Adakites without a slab: Remelting of hydrous basalt in the crust and shallow mantle of Borneo to produce the Miocene Sintang Suite and Bau Suite magmatism of West Sarawak

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Abstract

We present new geochronological and geochemical data for Neogene magmatism from West Sarawak. Zircon U-Pb geochronology divides Neogene magmatic rocks of West Sarawak into a Lower Miocene West Sarawak Sintang Suite with ages of c. 19 to 21 Ma, and a Middle Miocene Bau Suite with ages of c. 12 to 14 Ma. Magmatism occurred in multiple short-lived pulses from approximately 24 Ma and was coeval with magmatic activity in NW Kalimantan and East Kalimantan. The majority of, but not all, Bau Suite samples display adakitic chemistry, while the West Sarawak Sintang Suite is predominantly non-adakitic. There was no active subduction zone or subducted slab associated with this adakitic magmatism. Instead, the geochemical diversity is consistent with the Bau and West Sarawak Sintang suites representing mixtures of mafic, mantle-derived magma with felsic magma derived from remelting of hydrous, mafic rock that had been emplaced into the lithosphere of Borneo as arc basalt tens or hundreds of millions of years previously. This origin is most evident in the main Sintang Suite of central Borneo (Kalimantan) which has preserved less contaminated

examples of the mafic endmember. This endmember resembles basaltic rocks from several locations across Borneo suggesting that intraplate, mantle-derived magmatism was responsible for remelting older, hydrated basaltic rocks in the crust.

1. Introduction

Subduction zones have been major sites of crustal processing since at least the Neoproterozoic. While there is debate about early Precambrian geodynamics, including the role and importance of subduction (Stern, 2005; van Hunen and Moyen, 2012), modern subduction zones have produced, so called, adakitic magmatic rocks that resemble the tonalite – trondhjemite – granodiorite (TTG) suites which are common constituents of felsic Archean terranes (Campbell and Taylor, 1983; Kelemen, 1995; Drummond et al., 1996). Therefore, understanding the genesis of adakitic rocks is an important step in understanding the development of the Earth's continental crust.

Adakites were initially interpreted as melts derived from young subducted oceanic crust (Defant and Drummond et al., 1990), but there have since been many studies that have found adakitic rocks either in subduction zones lacking subducted young oceanic lithosphere (e.g. Sajona et al., 1993; Castillo et al., 1999; Macpherson et al., 2006), or formed by melting of basaltic rock in the highly thickened crust of collision zones (Chung et al., 2003; Hou et al., 2004; Guo et al., 2007). Thus, several different processes – some involving slab melting, some not – have been proposed to explain the generation of the adakitic chemical signature. Each of these has implications for the geodynamic settings in which adakites are found and potentially for processes that might have been common during the Archean.

In this paper, we explore the temporal, petrological, and geochemical development of a suite of Neogene magmatic rocks from Borneo that includes adakitic rocks. These were generated in a setting that had lacked subduction during, at least, the preceding 50 million years, and where there is no evidence of substantial crustal thickening. We show that these adakites were contemporaneous with (i) non-adakitic granodiorites which were derived from similar sources to the adakites, and (ii) mantle-derived magmas resembling ocean island basalts. This indicates that the hydrated basaltic source of the adakites was present in the Borneo lithosphere, and implies subduction before the Oligo-Miocene, but there was no active subduction zone or subducted slab associated with the adakitic melts, which probably resulted from intraplate processes.

2. Regional background

The Kuching Zone in Borneo of Haile (1974), extending from the Lupar Line in the north to the Schwaner Mountains in the south (Fig. 1 and 2), includes Palaeozoic to Cenozoic metamorphic, sedimentary and igneous rocks (e.g. Liechti et al., 1960; Hutchison, 2005; Breitfeld et al., 2017, 2018). The upper Cenozoic in the Kuching Zone is characterised by widespread, small igneous intrusions which form the focus of this study (Fig. 2). Geochemically similar rocks from Kalimantan and West Sarawak (Kirk, 1968; Williams and Harahap, 1987) are predominantly of Late Oligocene to Early Miocene age, and have been referred to as the Sintang Intrusives, the Sintang Intrusive Suite or the Sintang Suite (e.g. Doutch, 1992; Moss et al., 1998; Hutchison, 2005, 2010). We follow Hutchison in preferring the term Sintang Suite because not all of the igneous rocks are intrusive.

2.1. Pre-Oligocene magmatism in Borneo

The extensive Schwaner Mountains granitic batholith, which lies immediately south of the area of Sintang Suite magmatism (Fig. 2) formed during Cretaceous subduction that ceased at around 90 to 80 Ma (Pieters and Sanyoto, 1993; Hutchison, 1996; Moss, 1998; Hall, 2012; Davies et al., 2014; Breitfeld et al., 2017; Hennig et al., 2017). Subsequent minor magmatic episodes produced the upper Cretaceous Pueh and Gading batholiths of West Sarawak (Kirk, 1968; Hennig et al., 2017; Fig. 3), the Eocene Muller Volcanics, Nyaan Volcanics, Piyabung Volcanics and Serantak Volcanics in NW and central Kalimantan (Pieters et al., 1987; Bladon et al., 1989; Fig. 2), and the Eocene Piring stock in North Sarawak (Hennig-Breitfeld et al., 2019; Fig. 3) .

2.2. Sintang Suite: Upper Oligocene to Lower Miocene magmatism in Borneo

The Upper Oligocene to Lower Miocene Sintang Suite consists of small sills, stocks and dykes, which form distinctive topographic features across a broad swathe of western Borneo (Williams and Harahap, 1987 and references therein) between the Schwaner Mountains and the Lupar Line (Fig. 2). Compositions are predominantly dacitic, granodioritic, or subordinately dioritic to granitic, with I-type character (Williams and Harahap, 1987). Whole-rock, biotite, and hornblende K-Ar dating of 12 samples collected near Sintang in NW Kalimantan (Williams and Harahap, 1987) yielded two distinct age groups: an older group of 30.4 to 23 Ma in the Melawi Basin near Sintang (type locality), and a younger group of 17.9 to 16.4 Ma in the Ketungau Basin. One biotite age of c. 42 Ma was excluded as it came from a rock which intruded probable Oligocene sediments. The NW Kalimantan Sintang Suite includes geochemically distinctive Northern, Central and Southern groups (Harahap, 1993; Heryanto et al., 1993), which are retained in this study (Fig. 2).

In West Sarawak the Sintang Suite comprises sills (Fig. 4a), lava flows (Fig. 4b and d), dykes (Fig. 4c) and stocks which intrude the Kayan Sandstone and sediments of the northern Ketungau Basin. Kirk (1968) reported K-Ar biotite ages of 16 ± 4 Ma at Gunung Rawan and 19 ± 3 Ma at Pulau Satang (Fig. 3), while Schmidtke et al. (1990) reported K-Ar hornblende ages of 17.2 ± 1.9 for an intrusion south of Kuching and 25.8 ± 1.9 Ma for the Serapi dyke (Fig. 3). Prouteau et al. (1996, 2001) reported whole-rock K-Ar ages in West Sarawak of 22.3 to 23.7 Ma for calc-alkaline diorites and microdiorites in northern West Sarawak. These display similar geochemical diversity to the NW Kalimantan Sintang Suite, which they identified as having partly adakitic chemistry.

2.3. Northeast and East Kalimantan

In East Kalimantan K-Ar mica ages of 17.5 to 19.4 Ma (Bladon et al., 1989), and 21 to 24 Ma (Setiawan and Le Bel, 1987), as well as a Rb-Sr age of 26 Ma (Hutchison, 2010) were reported for the Long Laai granite province (Fig. 2). Van de Weerd et al. (1987) and van Leeuwen et al. (1990) reported K-Ar ages of 14.4 to 24 Ma for basic igneous rocks associated with gold mineralisation in the Kelian area, which are part of the Kalimantan gold belt. Andesites in the Kelian area yielded U-Pb zircon ages of 19 to 20 Ma (Setiabudi et al., 2001, 2007) and are intruded by rhyolites with U-Pb zircon ages of 19.5 to 19.8 Ma (Davies, 2002; Davies et al., 2008). K-Ar ages of 18 to 23 Ma for magmatic rocks near the Telen and Malnyu Rivers (northern Kutai Basin) were included in the Sintang Suite by Moss et al. (1998), Soeria-Atmadja et al. (1999) and Cullen et al. (2013), but we retain distinct location names (e.g. Kalimantan gold belt, Long Laai, Telen/Malnyu) in view of their significant spatial separation from our study area (Fig. 2).

2.4. Bau Suite: Middle to Upper Miocene magmatism

Intrusions around the town of Bau (Figs. 2 and 3), West Sarawak, have been dated as Middle to Late Miocene age. Therefore, this Bau Suite is younger than the Sintang Suite and magmatism in East and North Kalimantan. JICA (1985) reported whole-rock K-Ar ages of 10 to 12 Ma for quartz porphyries while Prouteau et al. (2001) reported whole-rock K-Ar ages of 6.4 to 14.6 Ma for microtonalites and dacites near Kuching and Bau, which they also classified as adakites. The Bau Suite is associated with gold mineralisation of Carlin-type (Percival et al., 1990; Schuh and Guilbert, 1990), and includes disseminated sediment hosted gold deposits within the Bau Limestone and the adjacent Pedawan Formation (e.g. Jugan field) (Schuh, 1993; Kirwin and Royle, 2018).

2.5. Geodynamic Setting of the Sintang Suite

A broad swathe of Borneo, including West Sarawak, experienced Sintang Suite magmatism from the Late Oligocene (Fig. 2) but the causes are not clear. Dating is limited, with most ages from K-Ar whole rock dating, and there has been limited geochemical study of this suite. A subduction-related origin was inferred by Hamilton (1979), Prouteau et al. (1996, 2001), Soeria-Atmadja (1999), and Hartono (2006) but, despite their widespread distribution, the Sintang rocks occur as small isolated bodies located far from any potential Oligo-Miocene subduction zone. Others have proposed post-collisional or post-subduction settings (Kirk, 1968; Williams and Harahap, 1987; Moss et al., 1998; Zaw et al., 2011).

Hutchison (1996) introduced the term Sarawak Orogeny to explain a major tectonic change in NW Borneo in the Late Eocene, to which Prouteau et al. (2001) attributed the Sintang Suite magmatism, but recent studies have questioned the implied collisional event (Hall, 2012; Hall and Sevastjanova, 2012; Hall and Breitfeld, 2017; Hennig-Breitfeld et al., 2019). Early tectonic models (e.g. Taylor and Hayes, 1983) suggested an Early Miocene collision in northern Borneo, from Sarawak to Sabah, but later work indicates that subduction beneath Sarawak west of the West Baram Line (Fig. 2) ceased in the Cretaceous at around 90 to 80 Ma (Williams et al., 1988; Moss, 1998; Hall & Spakman, 2015; Breitfeld et al., 2017; Hennig et al., 2017) although deep marine sedimentation continued until the Late Eocene (Galin et al., 2017; Breitfeld & Hall, 2018). Between the Late Eocene and Early Miocene, to the west of the West Baram Line, NW Borneo was an elevated region (Hall, 2013; Hennig-Breitfeld et al., 2019), and offshore and onshore Sarawak were extensive coastal and shelf areas (e.g. Hageman, 1987; Madon, 1999; Hassan et al., 2013). There is no evidence of a late Paleogene or Neogene subduction margin in Sarawak and subduction was restricted to Sabah, east of the West Baram Line, between the Late Eocene and Early Miocene (Hall, 2013; Hall and Spakman, 2015; Hall and Breitfeld 2017). Thus, there is no evidence for active subduction beneath west Borneo at the time of Sintang and Bau Suite magmatism.

We present below new geochemical data and U-Pb zircon ages from the Sintang and Bau suites of West Sarawak that show different pulses of magmatism. We integrate our new findings with published data to offer a new interpretation of their petrogenesis, and then discuss the origin of adakitic and non-adakitic geochemical characters in non-subduction environments.

3. Methodology

3.1. Sampling

Fresh rocks or rocks with minimal alteration were sampled (TB samples) from outcrops or nearby float in West Sarawak (Fig. 3). Additional samples from Bau (BYG) were provided by Menzies Mining. Nine samples from the West Sarawak Sintang Suite and thirteen from the Bau Suite were analysed for geochemistry, and zircons from seven samples were separated for radiometric dating. All sample locations and type of analysis can be found in Supplementary Tab. 1.

3.2. Geochemistry

Whole rock geochemical analysis by X-ray fluorescence (XRF) was conducted at Royal Holloway University of London (RHUL; Tab. 1). Samples were processed with a jaw crusher and a tungsten-carbide mill to produce powders. XRF analyses were mostly performed using a PANalytical Axios sequential X-ray fluorescence spectrometer with 4kW Rh-anode X-ray tube, while Bau Suite BYG samples were analysed using the previous Philips PW1480 XRF. On this latter instrument, a W-anode X-ray tube was used to determine Ba, La, Ce, Nd, Ni, Cr, V, Sc, Cu and Zn whereas a Rh-anode tube was used for the major elements, Pb, Th, Rb, Sr, Y, Zr, Nb, Cl, and Ga. Major elements were measured on fusion discs using the La_2O_3-bearing Spectroflux 105, after ignition of both rock powders and flux at 1100˚C. All concentrations are reported on a volatile-free basis. The heavy absorber La results in very small matrix corrections. SO_3 concentrations reported for samples analysed on the Axios reflect sulphur present as sulphate, as sulphide sulphur is largely volatilized during the fusion process. Trace elements were measured on pressed pellets, with matrix corrections calculated from the major elements. Ca and Ti were analysed on both pellets and discs to confirm that the same powder was used for both pellet and disc; the fusion disc data is of higher quality. An artificial glass bead was analysed every third sample to correct for instrumental drift, which was at the <1 % level on the Axios, and a few % on the PW1480, where the drift monitor was analysed for each element following the sample analyses for that element. 30 to 40 international rocks standards were used for calibration. Calibration graphs are publicly available at https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research/research-laboratories/x-ray-fluorescence-laboratory/. The quality of the straight line fit of these graphs is the best indicator of accuracy over a wide range of concentrations. Where there is more scatter, this can reflect poor precision of the XRF analyses relative to the calibrated concentration range (e.g. Sn, where precision is about ±2 ppm, and the calibrated range only 15 ppm); inaccuracies in the published standard data (e.g. S, Cl), or inaccuracies in the XRF data (e.g. at <100 ppm F). Precision of the XRF data is a function of detection limit at low concentrations, and of count rate at higher concentrations; this means that the concentration uncertainty is an absolute concentration at low levels, and a percentage concentration at higher levels. Estimates of these parameters are given in Tab. 1. An example of pellet reproducibility, and comparison between XRF and isotope dilution data, are given in the web link referred to above.

