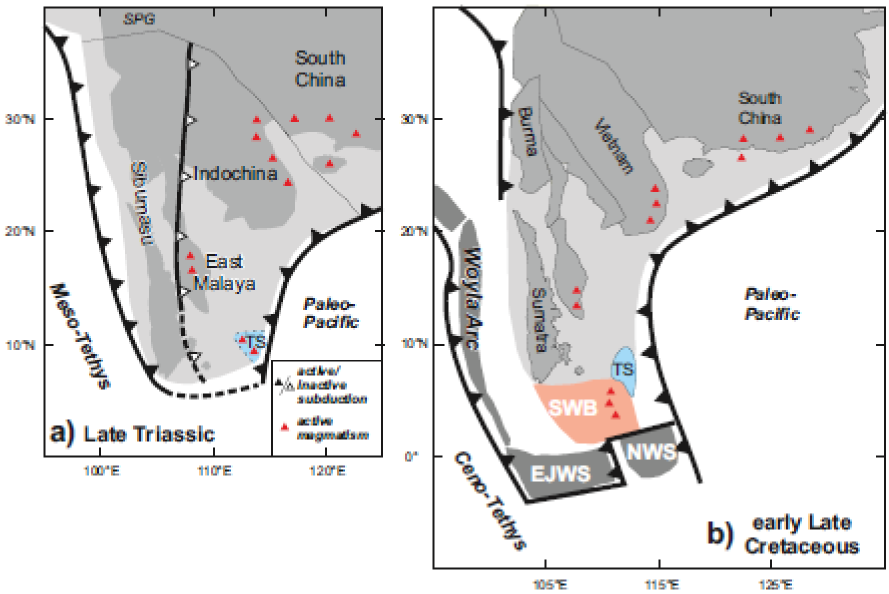


**Fig. 14:** Tectonic reconstruction for West Sarawak and central Kalimantan in the Mesozoic (modified from Hall, 2012). a) Late Triassic subduction of the Paleo-Pacific. The volcanic arc in Triassic Sundaland (West Sarawak) is formed by the Serian Volcanic Formation and the Jagoi Granodiorite with deposition of the volcaniclastic Kuching and Sadong Formations in the forearc basin. b) Early Late Cretaceous subduction of the Paleo-Pacific. The Schwaner Mountains form the volcanic arc in SW Borneo and the volcaniclastic Pedawan Formation is deposited in the forearc basin. (SPG – Songpan Ganzi accretionary complex, SWB - Southwest Borneo, TS – Triassic Sundaland of Borneo/western part of the Kuching Zone, NWS - Northwest Sulawesi, EJWS - East Java-West Sulawesi).

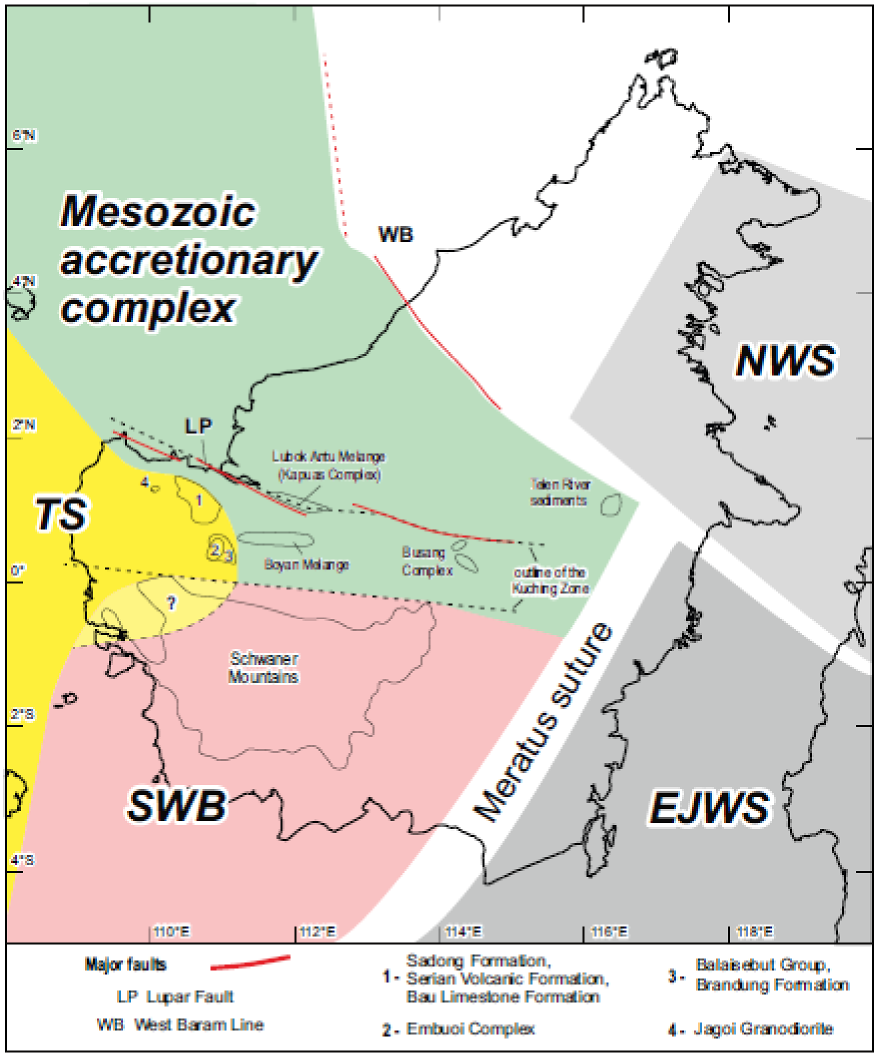


**Fig. 15:** Tectonic provinces of Borneo (basement map). (SWB - Southwest Borneo, TS - Triassic Sundaland of Borneo/western part of the Kuching Zone, NWS - Northwest Sulawesi and E Sabah, EJWS - East Java-West Sulawesi).