A wider range of trace elements were determined for BYG samples in the Department of Earth Sciences at Durham University using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) on a Perkin Elmer Elan 6000 following the procedure of Ottley et al. (2003). Briefly, 4 ml HF and 1 ml HNO_3 (SPA, ROMIL Cambridge) was added to 100 mg of powdered sample and sealed in a teflon vial on a hot plate at 150°C for 48 hours. The acid mixture was evaporated to near dryness followed by two cycles of adding a further 1 ml of HNO_3 and evaporation to near dryness. Finally, 2.5 ml HNO_3 was added and diluted to 50 ml after the addition of an internal Re and Rh standard to final concentrations of 20 ppb each. The internal standard allows compensation for analytical drift and matrix suppression effects. ICP-MS analyses were calibrated using international rock standards (BHVO1, AGV1, W2) which, along with analytical blanks, were prepared using the same procedure as samples. Reproducibility was monitored via replicate analysis of reference standards throughout the analysis sequence with % RSD always <3 % RSD, and typically <2 % RSD and by comparison of trace element analyses of ICP-MS with XRF (Supplementary Tabs. 2.1 and 2.2).

3.3. Zircon separation

A 63-250 µm fraction of zircon was separated at RHUL. This was purified using heavy liquids sodium polytungstate (SPT) and lithium heteropolytungstate (LST) at a density of 2.89 g/cm³ and a FRANTZ magnetic barrier separator, followed by additional heavy liquid separation with di-iodomethane (DIM) at 3.3 g/cm³ and hand picking of zircons. Grains were mounted in epoxy resin blocks and polished to expose mid-grain sections. Analysis spots for each grain were selected using transmitted light and cathodoluminescence scanning electron microscope (SEM-CL) images to avoid cracks and inclusions.

3.4. LA-ICP-MS U-(Th)-Pb dating

Zircon U-Pb geochronology was performed at the Birkbeck College, University of London (UCL), using New Wave NWR 193 (25 µm spot size) and New Wave NWR 213 nm (30 µm spot size) laser ablation (LA) systems coupled to an Agilent 7700 quadrupole-based plasma ICP–MS with a two-cell sample chamber. 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. GLITTER (Griffin et al., 2008) data reduction software 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.

For grains older than 1000 Ma, the ^{207}Pb/^{206}Pb ratio is given and for grains younger than 1000 Ma, the ^{238}U/^{206}Pb ratio is given, because ^{207}Pb cannot be measured with sufficient precision in these samples resulting in large uncertainties on the age (Nemchin and Cawood, 2005). Ages greater than 1000 Ma are considered to be concordant if the difference between the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U ages is <10%, and ages less than 1000 Ma were considered to be concordant if the ^{207}Pb/^{235}U and ^{206}Pb/^{238}U age difference is <10%. For young ages a simple concordance test is insufficient (Nemchin and Cawood, 2005) as the concordance range is too small to test reliably. Instead all analyses <25 Ma were considered for the age calculation, except analyses which were interpreted to be affected by lead loss, inheritance or common Pb.

Isoplot 4.11 (Ludwig, 2003) was used for graphical illustration of Tera-Wasserburg concordia diagrams (Tera and Wasserburg, 1972). Tera-Wasserburg plots were used to identify individual peaks or visually assess outliers (e.g. lead loss, inheritance and common lead) within the population which were then excluded from the weighted mean age calculation. The reject function of Isoplot was used to further exclude statistical outliers (Ludwig, 2003). The youngest significant population were interpreted as crystallisation ages and used to calculate the weighted mean age. U-Pb zircon data for each sample are presented in the Supplementary Tabs. 3.1 to 3.7 and a summary of weighted mean ages is displayed in Tab. 2. Conventional concordia plots are given in Supplementary Fig. 2.

4. Petrography

4.1. West Sarawak Sintang Suite

4.1.1. Intrusive rocks

Micro-tonalites/granodiorites (TB33, TB148a, STB36c, and STB61b) dominate the intrusive West Sarawak Sintang Suite. They are composed mainly of quartz, plagioclase, an opaque phase and alkali feldspar. Plagioclase is more abundant than alkali feldspar and both form large, zoned phenocrysts, commonly idiomorphic to hypidiomorphic. Larger plagioclase phenocrysts may be altered to epidote. The matrix consists of fine grained quartz, plagioclase and sericite. The composition of granodiorite TB58 closely resembles the micro-granodiorites/tonalites, but has a coarser grained phaneritic texture (Fig. 4e). Plagioclase occurs as abundant prismatic crystals (Fig. 4e). Scarce amphibole occurs as subhedral grains which show advanced epidote group mineral alteration (Fig. 4f). Biotite occurs as brown and green varieties with only minor chlorite alteration (Fig. 4e). There is some sericite alteration of feldspar and biotite. More mafic monzodiorites and (gabbro-) diorites (TB23, TB231) contain plagioclase, alkali feldspar, biotite, epidote, amphibole, quartz and an opaque phase. Plagioclase and alkali feldspar form large idiomorphic to hypidiomorphic phenocrysts. Biotite is often replaced by sericite, chlorite and titanite. Amphiboles are subhedral and replaced by epidote group minerals and calcite.

4.1.2. Volcanic rocks

Volcanic rocks of the West Sarawak Sintang Suite comprise felsic rhyolites to rhyodacites (TB18, TB141, TB176b, TB209a) and a mafic trachydacite (TB161). The felsic samples are porphyritic, containing idiomorphic to hypidiomorphic phenocrysts of quartz (Fig. 4g), alkali feldspar (Fig. 4h), and plagioclase (Fig. 4i), often zoned, in a very fine grained groundmass. Idiomorphic volcanic quartz commonly has a bipyramidal shape, embayments and inclusions of sericite, biotite and plagioclase. Sericite alteration of the matrix is common. TB161 is a more mafic trachydacite with phenocrysts of biotite, plagioclase, epidote, pyroxene and quartz. Quartz is monocrystalline and unstrained with bipyramidal idiomorphic or hypidiomorphic shapes. Plagioclase and clinopyroxene form hypidiomorphic phenocrysts in a very fine grained altered matrix of sericite, plagioclase and epidote group minerals (Fig. 4j). Biotite is commonly chloritised.

4.2. Bau Suite

Bau Suite samples are predominantly micro-granodiorites and micro-tonalites. Plagioclase, alkali feldspar and biotite form phenocrysts in a fine grained quartz and feldspar matrix. Plagioclase is zoned and forms idiomorphic to subidiomorphic crystals (Fig. 4k). Alkali feldspar is very rare, forming subidiomorphic crystals. Sericite alteration is common within feldspars, more so in alkali feldspar than plagioclase. Biotite commonly forms idiomorphic to subidiomorphic crystals (Fig. 4l), which may be heavily altered to sericite, epidote and titanite with chlorite rims. Hornblende forms idiomorphic to subidiomorphic crystals (Fig. 4m), but is uncommon.

A conspicuous feature of many Bau samples are large, resorbed quartz crystals. Up to 2 mm across, these display a variety of textures from slightly sub-angular to a majority which are highly rounded (Fig. 4m) or have scalloped margins. Some crystals also show evidence of newly-grown rims of microscopic quartz. Internal textures also vary from unstrained to significantly strained. In rare cases a number of quartz crystals, usually no more than 3 or 4, can be found together with contacts which suggest that they were part of a pre-existing quartz-rich mass. Together, these observations suggest that the Bau magma assimilated grains of a very quartz-rich lithology that has experienced various amounts of deformation and disaggregation.

5. Geochemistry

5.1. West Sarawak Sintang Suite

5.1.1. Intrusive rocks

Intrusive rocks of the West Sarawak Sintang Suite are predominantly felsic with a range of SiO_2 contents from 56 to 70 wt. %, classified as granodiorite, monzodiorite and gabbro-diorite (Supplementary Fig. 1). On the basis of their K_2O contents of 1.28 to 2.65 wt. % (Tab. 1) they are calc-alkaline (Supplementary Fig. 1). According to the granite classification of Frost et al. (2001) they are magnesian calcic or magnesian calc-alkaline, peraluminous or metaluminous granitoids (Supplementary Fig. 1).

The new analyses show major element variations that are coherent with those previously recorded for Sintang Suite diorites from the Kuching area (Prouteau et al., 2001), but over a slightly wider SiO_2 range (Fig. 6). Al_2O_3, Fe_2O_3, MgO, CaO and TiO_2 decrease with increasing silica contents while K_2O increases slightly and Na_2O shows no systematic variation. Major element variations in the West Sarawak Sintang intrusive rocks are also coherent with those of Sintang intrusive rocks from Kalimantan (Fig. 5a). Like the Northern and Southern Kalimantan Sintang groups, West Sarawak Sintang intrusive rocks have a wider range of silica and slightly lower Al_2O_3 and higher K_2O than the Central Kalimantan Sintang Suite group for any SiO_2 content (Fig. 5a & g). Intrusive rocks with less than 55 wt. % SiO_2 have not been found in West Sarawak.

Like major elements, the incompatible trace element concentrations in West Sarawak Sintang intrusive rocks are coherent with diorites previously analysed from this area (Prouteau et al., 2001), having substantial enrichment in the most incompatible elements with pronounced depletions of Nb compared to MORB (Fig. 6a). This means that their trace element ratios broadly resemble volcanic arc or post-collision rocks (Supplementary Fig. 1). However, the new analyses show that the Nb depletion is accompanied by large enrichments in Pb. While these characteristics can be indicative of subduction, they can also be produced or enhanced if crust contaminates intruding magma, as demonstrated for the Semporna peninsula of northeast Borneo in Sabah (Fig. 7a; Macpherson et al., 2010). Likewise, melting of a crustal source with such patterns would also generate these features. The new Kuching intrusive rock data show concentrations of Y and Yb that are similar to or slightly lower than N-MORB (Fig. 6a). We found no West Sarawak Sintang intrusive rocks showing the strong depletion of Y and heavy rare earth elements that led Prouteau et al. (2001) to identify adakites in this area. Trace element ratios support the conclusion from major element data, that these West Sarawak Sintang intrusive rocks more closely resemble the Northern and Southern Kalimantan Sintang groups than the Central Kalimantan Sintang group (Fig. 6d).

5.1.2. Volcanic rocks

Volcanic samples are rhyolites and rhyodacites with SiO_2 ranging from 74 to 77 wt. %, and a single trachydacite with SiO_2 = 61 wt. % (Supplementary Fig. 1). Major elements in TB161 are similar to West Sarawak Sintang intrusive rocks with similar SiO_2 contents, except for lower CaO and higher Na_2O (7.87 wt. %; Fig. 5). The more silicic volcanic rocks lie on extensions of the array for West Sarawak Sintang intrusive rocks. Based on potassium contents the volcanic rocks are calc-alkaline, and they are predominantly peraluminous (Supplementary Fig. 1).

Normalised incompatible element patterns show slight differences from the intrusive rocks. The most incompatible elements show similar ratios with similar to slightly higher contents. However, compared to intrusive rocks these more silicic rocks display depletions of several elements that can be accommodated in phases crystallised from felsic melts (Fig. 6b). Thus, pronounced depletions in P suggest crystallisation of apatite while depletion of Sr, along with Al_2O_3 and CaO, is consistent with plagioclase fractionation, and Zr depletion may result from zircon fractionation. Relative depletion of Ti could reflect fractionation of oxide phases or of amphibole. The mild, overall enrichment of incompatible elements with relative depletion of compatible elements is consistent with the West Sarawak Sintang volcanic rocks being more differentiated equivalents of the West Sarawak Sintang intrusive rocks. High-silica rocks with very similar trace element patterns are found in the Northern, Central, and Southern groups of the Kalimantan Sintang Suite (Williams and Harahap, 1987; Harahap, 1993).

5.2. Bau Suite

Rocks from the Bau District are granodiorites and can be described as magnesian calcic and range from peraluminous or metaluminous (Supplementary Fig. 1). Based on K_2O content, they are calc-alkaline (1.3 to 2.9 wt. %; Supplementary Fig. 1). SiO_2 contents range from 67.5 to 71.8 wt. %. This extends the range previously recognised by Prouteau et al. (2001) to slightly higher silica values, while other major elements are similar to those by Prouteau et al. (2001) except for slightly higher Al_2O_3 in the least silicic rocks. Major elements of the Bau Suite resemble West Sarawak Sintang rocks with similar SiO_2 although they have slightly more elevated Al_2O_3 and CaO. This makes the Bau Suite more similar to Kalimantan's Central Sintang group than the Northern or Southern groups (Fig. 5).

Compared to N-MORB, the most incompatible trace elements are the most enriched in Bau Suite rocks. For most elements, the level of enrichment gradually diminishes through to the middle rare earth elements and then remains constant or becomes progressively depleted for less incompatible elements (Fig. 6c). Superimposed upon this pattern are relative depletions in Nb, Ta, and Ti and, to a lesser extent, P along with pronounced enrichments in K and Pb and, to a lesser extent, Sr as discussed above (Fig. 6c).

The new analyses of the Bau Suite rocks show contents and ratios of incompatible trace elements similar to prior analyses of the Bau Suite and other adakitic rocks from the Kuching/Bau area (Prouteau et al., 2001; Fig. 7b). For both, contents of and ratios between more incompatible elements are similar to the West Sarawak Sintang intrusive rocks with similar SiO_2, but the heavy rare earth elements and Y are more variable. Some resemble the West Sarawak Sintang Suite but most are relatively depleted in Y and HREE (Fig. 6c). Compared to the Kalimantan Sintang Suite, the Bau Suite most closely resembles the Central group (Fig. 6d, Fig. 7b), consistent with the conclusion drawn from major elements.

6. U-(Th)-Pb zircon geochronology

6.1. West Sarawak Sintang Suite

6.1.1. Intrusive rocks

Sample TB63b

TB63b is a granodioritic sill intruding the Kayan Sandstone at Tanjung Santubong. Zircons are usually euhedral to subhedral or anhedral. Simple internal zoning is evident in most grains. Concentric, patchy and sector zoning are rare.

86 U-Pb ages were obtained from 86 zircon grains (Fig. 8a). The zircon age population is predominantly Early Miocene (83 ages) with one inherited age of 256 ± 4 Ma. Two Miocene ages were excluded because of high common lead. Two outliers of Miocene age were excluded from the weighted mean age calculation because of lead-loss, resulting in a unimodal population (Fig. 9a) of 81 Miocene ages (98% of total Miocene ages) that cluster between 19 and 23 Ma with a weighted mean age of 21.1 ± 0.2 Ma (MSWD = 3.5).

Sample TB58

TB58 is a stock that intrudes sediments of the Silantek Formation sampled from a granodiorite boulder in a small gully from Bukit Kelambi (Klambi). Zircons are angular, with a euhedral to subhedral or anhedral shape. Elongate zircons dominate. Simple internal zoning is evident in most grains. Concentric, oscillatory, patchy and sector zoning were also observed. Zircons with inherited ages are commonly oscillatory zoned and subrounded.

51 U-Pb ages were obtained from 51 zircon grains (Fig. 8b). A single Miocene age was excluded because of high common lead. The population is predominantly Early Miocene (43 ages) with 7 inherited zircons of Mesozoic to Permian age, ranging from 114 to 267 Ma. 7 outliers of Miocene ages (grey in Fig. 8b) have either lead-loss or inheritance, and were excluded from the weighted mean age calculation. This includes a small population composed of 5 inherited Miocene zircons at

around 23 Ma, leaving a unimodal population of 36 of the 43 Miocene ages (84% of the Miocene ages), which cluster between 19.4 and 21.8 Ma with a weighted mean age of 20.3 ± 0.2 Ma (MSWD = 3.0).

Sample TB33

TB33 is a dyke sampled from Gunung Bawang at 300 m above sea level and close to the Serapi dyke dated by the K-Ar method as 25.8 ± 1.9 Ma (Schmidtke et al., 1990). Zircons are euhedral to subhedral or anhedral. Elongate varieties are common. Simple internal zoning is evident in most grains. Concentric, patchy and sector zoning is also observed. Oscillatory zoned grains are rare. Zircons are bright to grey with darker edges in CL. Very thin light coloured, potentially magmatic, rims are observed in a few grains.

66 U-Pb ages were obtained from 61 zircon grains (Fig. 8c). Two ages were excluded because of partial ablation of the resin mount. The zircon population is predominantly Early Miocene (63 ages) with one inherited age of 500 Ma. Six Miocene outliers, including a small population of inherited Miocene zircons at around 24 Ma and a number of zircons affected by lead-loss, were identified and excluded from the weighted mean age calculation. The remaining Miocene population has a unimodal distribution (Fig. 9c) including 57 of the 63 (91% of all) Miocene ages, clustering between 18 and 22 Ma with a weighted mean age of 20.1 ± 0.2 Ma (MSWD = 2.1).

6.1.2. Volcanic rocks

Sample TB141

TB141 is a rhyolite from a lava flow exposed in a road cut near Kampung Matang in the Gunung Serapi area and contains zircons of two different varieties. The majority are elongate euhedral needle-like grains with simple internal or sector zoning, which are Miocene (see below). Other zircons are subhedral to subrounded with simple internal or oscillatory zoning which yielded inherited ages.

42 U-Pb ages were obtained from 41 zircon grains (Fig. 9a). Six ages were excluded because of discordance or lead-loss (not displayed in the Tera-Wasserburg diagram). The remainder are mainly Early Miocene (23 ages), with inherited zircons of Oligocene (33 ± 0.5 Ma), Cretaceous (66.6 ± 0.8 Ma and 100 ± 1 Ma), Triassic (216 to 240 Ma), Permian (271 ± 4 Ma) and Proterozoic (773 to 1911 Ma) age. After rejection of one age, potentially affected by lead-loss, the Miocene population is bimodal. 7 Miocene ages (violet in Fig. 10a) range from 20.9 to 22.3 Ma with a weighted mean age of 21.5 ± 0.4 Ma (MSWD = 1.5) and are interpreted as inherited from an early phase of magmatism. The younger population includes 15 of the 23 (65% of all) Miocene clustering between 19 and 20.5 Ma with a weighted mean age of 19.8 ± 0.3 Ma (MSWD = 1.3) interpreted as the eruption age.

Sample TB209a

Sample TB209a was sampled from a rhyolite boulder field near Bukit Buwaya. Like TB141, there are two varieties of zircon from TB209a. Euhedral to subhedral elongate needle varieties have simple internal or sector zoning with bright to greyish CL imagery and are Miocene (see below). Inherited zircons are subrounded to anhedral, usually with sector or oscillatory zoning.

41 U-Pb ages were obtained from 38 zircon grains (Fig. 9b). Two inherited ages were excluded for failing the 10% discordance criteria and two Miocene ages were also excluded because of abundant common lead. The age population is mainly Miocene, with inherited Eocene (47.1 ± 0.6 Ma), Cretaceous (68.5 to 105 Ma), and Neoproterozoic (649 ± 7 Ma) ages. Two Miocene outliers (violet colour) were identified and are interpreted as inherited ages of c. 20.3 Ma. The remaining unimodal population (Fig. 10b) includes 25 of 27 (93% of all) Miocene ages clustering between 17.9 and 19.4 Ma with a weighted mean age of 18.6 ± 0.2 Ma (MSWD = 2.0).

6.2. Bau Suite

Sample TB9

TB9 is a micro-tonalite from the Bukit Stigang quarry southeast of Kuching (Kota Samarahan). Euhedral, elongated zircons with simple or concentric zoning and greyish CL imagery are common.

25 U-Pb ages were obtained from 22 zircons (Fig. 9c). Two inherited ages were excluded for failing the 10% discordance criteria. The youngest grain of 5 Ma is interpreted to be affected by lead-loss and was also excluded. Of the valid ages 19 are Miocene, with three Miocene outliers either affected by lead-loss or inheritance (marked in grey) and excluded from the weighted mean age calculation, leaving a unimodal population which includes 16 of 19 (84% of all) Miocene ages which cluster between 12.6 and 14.5 Ma with a weighted mean age of 14.1 ± 0.1 Ma (MSWD = 0.5).

Sample TB61

Sample TB61 is a micro-granodiorite collected from the Bukit Stapok quarry in Batu Kawa near Kuching that contains euhedral, elongate zircons with simple or oscillatory zoning. Larger zircons are anhedral, can be easily distinguished from elongate varieties, and are inherited. 10 U-Pb ages were obtained from the sample (Fig. 9d). Two inherited ages were excluded after failing the 10% discordance criteria and one Miocene age was excluded because of abundant common lead. The sample has one concordant inherited Proterozoic age around 850 Ma. The youngest population of the sample ranges from 4.6 to 18.5 Ma (Fig. 9d). The youngest grain of 4.6 Ma is interpreted to be affected by lead-loss. Three analyses lie close to 12 Ma (and the excluded Miocene age with abundant common lead as well) and the age is interpreted as a crystallisation age with a weighted mean age of 12.4 ± 0.9 Ma (MSWD = 1.4). Two ages of 15 and 18.5 Ma are interpreted as inherited.

7. Discussion

7.1. Age of Neogene magmatism

7.1.1. West Sarawak Sintang Suite

Our U-Pb dating of zircons in volcanic and intrusive rocks from West Sarawak yielded a restricted range of ages (Fig. 10a), suggesting relatively short-lived Miocene magmatic episodes. The intrusive rocks gave weighted mean ages of 20.1 to 21.1 Ma (Tab. 2; Fig. 10a). We interpret the slightly older, inherited ages of 22 to 24 Ma (n = 7) as recording earlier magmatic activity during the latest Oligocene to earliest Miocene. We obtained a U-Pb age of 20.1 ± 0.2 Ma for the Bawang dyke

(TB33), which is only a few metres away from the Serapi dyke previously dated by the K-Ar method as 25.8 ± 1.9 Ma (Schmidtke et al., 1990). Both dykes are likely to be part of the same magmatic phase and we suggest the U-Pb age is more accurate.

Since West Sarawak Sintang volcanic rocks gave ages of 18.6 ± 0.2 Ma and 19.8 ± 0.3 Ma (Tab. 2; Fig. 10a), which are within analytical uncertainty of the intrusive rocks, we interpret both to be part of the same suite. This is consistent with the geochemical data which indicate that the volcanic rocks are silicic differentiates of the intrusive magmas. It is notable that both volcanic samples contain inherited zircons with ages ranging from 19.8 to 22.7 Ma, which resemble the ages of the intrusive rocks (Fig. 10a). This is further evidence for pulsed early Miocene magmatic activity. Thus, we suggest the West Sarawak Sintang Suite records a period of magmatism from c. 24 to 18.5 Ma during which there were potentially three pulses. A tuff layer in the Temburong Formation on Labuan (Fig. 2) was recently dated as c. 19.5 ± 0.1 Ma (S. Burley, pers. comm., 2018). The age is indistinguishable from the Sintang Suite, and the tuff could be an airfall record of the same activity, 650 km from the Sintang rocks.

7.1.2. Bau Suite

The youngest magmatic activity we dated in West Sarawak is the 12.4 to 14.1 Ma Bau Suite (Tab. 2; Fig. 10a), with ages similar to K-Ar dates from Bau quartz-porphyries (10 to 12 Ma; JICA, 1985), and K-Ar dates of adakitic microtonalites in Bau and south of Kuching (6.4 to 11.6 Ma; Prouteau et al., 2001). The range of our U-Pb ages is narrower than those of Prouteau et al. (2001), but each of our samples contain a younger zircon of c. 5 Ma showing lead loss, which suggest Pliocene thermal effects of magmatism or hydrothermal activity. Basaltic magmatism at c. 5 Ma has been reported from Mount Niut in Kalimantan (Harahap, 1994), only 30 km south-southwest of the Bau intrusive field (Fig. 2). Pliocene thermal activity could have affected Miocene whole rock ages obtained by the K-Ar method.

We conclude that the Bau episode was confined to a relatively short interval in the Middle Miocene, which may be contemporaneous with the Kuching adakites reported by Prouteau et al. (2001). Ramkumar et al. (2018) obtained U-Pb ages of 11.44 to 11.76 Ma (n = 3), indistinguishable from our younger Bau age, for a tephra layer in coal beds near Mukah, approximately 300 km northeast of Bau (Fig. 2). This tephra layer is around 6 cm thick, contains no large pyroclastic fragments, and contains non-vesicular glass along with clasts of non-juvenile origin, which Ramkumar et al. (2018) interpreted as reflecting the distal deposit of a large volcanic event. Geochemical characterisation of the tephra is complicated by deposition of contemporaneous sediment and then by significant post-depositional alteration. Some trace element ratios of Mukah tephra resemble Bau, although others are more similar to the West Sarawak Sintang Suite, and all have a strong alteration overprint on the most mobile elements (Ramkumar et al., 2018). The chemistry of this tephra layer is, however, not inconsistent with an origin from Bau. Potential eruptive products near Bau town include a 1 x 2 km dome of rhyodacite flow breccia at Gunung Sirenggok (Schuh, 1993). Such silicic magmas are often associated with highly explosive eruptions that can disperse large ash falls up to hundreds of kilometres from their source. Furthermore, the Bau granites were emplaced into Mesozoic limestones (Schuh, 1993), which could have enhanced the volatile content, and therefore the explosivity, of magma that reached the surface. Schuh (1993) documents several instances of brecciation of Bau intrusive bodies, which could reflect syn-emplacement magmatic activity or late-stage mineralisation.

The main phase of magmatism at Bau is Middle Miocene. We suggest this was part of more widespread igneous activity, forming adakitic stocks south of Kuching (Prouteau et al., 2001) and explosive volcanism that produced widespread blankets of ash towards the northeast (Ramkumar et al., 2018). A single, slightly older, zircon age of c. 19 Ma in TB61, indistinguishable from the age of West Sarawak Sintang rocks (Fig. 10a) suggests Early Miocene magmatism in the Bau area.

7.2. *Implications of inherited ages*

The West Sarawak Sintang Suite volcanic rocks contain abundant inherited Cenozoic, Cretaceous, Permian-Triassic, and Proterozoic zircons (Fig. 10b). Although the intrusive rocks and Bau Suite contain fewer inherited zircons, their ages are similar to those in the volcanic rocks. Two inherited zircons of Oligocene to Eocene age indicate activity in West Sarawak at a similar time to K-Ar ages for NW Kalimantan (Pieters et al., 1987; Bladon et al., 1989). Late Cretaceous inherited ages (c. 66 to 80 Ma) resemble those from Upper Cretaceous intrusions in West Sarawak (Kirk, 1968; Hennig et al., 2017), and in NW Kalimantan (Williams et al., 1988). The peak in Cretaceous inherited zircon ages between 85 to 100 Ma coincides with that of the Schwaner Mountains (Haile et al., 1977; Williams et al., 1988; van Hattum et al., 2013; Davies et al., 2014; Hennig et al., 2017). Triassic inherited zircon ages resemble the Triassic Sundaland part of West Sarawak (Breitfeld et al., 2017) and in the Northwest Schwaner Zone (Hennig et al., 2017). Precambrian inherited zircons show a distribution similar to the Pedawan Formation (Breitfeld et al., 2017) and, although low in number, could indicate either re-melting of Pedawan Formation or re-melting of source rocks of the Pedawan Formation. The inherited zircons provide clear evidence of significant crustal input to both the Sintang and Bau magmatism.

7.3. *Magma source*

The absence of active subduction to the west of the West Baram Line at the time of emplacement of the Bau, the West Sintang-Sarawak, and Kalimantan Sintang suites (Section 2) eliminates fractional crystallisation of arc magma as a possible source for these suites (Macpherson et al., 2006). Any petrogenetic model for these suites must also reconcile the restricted contrasts in composition between the adakitic and non-adakitic rocks of western Sarawak, and recognise the presence of some non-adakitic rocks amongst the Bau Suite. Other than the depletion of heavy rare earth (and associated) elements in the adakitic rocks there are few differences between West Sarawak Sintang and Bau suites, after accounting for crystallisation of minor phases e.g. apatite and oxides (Fig. 6). This leads us to conclude that Bau and West Sarawak Sintang rocks are, ultimately, derived from similar sources. Furthermore, the non-HREE-depleted, dioritic West Sarawak Sintang Suite rocks resemble Kalimantan's Northern and Southern Sintang groups, while the HREE-depleted Bau rocks more closely resemble the Central Sintang group from Kalimantan (Figs. 5 to 7). This suggests that the source(s) of these magmas were present throughout large parts of western Borneo from the late Paleogene until the middle Neogene.