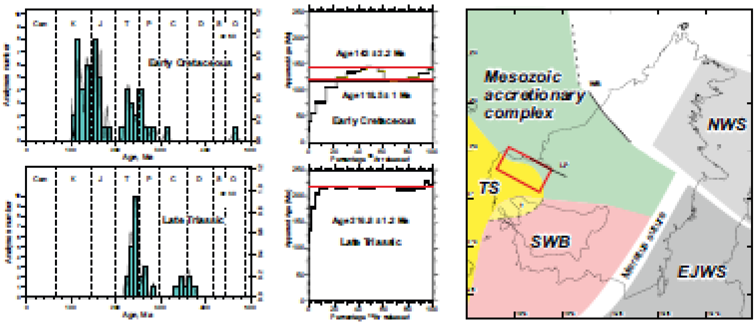
**Table 1**: Summary of the identified fossil assemblage of sample STB61a of the upper part of the Pedawan Formation (classification scheme by BouDagher-Fadel, 2013).

| Sample | Description | Fossil assemblage | Environment | Age/Zone |
|---|---|---|---|---|
| **STB61a** | Micritic packstone with intensive reworking | *Dicarinella imbricata, Globotruncana* spp.*, Helvetoglobotruncana helveticae, Concavatotruncana canaliculata, Dicarinella hagni, Concavatotruncana* sp.*, Sigalitruncana sigali, Sigalitruncana schneegansi* | Inner neritic | Late Cretaceous, Turonian (Zone 2, 92.8-91.3Ma) |

**Table 2**: Summary of radiometric ages obtained in this study. (1σ error for U-Pb; 2σ error for $^{40}Ar/^{39}Ar$).

| Location | Sample | Longitude | Latitude | Sample type | Rock type | Formation | Mineral | Method | Weighted mean/ plateau age (Ma) | Error (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|
| STB68 | STB68b | 110.14464 | 1.49882 | outcrop | pyroclastic deposit | Pedawan Formation | zircon | U-Pb | 88.5 | 1.5 |
| STB07 | STB07a | 109.89238 | 1.57748 | outcrop | volcaniclastic sediment | Pedawan Formation | zircon | U-Pb | 86* | 1 |
| STB34 | STB34 | 110.26065 | 1.18386 | outcrop | volcaniclastic sediment | Pedawan Formation | zircon | U-Pb | 102* | 1 |
| TB10 | TB10 | 110.29034 | 1.47734 | outcrop | chlorite schist | Upper Mesozoic metamorphic rocks | white mica | $^{40}Ar/^{39}Ar$ | 118.5 | 1 |
| | | | | | | | white mica | $^{40}Ar/^{39}Ar$ | 143 | 2.2 |
| TB114 | TB114 | 109.99646 | 1.33366 | float | granodiorite | Jagoi Granodiorite | zircon | U-Pb | 208.3 | 0.9 |
| TB249 | TB249 | 110.32029 | 1.49617 | outcrop | quartz-mica schist | West Sarawak Metamorphics (Tuang Formation) | white mica | $^{40}Ar/^{39}Ar$ | 216.8 | 1.2 |
| TB35 | TB35 | 110.65461 | 1.17556 | outcrop | quartz-mica schist | West Sarawak Metamorphics (Kerait Schist) | white mica | $^{40}Ar/^{39}Ar$ | 219.6 | 3 |
| TB250 | TB250a | 110.36448 | 1.53395 | outcrop | volcaniclastic sediment | Kuching Formation | zircon | U-Pb | 221* | 3 |
| 713 | 713b | 110.60248 | 0.996716 | outcrop | volcaniclastic sediment | Sadong Formation | zircon | U-Pb | 225* | 2 |
| 712 | 712 | 110.54335 | 0.94992 | outcrop | volcaniclastic sediment | Sadong Formation | zircon | U-Pb | 231* | 3 |

* U-Pb age of the youngest detrital zircon, that is interpreted as maximum age of deposition



**Graphical abstract**

## Highlights

- $^{40}$Ar/$^{39}$Ar dating of metamorphics in Sarawak revealed Late Triassic metamorphism.
- Volcaniclastics have Mesozoic zircons indicating contemporaneous magmatism.
- Detrital U-Pb zircon ages reveal reworking of Paleoproterozoic crust.
- Part of West Sarawak was connected to Sundaland from the Triassic onwards.
- A new reconstruction for West Sarawak from the Triassic onwards is proposed.