To explain the adakitic character of the Bau Suite in the absence of active subduction, Prouteau et al. (2001) proposed that a previously subducted piece of oceanic lithosphere had stalled in the mantle and melted. Neither the seismic tomography images available at the time (Rangin et al., 1999) nor since (Hall and Spakman, 2015) have identified an anomaly at suitable depths in the mantle suggesting such a slab.

The tomographic observations are insufficient to disprove the absence of a slab, but we note that the compositions of Bau Suite rocks show several differences from experimentally-generated melts of hydrated basalt at mantle pressures (Winther and Newton 1991; Sen and Dunn, 1994; Rapp and Watson, 1995). At any particular SiO_2 content, Bau Suite adakitic rocks are displaced to lower Na_2O, TiO_2, and Al_2O_3, and to higher MgO than predicted by experiments (Fig. 5). The deviation from experimental slab melt compositions cannot be due to interaction between slab melts and mantle (Kay, 1978; Martin, 1999; Martin et al., 2005; Yogodzinski et al., 2001) since the Borneo rocks do not display the systematic decrease in the aluminium saturation index (molar [Al / Ca + K + Na]) with only a small change in SiO_2 that Rapp et al. (1999) have showed would result from such a process (Fig. 5). In all respects, the major element compositions of the Bau Suite behave more coherently with the non-adakitic West Sarawak Sintang Suite than with the experimental slab melts. For trace elements the two suites show differences only in the HREEs and Y, with all West Sarawak Sintang and some Bau rocks showing no trace element adakitic signature (Fig. 6).

In view of these observations, we conclude that both the adakitic and non-adakitic rocks of Bau and Sintang were derived from similar sources. Although it is reasonable to conclude that this was a basaltic source, production of non-adakitic magma from a basaltic composition requires melting at pressures of less than 10 kbar which is not feasible for the depth of any subducted slab that may be postulated beneath Borneo. Therefore, we conclude that the magmatism of West Sarawak and, by extension, the main Sintang Suite of Kalimantan, do not support the model of a stalled slab beneath Borneo.

7.3.1. Crustal melting at low pressure

The involvement of crust in the genesis of the compositional intermediate magmatism is indicated by the zircons with inherited ages in all suites (Fig. 10b). Major element compositions of Sarawak igneous rocks are well approximated by melting experiments conducted at pressures below 7 kbar where dehydration-melting and water saturated-melting of amphibolites yield intermediate composition melts with Al_2O_3, TiO_2, and Na_2O contents that are lower than those from experiments above 10 kbar (Beard and Lofgren, 1991). These lower pressure, particularly dehydration, experiments also produce intermediate composition melts with MgO contents more elevated than from high pressure melting, although not quite to the level of the Sarawak rocks. Thus, melting of hydrated basalt in the mid- to deep-crust below Borneo could produce much of the major element variation character of non-adakitic rocks of West Sarawak, and in the Northern and Southern groups of the Kalimantan Sintang Suite. Such magmas would not have significant depletions in the heavy rare earth elements, and therefore would not appear adakitic, because melting occurred at pressures below those at which garnet is stable.

7.3.2. Crustal melting at high pressure

We have discounted slab melting for the Sintang and Sarawak adakitic rocks principally because (i) they show many similarities to contemporaneous non-adakitic rocks which lack heavy rare earth element depletion, and (ii) they show negligible sign of having interacted with the mantle. These factors do not exclude melting of hydrated basalt with garnet present at greater depths in the crust. Such melting would produce an adakitic signature (strong depletion of HREE and Y) while having negligible effect on other trace elements (Fig. 6). Furthermore, because melting occurred in the crust, the intermediate to evolved composition magma would not interact with the mantle (Fig. 11a and b). High silica magmas would equate to low degrees of melting, and as the degree of melting increase SiO_2 would decrease (Rapp and Watson, 1995). However, on its own, this mechanism has two problems. First, for any realistic SiO_2 content the lowest MgO contents of the Sintang and Bau Suite rocks are at the upper range of even the low pressure melting experiments (Beard and Lofgren, 1991). Second, the presence of mafic rocks, including andesitic compositions in the West Sarawak Sintang Suite and basaltic compositions in the Kalimantan Sintang Suite (Fig. 5), would require very high degrees of melting, in excess of 50 % at temperatures well above 1050°C (Rapp and Watson, 1995). These issues can be resolved by considering the origin of the most mafic Sintang Suite rocks (MgO> 3 wt. % and SiO_2 < 58 wt. %).

7.3.3. Crustal melting with a contemporaneous mafic input

Mafic rocks from the Sintang Suite are different to the intermediate and evolved rocks. The mafic rocks have basaltic to low-silica andesitic compositions (Williams and Harahap, 1987; Harahap, 1993; Heryanto et al., 1993; Prouteau et al., 2001) in which silica correlates positively with Al_2O, K_2O and Na_2O, and shows a strong, negative correlation with MgO (Fig. 5). These mafic rocks show less extreme ratios of fluid-mobile to non-mobile incompatible trace elements and less marked depletion of the moderately incompatible elements (Nd to Y) than the more silicic rocks leading to smoother normalised trace element patterns (Fig. 7a). The mafic rocks also tend to have steeper patterns for the heavy rare earth elements which, for basaltic rocks, is likely to indicate melting of garnet peridotite. Most show notable depletion in Nb, which might be interpreted as indicating a subduction setting. However, HFSE depletion can also be produced by crustal contamination even in relatively mafic melts (Thompson et al., 1983), and this has been proposed for basalts from the Semporna Peninsula in Sabah, NE Borneo (Macpherson et al., 2010). The major and trace element compositions of mafic Sintang rocks resemble basalts from Semporna (Fig. 7a), and we therefore interpret the mafic members of the Sintang Suite to be mantle-derived magma that has been contaminated by crust. The presence of such rocks among the Sintang Suite has two important implications. First, mantle melting was contemporaneous with the emplacement of intermediate to evolved magma that makes up the bulk of the Neogene activity. Second, those mafic magmas interacted with the crust, both bringing extra heat into, and causing sufficient localised melting of, those rocks to allow contamination to occur.

Projections from compositions of intermediate and evolved West Sarawak and Kalimantan Sintang rocks toward lower SiO_2 tend towards the more evolved end of the array of mafic rocks for all major elements (Fig. 5). This is particularly evident for Al_2O_3, TiO_2, and Na_2O, where the Borneo rocks diverge from the fields for high pressure melting experiments of hydrated basalt towards lower concentrations, and even more striking for the displacement to relatively high MgO contents (Fig. 5d). We propose that, rather than recording variable degrees of partial melting of hydrated basalt, the wide range of silica contents observed in the intermediate and evolved rocks from West Sarawak and Kalimantan reflects mixing of mantle-derived and crustal-derived magmas. The low-silica end of the array is directed towards input of mantle melts, which must have experienced some differentiation to produce the range from basalt through to low-silica andesite. This differentiation also involved interaction with crust to lower the Nb contents. The high-silica end of the West Sarawak and Kalimantan Sintang array is directed towards crustal melts, which appear to represent a restricted range of very high-silica compositions, in turn suggesting relatively low degrees of partial melting of hydrated basaltic crust. However, some of the scatter, particularly of Central Sintang rocks from Kalimantan, may reflect higher degrees of melting and/or involvement of more deeply derived crustal melts. The depth of melting would determine the strength of the adakitic signature i.e. the extent of the HREE-depletion, in the crustal contribution to each melt batch. Thus, for example, it is not paradoxical that intermediate rocks of the Central Sintang group have more elevated Sr/Y than the more silicic Bau Suite. This is simply a function of the crustal component in the Central Sintang magmas being derived from greater depth than the Bau Suite, but that these then mixed with a greater volume of mantle-derived mafic magma than occurred at Bau.

We conclude that the intermediate to evolved rocks from West Sarawak and Kalimantan are mixtures of mafic magma generated in the mantle with crustal melt derived from basalt that was originally hydrated or became so through subsequent metamorphism (Johnson et al., 1978; Smith et al., 1979; Rogers et al., 1985; Macpherson et al., 2006, 2010; Macpherson, 2008). As mixtures, it is difficult to place firm constraints on the depth at which crust melted because none of the intrusive rocks represent pure crustal melt. The presence of adakitic chemistry does indicate that zone of crustal melting extends across the garnet-in boundary.

7.3.4. Source of the crustal melt

There are various potential sources of hydrated basaltic rock in the Borneo crust. The Bau Suite intrudes crust that contains Triassic arc rocks (e.g. Serian Volcanics, Jagoi Granodiorite), attesting to prior arc activity which affected that lithospheric block (Schuh, 1993; Breitfeld et al., 2017). This Triassic block does not extend east across the whole area of the Sintang Suite (Breitfeld et al., 2017; Hennig et al., 2017), but the Schwaner Mountains granitoids represent a long-lived Mesozoic convergent margin (Williams et al., 1988; Davies et al., 2014; Hennig et al., 2017; Hall and Breitfeld, 2017 and references therein) at which basaltic magma could have been emplaced into the arc/forearc region that is now occupied by the Melawi and Ketungau basins, which host most Sintang intrusions (Figs. 2 and 11a). Alternatively, these basins may be partly underlain by accreted continental crust intruded by basaltic magmas and fragments of oceanic crust (e.g. Haile et al., 1994; Moss, 1998; Breitfeld et al., 2017). In either case there is scope for the Borneo crust to contain hydrated basaltic sources (Fig. 11a). The melanges observed at the margins of the Melawi and Ketungau basins are further evidence of the presence of basaltic rocks and the significant deformation they have experienced (Tan, 1979; Williams et al., 1988; Haile et al., 1994). Melting of such basalts could produce the felsic components of the Neogene intrusives in western Borneo by melting at higher pressures to produce adakitic magma, and at lower pressures to produce non-adakitic magma (Fig. 11a and b).

7.4. Cause of magmatism

We have discussed how the crustal thickening (Williams and Harahap, 1987) and/or melting of subducted crust (Prouteau et al., 2001) that have previously been proposed for the Sintang and Bau suites are inconsistent with the geology of Borneo (Section 2). Instead, we have identified that emplacement of these suites was accompanied by contemporaneous, mafic, mantle-derived magmatism. This magmatism, or the increased heatflow associated with it, was most probably responsible for causing crustal melting.

Roberts et al. (2018) suggested that the mantle beneath Borneo is hotter than ambient mantle but a hotspot origin can be discounted for the West Sarawak and Kalimantan Sintang magmatism. Postulated plumes with similar dimensions to the Sintang province tend to be associated with extensive, tholeiitic flood basalt magmatism and/or formation of large-scale batholiths and volcanoes (Coffin and Eldholm, 1994; Bryan and Ernst, 2008). In contrast, the Sintang and Bau suites form only isolated, and predominantly felsic, stocks, dykes, sills and rare lavas. Furthermore, hotspot models allow for a broadly distributed "plume head" stage giving way to more spatially-restricted magmatism, usually showing an age progression in a particular direction. However, the post-Miocene, mafic magmatism on Borneo – from Niut in the west to Semporna in the east – has an even broader geographic range than the Oligo-Miocene products (Fig. 2). We consider it highly unlikely that a hotspot could produce the widely dispersed, episodic Cenozoic magmatism in Borneo.

A west to east younging of Oligo-Miocene magmatism of western and central Borneo has been proposed by several studies (Kirk, 1968; Williams and Harahap, 1987; Schmidtke et al., 1990; Moss et al., 1998), but our new geochronological data suggest that this is not the case. First, the youngest part of this magmatism occurred in the west of Sarawak at Bau and around Kuching. Second, at Bau there are older magmatic zircons, similar in age to the West Sarawak Sintang intrusive rocks. Third, the West Sarawak Sintang intrusive rocks also show evidence of pulsed magmatism at individual sites, albeit over shorter timescales than previously proposed for the magmatic evolution of the whole area (Fig. 10a). Fourth, our U-Pb ages suggest that previous K-Ar data may have overestimated the spread of ages for magmatism (cf. Bawang and Serapi dykes). Fifth, U-Pb dating of Sintang-type magmatism elsewhere in Borneo has obtained ages of 19 to 20 Ma for igneous rocks in the Kelian district (Setiabudi et al., 2007; Davies et al., 2008). Although Kelian is about 500 km from Kuching (Fig. 2) the similarity of high-precision radiometric ages is striking and suggest a widespread, short-lived, Early Miocene magmatic episode across much of central Borneo.

7.4.1. Extension or transtension

The distribution of magmatism in western Sarawak appears to represent repeated exploitation of particular sites in the lithosphere by multiple phases of magmatism. Williams & Harahap (1987) proposed significant crustal control on the intrusion of the Sintang Suite in west Kalimantan, where they noted both that intrusions were aligned with one another and that larger intrusions tended to be associated with the central parts of basins. Similarly, the overall trend of the West Sarawak Sintang Suite suggests reactivation of WNW-ESE-directed faults of similar orientation to the Lupar Line (Fig. 2 and Fig. 11b). Schuh (1993) attributed the Bau Suite intrusions to one or two deep batholiths intruded along an existing, ENE-striking crustal weakness which he interpreted as a transtensional system. Stocks from this intrusion then intruded to shallower levels where an active, NNE-striking, regional, transtensional fault system intersected other existing structures in the crust. Thus, the actual emplacement of individual intrusive bodies now seen at the surface was controlled locally at relatively shallow scale. Evidence that this Bau trend has been a site of magmatism throughout the Neogene comes from the inherited 19 Ma zircon in TB61, and the resetting of some Bau zircon ages to the age of younger (c. 5 Ma), Niut magmatism, which lies along the same NNE-trending fault system (Harahap, 1994).

Association of magmatism with transtensional settings, similar to the Lupar Line fault system, is known from modern and ancient locations such as Death Valley, the Red River Fault, and the Midland Valley of Scotland (e.g. Calzia and Ramo, 2000; Monaghan and Parrish, 2006; Hussein et al., 2011). Crustal thinning associated with tension allows the mantle to upwell and, hence, melt (McKenzie and Bickle, 1988).

The timing of extension and crustal thinning in Borneo is best constrained by the depocentre of the Kuching Supergroup basins, which Breitfeld et al. (2018) interpreted as strike-slip basins. A transtensional component to this system could be indicated by the basement pop-up structures that bound these sedimentary basins. However, the Maastrichtian to Eocene ages of these deposits significantly pre-date the Oligo-Miocene magmatism studied in this paper (Fig. 10a). The Neogene igneous rocks are not deformed and indicate that significant movement along these faults had stopped prior to magma emplacement. Van Leeuwen et al. (1990) and Doutch (1992) proposed emplacement of the Sintang Suite in Kalimantan after folding of Eocene/Oligocene sediments, and Moss et al. (1998) concluded that they were emplaced immediately after a phase of deformation at about c. 25 Ma. Breitfeld et al. (2017) presented $^{40}Ar/^{39}Ar$ ages from white micas in schists south of Kuching, which can be interpreted as evidence of deformation in West Sarawak at c. 25 to 30 Ma. Therefore, the magmatism is unlikely to be associated with large scale active extension or transtension of the Borneo crust.

7.4.2. Lithospheric thinspots and plate motion

Basaltic magmatism can be generated by mantle melting beneath lithospheric thin spots, even in the absence of active extension. As long as there is a mechanism for mantle to rise into, and through, those thin spots, then melting can occur (King and Anderson, 1998). A number of studies have recently advocated plate motion as such a mechanism to allow such upwelling (Macpherson et al., 2010; Conrad et al., 2010, 2011; Ekici et al., 2012, 2014).

The lithosphere of Borneo is thinner than adjacent portions of the Sunda Shelf (Roberts et al., 2018) and the extensive Kuching depocentre implies that a broad swathe of crust between the Lupar Line and the Schwaner Mountains experienced substantial crustal thinning from the Cretaceous until the mid-Cenozoic (Eocene-Oligocene) (Fig. 11a). Thermal relaxation times mean that such thin spots would persist for the few million years until, at least, the Late Oligocene. Thus, any subsequent rotation or translation of Borneo relative to the underlying mantle (Hall et al. 2008; Hall and Spakman, 2015) could have caused mantle upwelling and melting where the thinning had been greatest. It is possible that the Lupar Line and related structures might have been reactivated at the time of magma emplacement to enhance the potential for upwelling, although there is no evidence to support this from the sedimentary record or deformation of the Oligo-Miocene intrusives rocks. The structural fabric of the basement could, however, have provided conduits for magma transport. This is evident in the tectono-magmatic relationships at Bau (Schuh, 1993) but is also seen in alignment of stocks in other areas of the Sintang Suite (Williams and Harahap, 1987). The resorbed, variably deformed quartz crystals found in the Bau granitoids would be consistent with assimilation of vein deposits contained in such basement fault networks.

7.5. Adakites without subduction

Their presence in continental collision zones with substantially thickened crust should provide prima facie evidence that not all magmatic rocks with adakitic chemistry can be treated as evidence of slab melting (Chung et al., 2003; Hou et al., 2004; Guo et al., 2007). Outside collision zones, the sources of adakitic magmatism are more controversial, but we have noted the absence of evidence for subduction in western Borneo for several tens of millions of years before the Sintang and Bau magmas were emplaced. Furthermore, the petrogenetic model most consistent with their composition does not support or require a subducted slab. Instead, melting of hydrous basaltic rock in the lithosphere of Borneo is the most probable cause of these rocks. Our findings extend the range of known non-subduction occurrences of adakite emplacement to a continental block that has not experienced significant, prior or contemporaneous crustal thickening.

Borneo is not the first non-collisional location where adakitic rocks have been documented with an absence of contemporaneous subduction (Johnson et al., 1978; Smith et al., 1979; Rogers et al., 1985; Sajona et al., 2000). The cause of magmatism in these other settings has been difficult to ascertain due to subduction ceasing only recently before adakite emplacement and the potential for remnants of subducted oceanic lithosphere in the subjacent mantle (Sajona et al., 2000; Haschke and Ben-Avraham, 2005). Our findings for Borneo suggest that, rather than considering the subducted plate, melting of the upper plate should be considered as a possible source for such adakites. In each of these cases, adakitic magmas were emplaced into tectonically active blocks and in several cases were accompanied by basaltic magmatism. Therefore, Borneo may provide a better analogue for formation of those adakites than examples found in active subduction zones.

These conclusions indicate that adakitic chemistry alone should not be used as a direct proxy for slab melting, either in modern or ancient subduction zones. In the case of Borneo, hydrated basaltic rocks were emplaced and then remained undisturbed for many tens of millions of years, if produced by the Schwaner Mountain margin, or even hundreds of millions of years, if produced by the Triassic margin that generated the Serian Volcanics and the Jagoi Granodiorite. Thus, while it is reasonable to infer that subduction produced the hydrated, mafic rocks in the crust of Borneo from which the adakitic signature was derived, this required no more melting of a subducted slab than has been inferred to produce non-adakitic arc tholeiites and andesites (Macpherson et al., 2006; Plank et al., 2009; Bouilhol et al., 2015). Furthermore, for any location, it is not possible to conclude that the emplacement of such hydrous, mafic sources was contemporaneous with generation of the adakites themselves, without considering the prior history of the margin. Similarly, the presence of adakitic magma or rocks in modern subduction zones should not be taken as unequivocal evidence that current slabs are unusually hot. Our findings from Borneo suggest that remelting of hydrous, mafic rock produced during an earlier stage of the same margin or during the earlier history of the overriding plate should also be considered (Macpherson et al., 2006).

Conclusions

1. Neogene magmatism in West Sarawak produced the Lower Miocene West Sarawak Sintang Suite with ages of c. 19 to 21 Ma and the Middle Miocene Bau Suite with ages of c. 12 to 14

Ma (that could extent into the early Late Miocene). Inherited zircons in the West Sarawak Sintang Suite suggest magmatism was active by c. 24 Ma.

2. The Neogene magmatism was not related to active subduction. Geochemistry shows an adakite character for the Bau Suite while the Sintang Suite samples plot predominantly outside the adakite field. The latter appear to be part of a broader magmatic suite in west and central Borneo that does include other instances of adakitic rocks. The geochemical character of both suites is consistent with remelting of hydrous mafic rocks in the lithosphere of Borneo that were emplaced as arc basalt tens or hundreds of millions of years previously. Melting across a range of depths, from the mid- to deep-crust and the shallow lithospheric mantle, produced the range of geochemical compositions observed in the Sintang and Bau Suites.
3. The Neogene magmatism of west Kalimantan included a mafic component bearing within-plate trace element signatures. The mechanisms that generated this magmatism could have provided the heat to re-melt the crust, which yielded the intermediate and evolved intrusive rocks of the Sintang and Bau suites.
4. Production of the intraplate magmatism was the result of mantle upwelling into lithospheric thinspots. These may have been relicts from the extension which formed the Melawi and Ketungau basins and/or products of contemporaneous extension/transtension. In the absence of strong evidence for the latter, upwelling into thin spots as the plate migrated is most likely to have produced the intraplate magma.
5. Inherited zircons within the samples are consistent with the ancient basement of Borneo playing a role in the petrogenesis of the Neogene magmatic suite of western Borneo.

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Figure Captions

Fig. 1: Tectonic provinces of NW Borneo (modified after Haile, 1974; Hennig et al., 2017). The red frame shows the outline of Sintang Suite. The West Borneo basement (Triassic Sundaland) underlies also the western part of the Kuching Zone.

Fig. 2: Cenozoic magmatism in Borneo. Grey shaded area shows the outline of the Neogene igneous rocks. Distribution and ages from Kirk (1968), Williams and Harahap (1987), Pieters et al. (1987), van de Weerd et al. (1987), Setiawan and Le Bel (1987), Bladon et al. (1989), van Leeuwen et al. (1990), Heng (1992), Moss et al. (1998), Prouteau et al. (1996, 2001), Hutchison (2010) and Cullen et al. (2013).

Fig. 3: Uppermost Cretaceous to Cenozoic igneous rocks of West Sarawak with sample locations of the West Sarawak Sintang Suite and the Bau Suite. Map is based on fieldwork observations and on the geological map of Liechti et al., (1960), Heng (1992) and Hutchison (2005). Samples in bold and underlined are dated by U-Pb zircon geochronology. (Exact location of BYG8 is not known).

Fig. 4: Field photographs and thin section photomicrographs of Neogene igneous rocks in West Sarawak. a) Granodiorite sill at the northern tip of Tanjung Santubong intruding Paleocene sediments of the Kayan Sandstone. b) Rhyolite/rhyodacite exposure north of Gunung Serapi. c) Columnar jointed micro-granodiorite dyke of Gunung Bawang. d) Zoomed in of rhyolite lava. e) Abundant plagioclase needles and crystals with xenomorphic biotites (crossed polars; TB58). f) Epidote pseudomorph after amphibole (plane polars; TB148a). g) Monocrystalline undulose volcanic quartz with embayments and inclusions (crossed polars; TB18). h) Alkali feldspar phenocryst with twinning and sericite alteration (crossed polars; TB18). i) Intergrowth of plagioclase phenocrysts (crossed polars; TB209a). j) Subhedral clinopyroxene phenocryst (plane polars; TB161). k) Subhedral plagioclase phenocryst (crossed polars; TB9). l) Biotite with alteration corona, plagioclase and quartz phenocrysts in quartz-sericite matrix (plane polars; TB61). m) Highly rounded quartz grain, plagioclase and hornblende phenocryst (crossed polars; BYG12). (Bt = biotite, Plg = plagioclase, Ep = epidote, Am = amphibole, Qv = volcanic quartz, Kfs = alkali feldspar, Cpx = clinopyroxene, Ser = sericite, Hbl = hornblende).

Fig. 5: Major element variations in igneous rocks from Bau and Kuching from this work and compared with previously published data for these locations (P; Prouteau et al., 2001). Sintang Suite from northwest Kalimantan divided into Northern, Central, Southern and unattributed (NW Kalimantan) from Williams and Harahap (1987) and Harahap (1993). Basalt and basaltic andesite from Tawau on the Semporna Peninsula, NE Borneo (Macpherson et al., 2010). Hydrated basalt melting experiments at high-pressure under fluid-present melting conditions (H_2O-pres; Winther and Newton, 1991), and dehydration melting conditions at and above 8 kbar (DehydMelt; Rapp and Watson, 1995). In panel b) only experimental equilibration of slab melt with peridotite (AB-1 + AVX; Rapp et al., 1999). ASI is aluminium saturation index [Al / (Ca + Na + K)].

Fig. 6: Incompatible trace elements contents of Borneo igneous rocks normalised to N-MORB (Sun and McDonough 1989). a) Intrusive rocks from Kuching. b) Volcanic rocks from Kuching with one Kuching intrusive rock (TB 58) for comparison. c) Bau intrusive rocks with Kuching intrusive (TB 58)

for comparison. d) Intermediate rocks from Kuching and Bau compared to representative rocks from Northern (N), Central (C), and Southern (S) groups of Kalimantan Sintang intrusives (Harahap, 1993). Comparators from different locations were chosen for their similar SiO_2 to the specimens from the primary location displayed on each panel.

Fig. 7: a) Incompatible trace elements normalised to N-MORB (Sun and McDonough 1989) for the least silicic sample from Kuching (TB 23) compared with basaltic or basaltic andesite sample from the Northern and Southern Sintang groups of Kalimantan (Harahap, 1993) and Semporna Peninsula, NE Borneo (Macpherson et al., 2010). b) Y vs Sr/Y plot showing the adakite field (after Defant and Drummond, 1990). Shaded areas are literature data from *Prouteau et al. (2001) and Williams and Harahap (1987) and **Thompson et al. (1994), Simmons and Browne (1990), Harahap (1993), Heryanto et al. (1993) and Moss et al. (1998). Bau Suite samples fall predominantly in the adakite field, while the West Sarawak Sintang Suite samples are mainly outside the field.

Fig. 8: U-Pb zircon age dating for the West Sarawak Sintang Suite - intrusive rocks. a) Sample TB63b dated as 21.1 ± 0.2 Ma. b) Sample TB58 dated as 20.3 ± 0.2 Ma. c) Sample TB33 dated as 20.1 ± 0.2 Ma. Colour code for circles in the Tera-Wasserburg plot: red – concordant, black – discordant, grey – concordant, discount for weighted mean age calculation due to inheritance, large uncertainty or slight Pb loss.

Fig. 9: U-Pb zircon age dating for the West Sarawak Sintang Suite - volcanic rocks (a, b) and the Bau Suite (c, d). a) Sample TB141 dated as 19.8 ± 0.3 Ma. A slightly older population is dated as 21.5 ± 0.4 Ma. Only concordant ages are displayed. b) Sample TB209a dated as 18.6 ± 0.2 Ma. c) Sample TB9 is dated as 14.1 ± 0.1 Ma (only 24 ages are displayed to improve the display). d) Sample TB61 is dated as 12.4 ± 0.9 Ma. Both samples have a younger zircon at c. 5 Ma that is interpreted as lead-loss due to hydrothermal overprint.

Fig. 10: a) Summary of high precision ages for the Neogene magmatism in Borneo. Red colour indicates crystallisation ages. Yellow colour indicates inheritance (slightly older ages). For inheritance

ages of Phanerozoic to Precambrian age see Figure 13. (Note: Period/Epoch is not to scale).* Mukah tuff U-Pb zircon LA-ICP-MS data from Ramkumar et al. (2018). ** Kelian volcanics U-Pb LA-ICP-MS zircon data from Setiabudi et al. (2007) and Davies et al. (2008). *** Temburong tuff U-Pb zircon LA-ICP-MS data (S. Burley, pers. comm., 2018). b) Age histogram of all inherited U-Pb zircon ages analysed in the upper Cenozoic magmatic rocks derived by re-melting of basement. Mesozoic ages resemble the Schwaner Mountains, the Jagoi Granodiorite, the Sadong and Kuching Formations and other Triassic rocks of NW Kalimantan (Davies et al., 2014; Breitfeld et al., 2017; Hennig et al., 2017). Proterozoic ages indicate a heterogeneous basement.

Fig. 11: a) Schematic diagram of western Borneo showing the genesis of adakitic and non-adakitic melts. Mantle upwelling into lithospheric thinspot results in melting of crust and intra-plate basalt at various depths. The zones of melting are bounded by deep rooted faults that are associated with the large sedimentary basins in Kalimantan (Melawi) and Kalimantan-Sarawak (Ketungau). b) Schematic block diagram of the Neogene magmatism in West Sarawak. Early Miocene Sintang Suite associated with the Lupar fault trend is dominated by non-adakitic melts. Melting occurs above the garnet-in boundary. Middle Miocene Bau Suite is associated with the Bau fault trend and dominated by adakitic melts. Melting occurs in deeper levels below the garnet-in boundary.

Table Captions

Tab. 1: Major and trace element concentrations for West Sarawak Sintang Suite and Bau Suite. All data from XRF analyses, except [a)], which are from ICP-MS analyses. LOI = loss on ignition. (**estimated uncertainty is the largest of the absolute ± error and the percentage error.)

Tab. 2: Summary of U-Pb zircon dating of this study, subdividing the Neogene igneous rocks into the Lower Miocene West Sarawak Sintang Suite (intrusive and volcanic rocks) and into the Middle Miocene Bau Suite.

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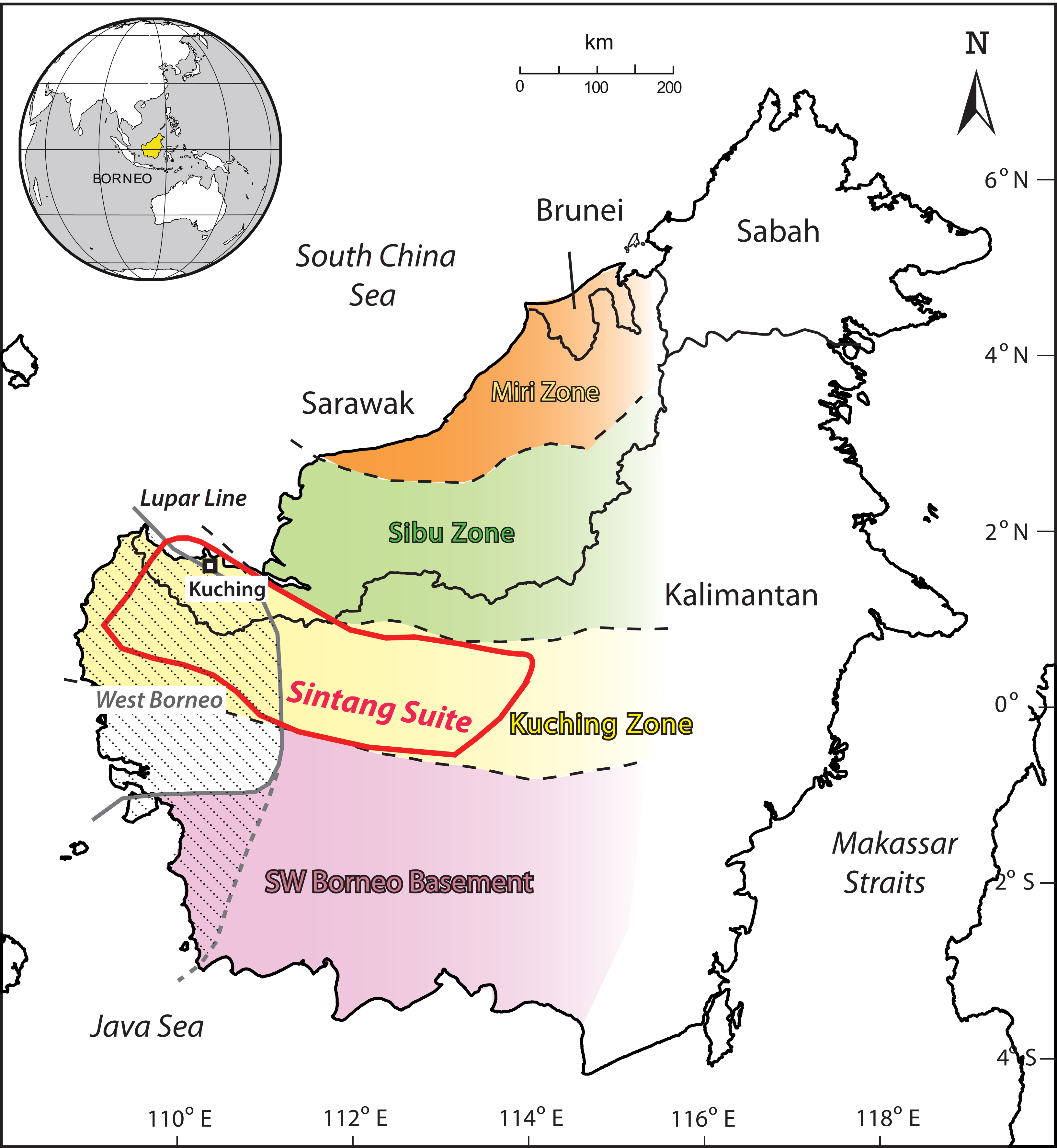
Figure 1



BORNEO
km
0
100
200
N
6° N
4° N
2° N
0°
2° S
4° S
110° E
112° E
114° E
116° E
118° E
Brunei
Sabah
South China Sea
Sarawak
Miri Zone
Sibu Zone
Lupar Line
Kuching
Kalimantan
West Borneo
Sintang Suite
Kuching Zone
SW Borneo Basement
Makassar Straits
Java Sea

Figure 2

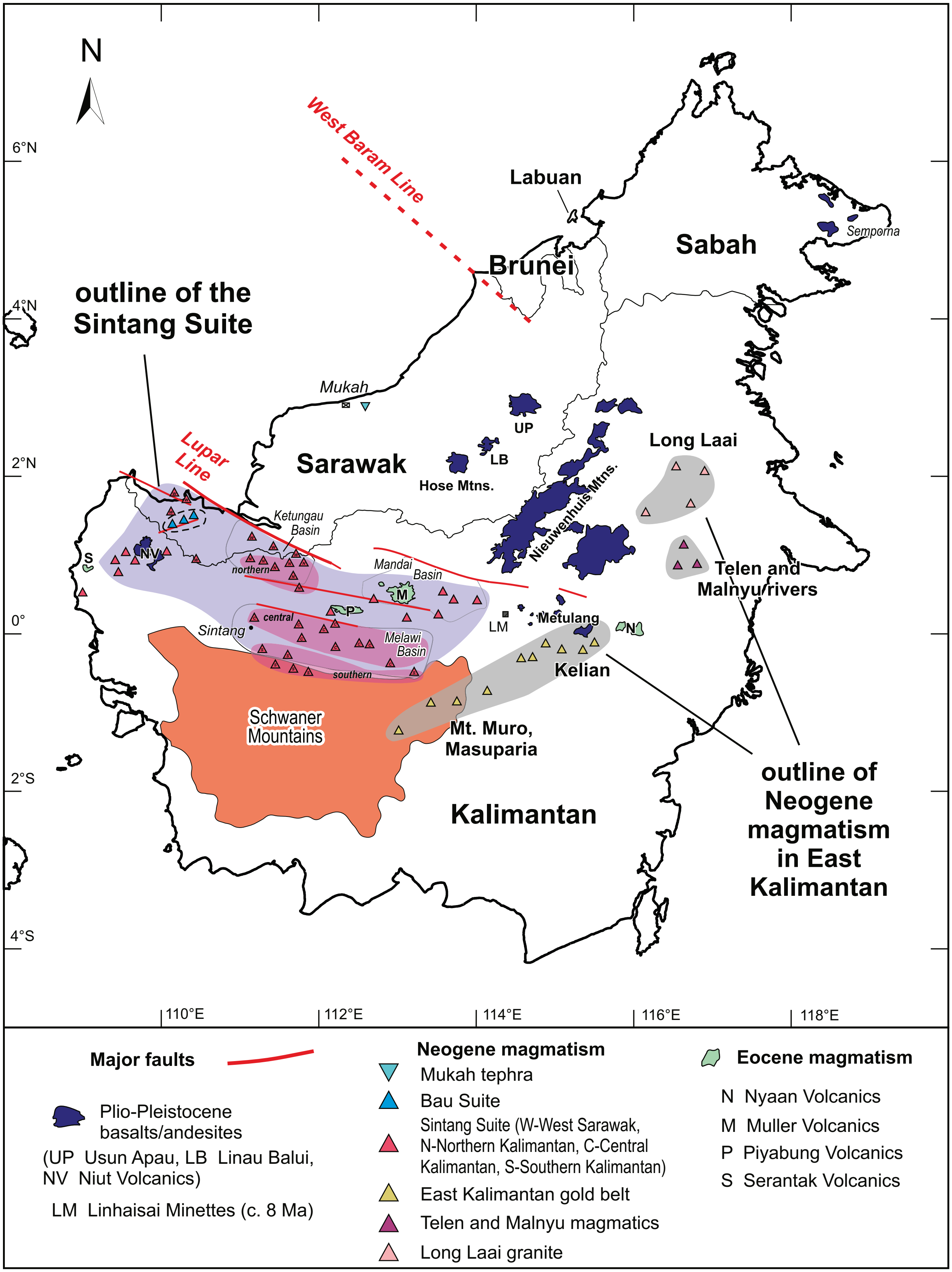


Fig. 2

Figure 3

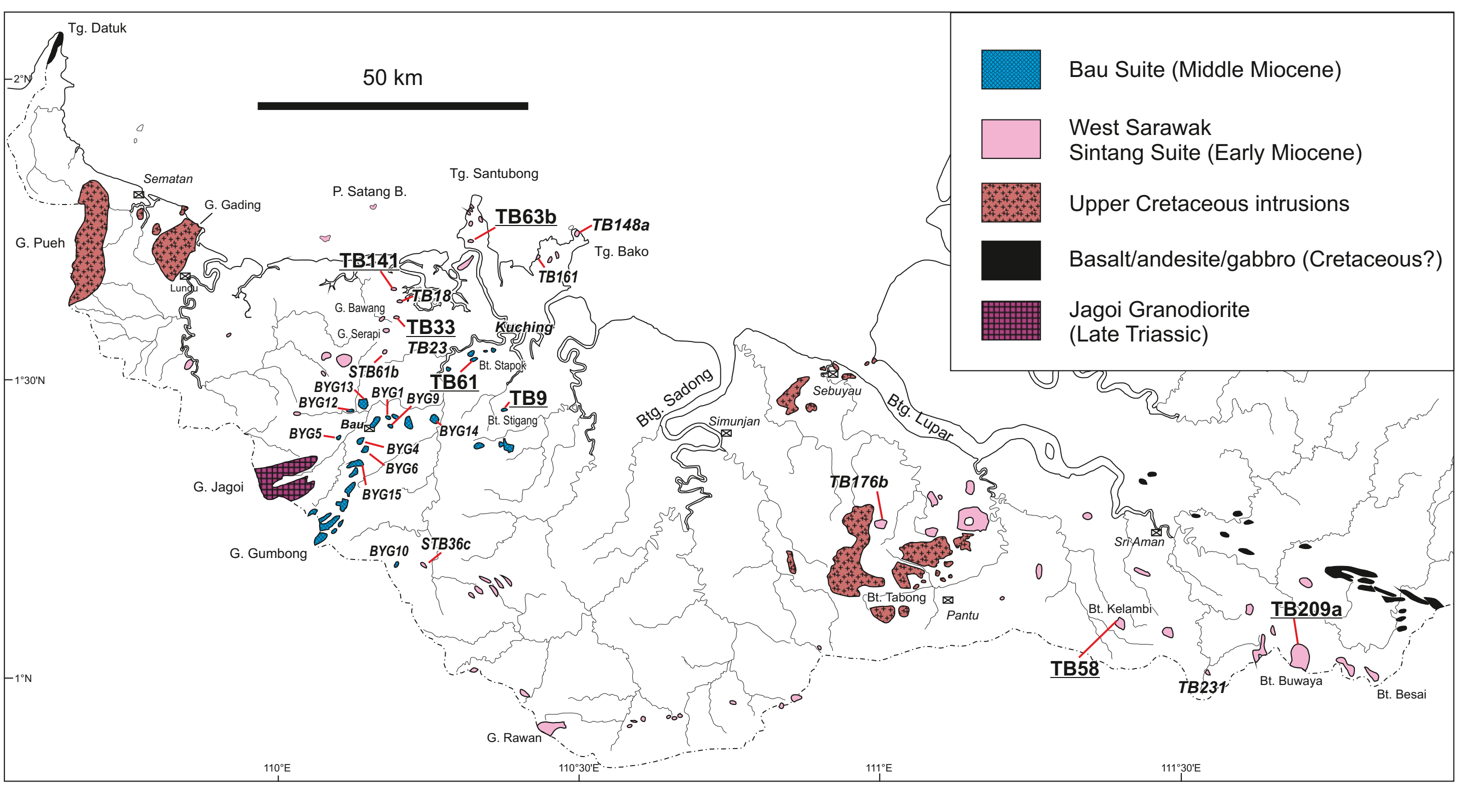


Fig. 3

Figure 4

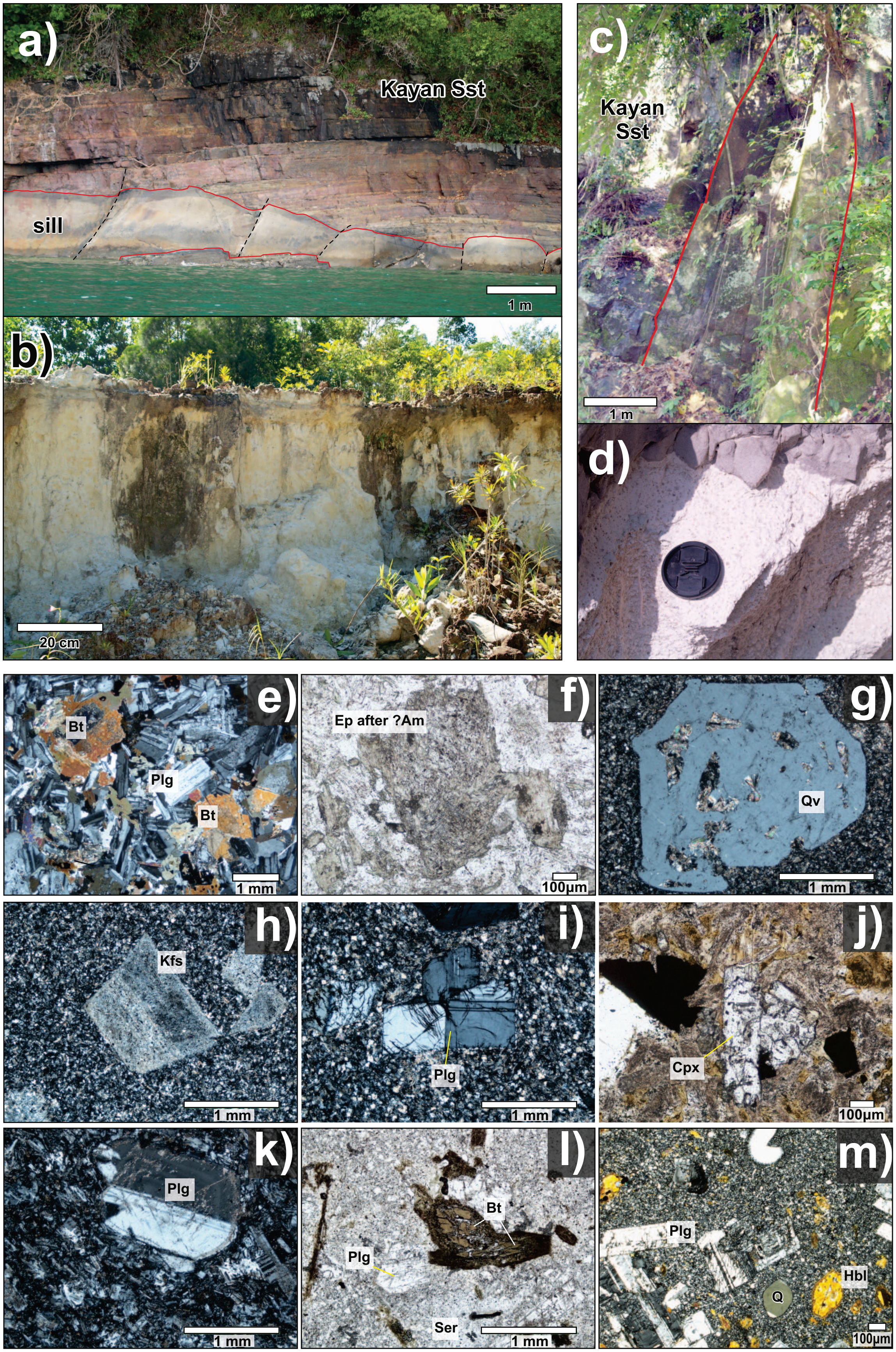
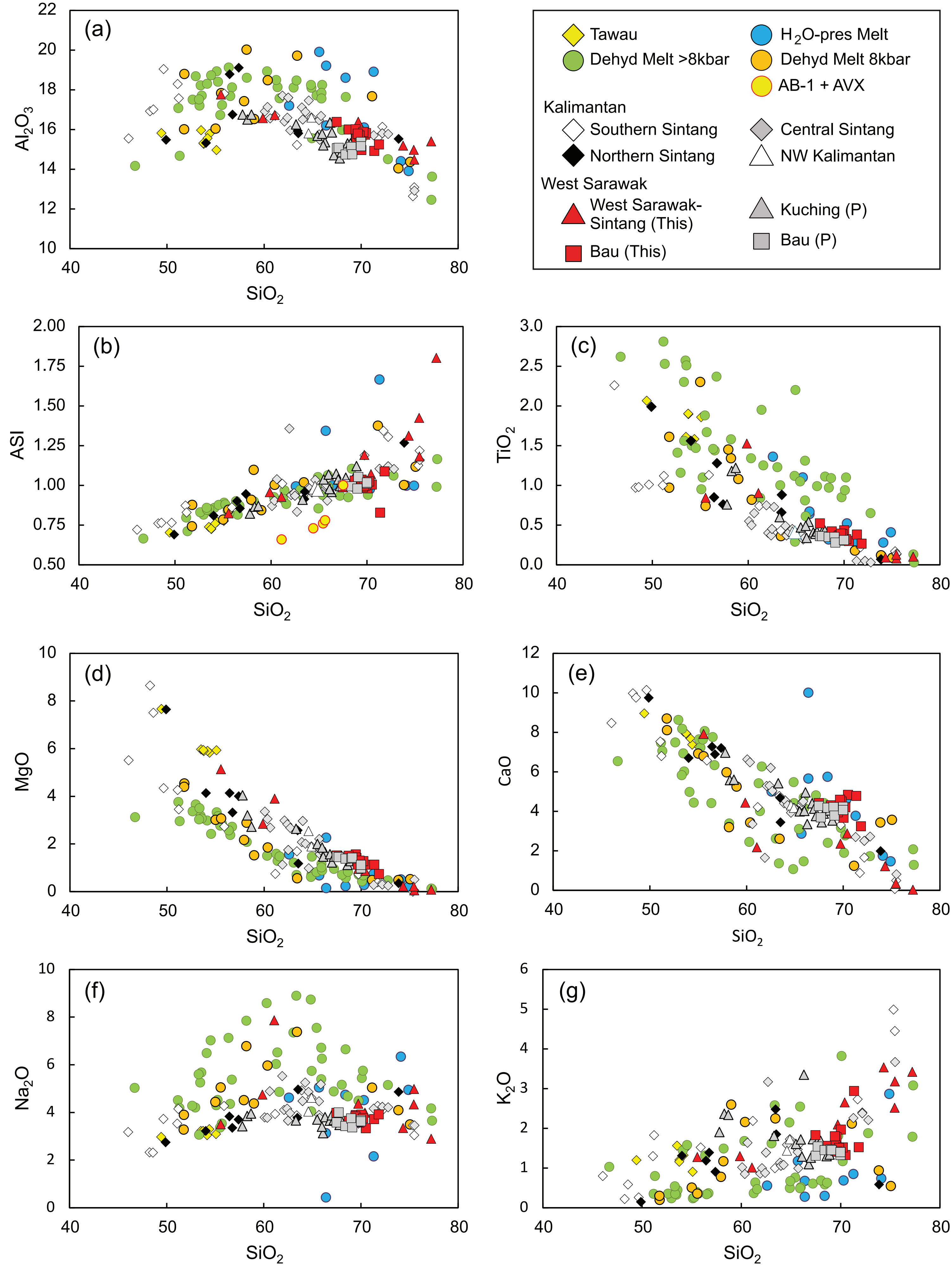


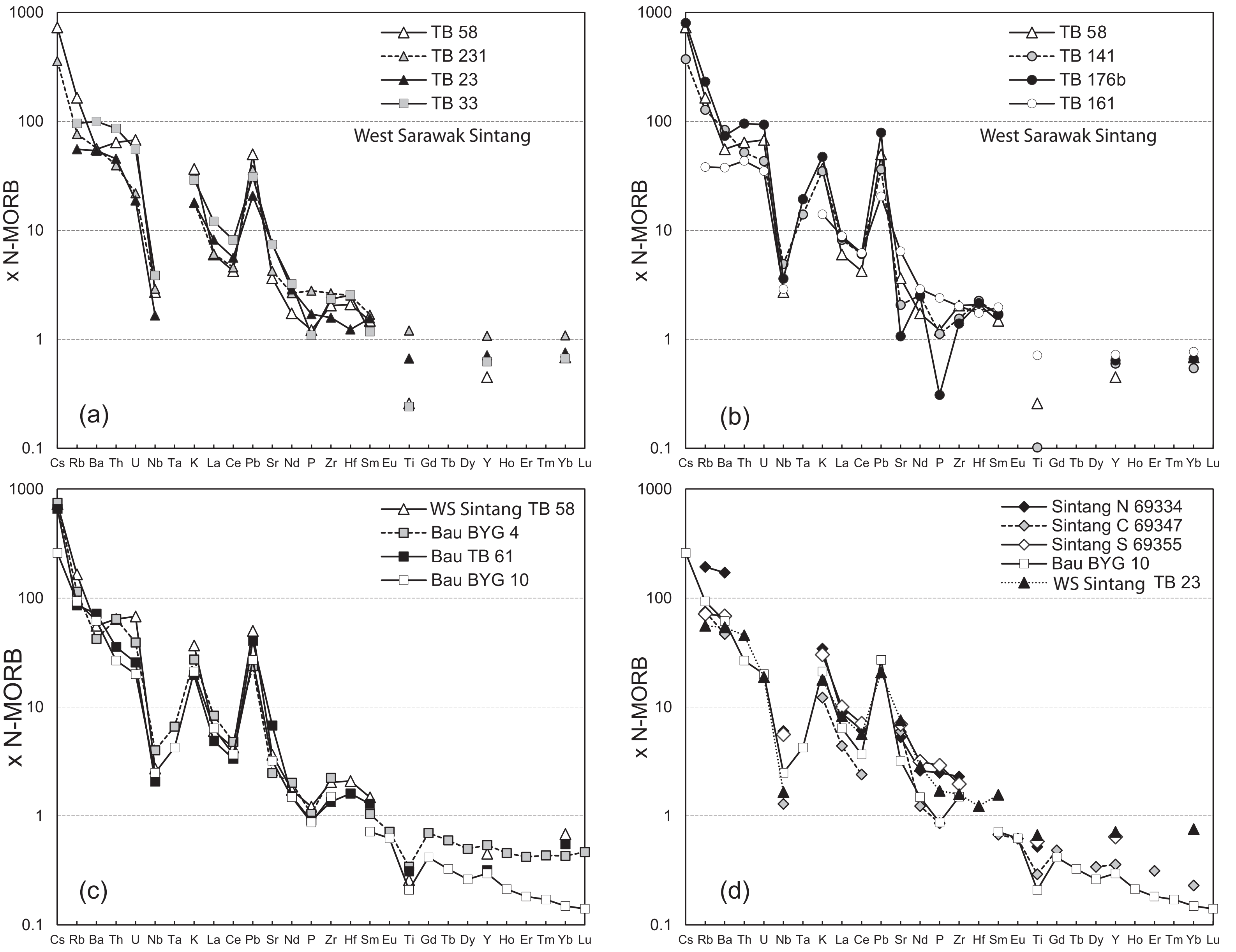
Fig. 4

Figure 5



(a)
Al_2O_3
SiO_2
Tawau
Dehyd Melt >8kbar
H_2O-pres Melt
Dehyd Melt 8kbar
AB-1 + AVX
Kalimantan
Southern Sintang
Central Sintang
Northern Sintang
NW Kalimantan
West Sarawak
West Sarawak-Sintang (This)
Kuching (P)
Bau (This)
Bau (P)
(b)
ASI
(c)
TiO_2
(d)
MgO
(e)
CaO
(f)
Na_2O
(g)
K_2O

Figure 6



(a)
TB 58
TB 231
TB 23
TB 33
West Sarawak Sintang
x N-MORB
1000
100
10
1
0.1
Cs Rb Ba Th U Nb Ta K La Ce Pb Sr Nd P Zr Hf Sm Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu
(b)
TB 58
TB 141
TB 176b
TB 161
West Sarawak Sintang
x N-MORB
1000
100
10
1
0.1
Cs Rb Ba Th U Nb Ta K La Ce Pb Sr Nd P Zr Hf Sm Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu
(c)
WS Sintang TB 58
Bau BYG 4
Bau TB 61
Bau BYG 10
x N-MORB
1000
100
10
1
0.1
Cs Rb Ba Th U Nb Ta K La Ce Pb Sr Nd P Zr Hf Sm Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu
(d)
Sintang N 69334
Sintang C 69347
Sintang S 69355
Bau BYG 10
WS Sintang TB 23
x N-MORB
1000
100
10
1
0.1
Cs Rb Ba Th U Nb Ta K La Ce Pb Sr Nd P Zr Hf Sm Eu Ti Gd Tb Dy Y Ho Er Tm Yb Lu

Figure 7

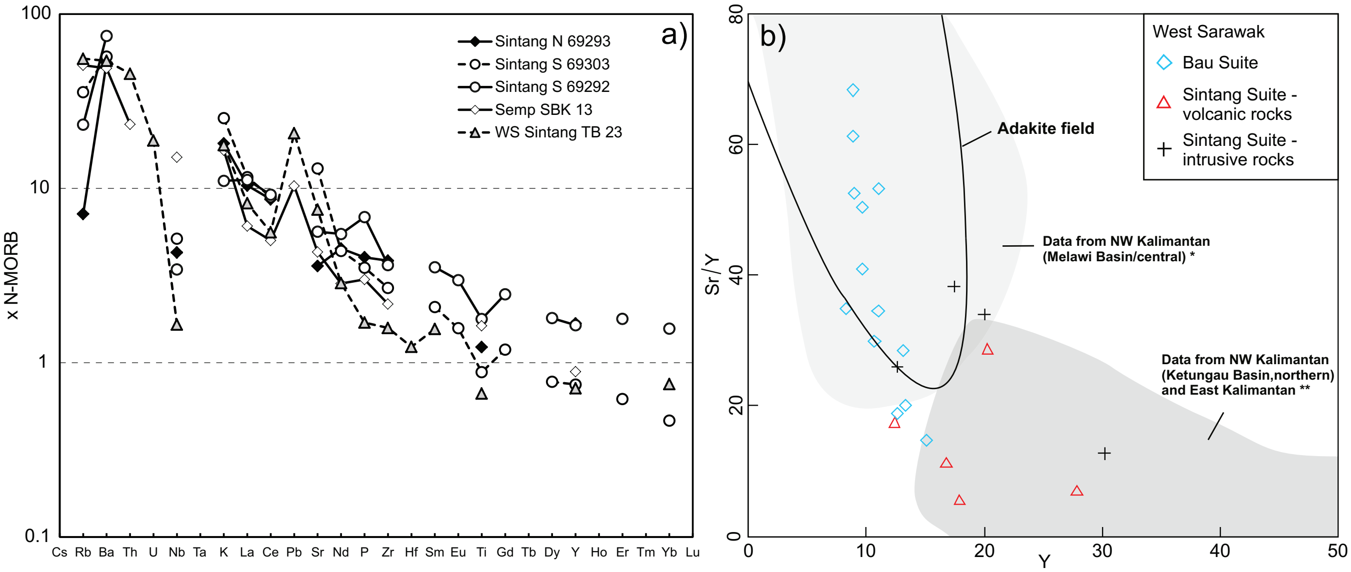


Fig. 7

Figure 8

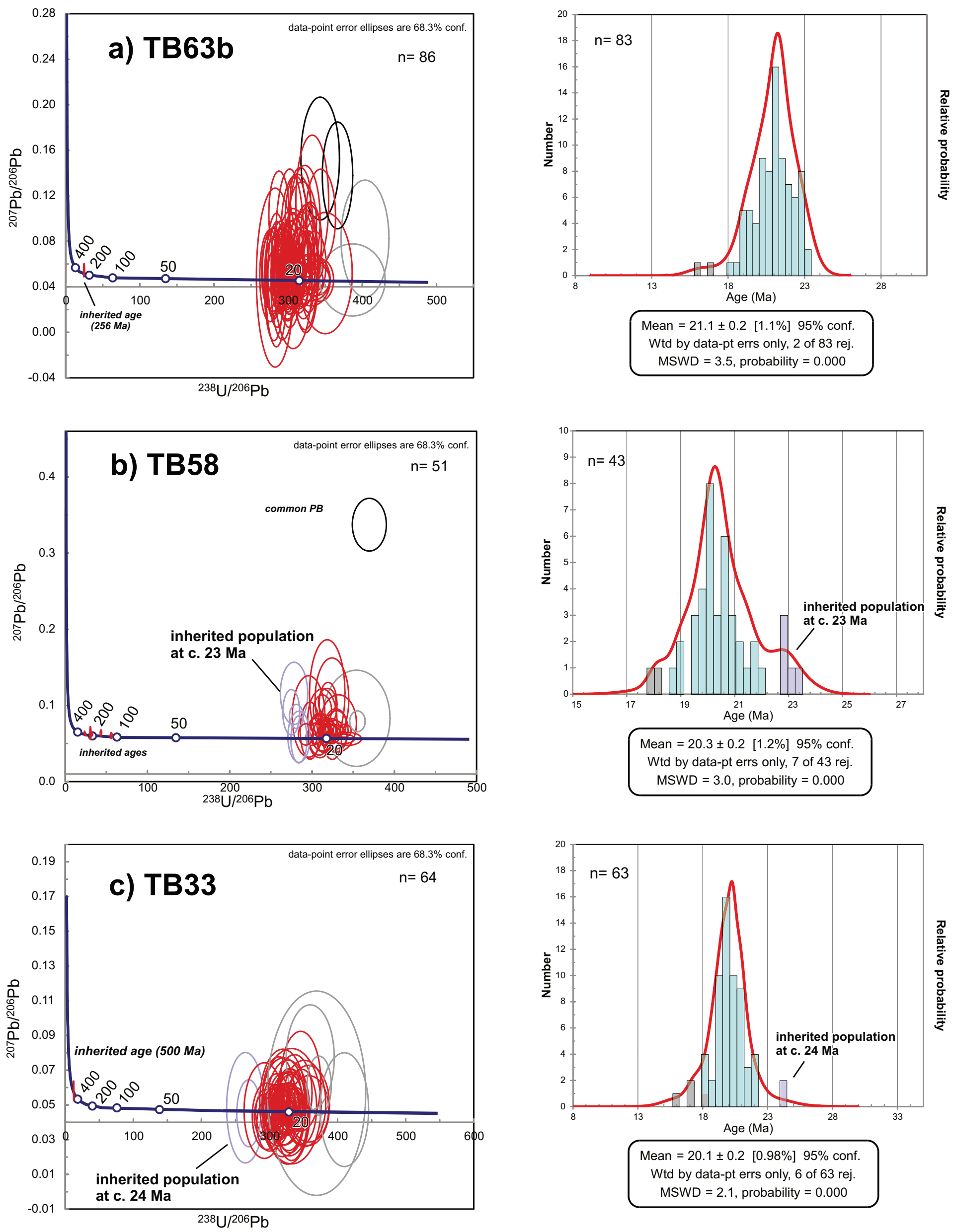


Fig. 8

Figure 9

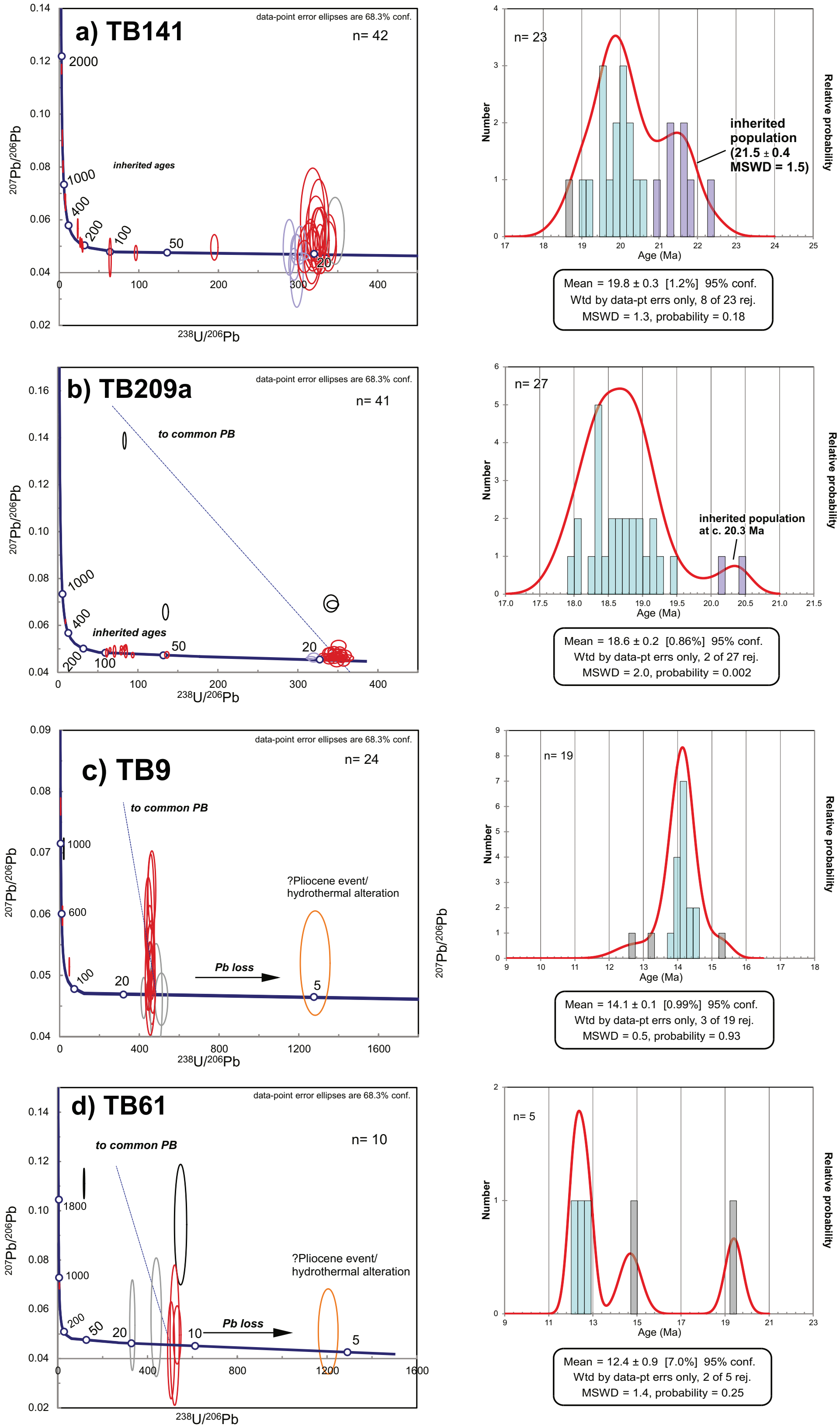


Fig. 9

Figure 10

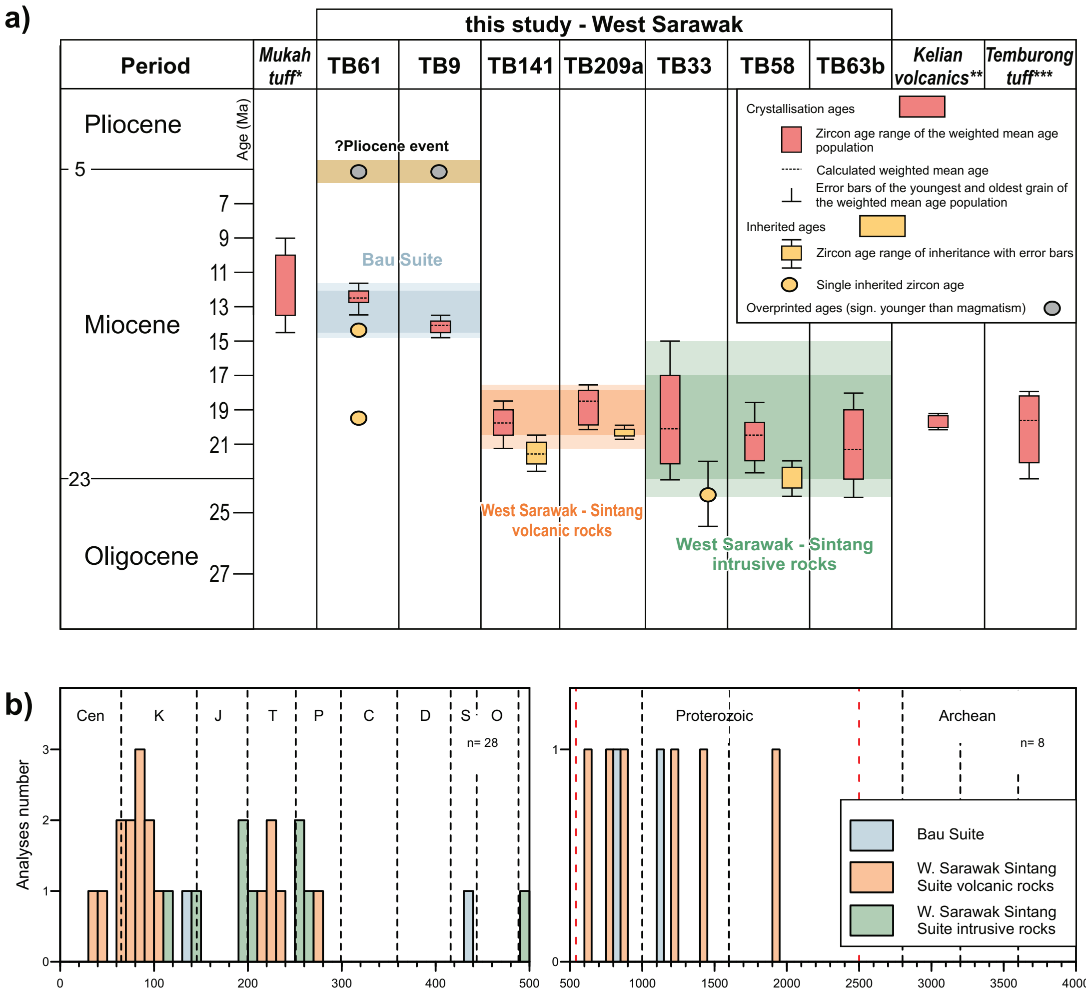
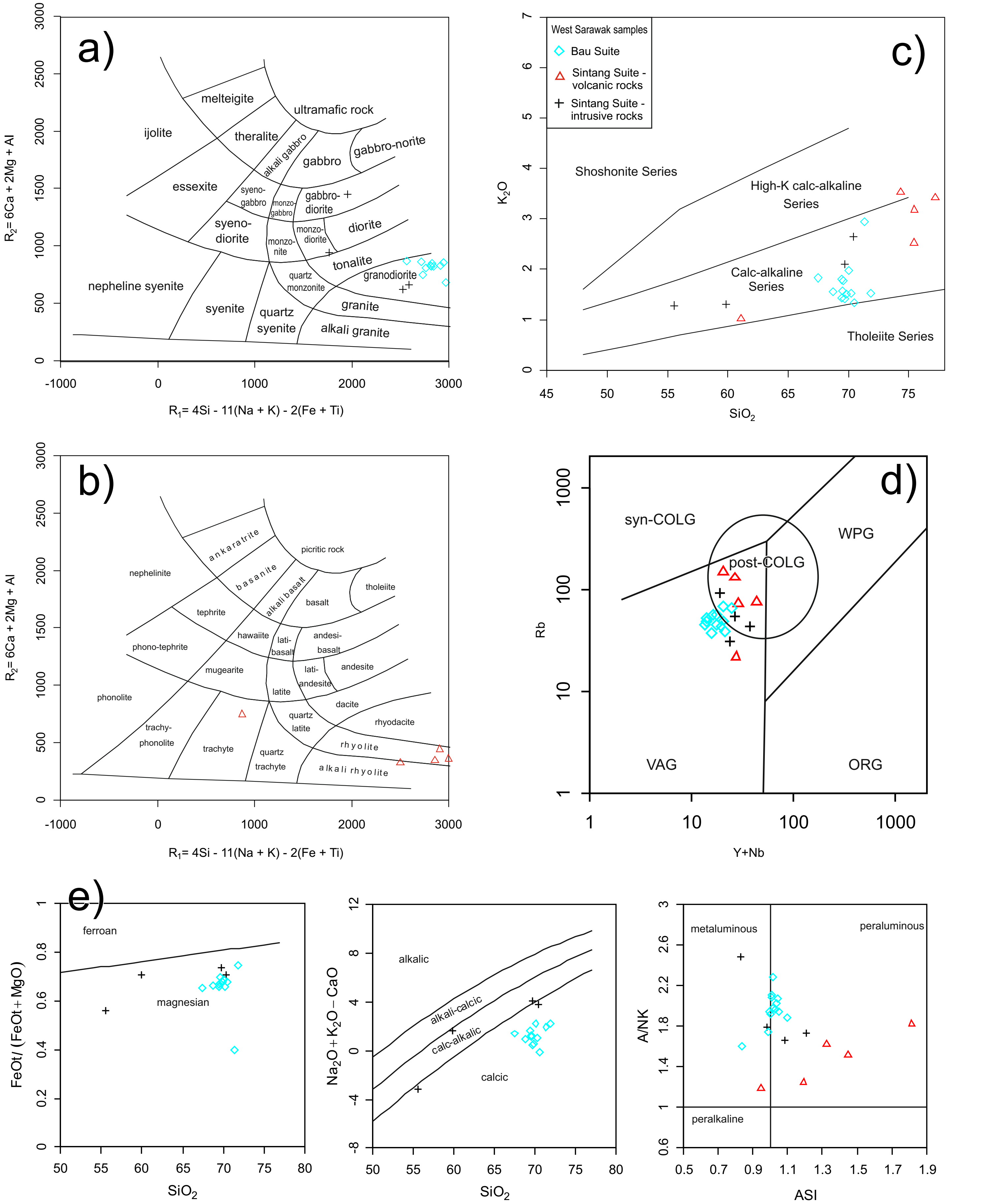


Fig. 10

Group	West Sarawak Sintang Suite									Bau Suite														
Sample	**TB176b**	**TB18**	**TB141**	**TB209a**	**TB161**	**TB58**	**TB33**	**TB231**	**TB23**	**TB61**	**TB9**	**BYG1**	**BYG4**	**BYG5**	**BYG6**	**BYG8**	**BYG9**	**BYG10**	**BYG12**	**BYG13**	**BYG14**	**BYG15**	**± 2sd**	**% 2sd**
Rock type	rhyolite	rhyo-dacite	rhyolite	rhyolite	trachy-dacite	grano-diorite	micro-grano-diorite	monzo-diorite	gabbro-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	grano-diorite	**XRF reproducibility (estimated)****	
Character	calc-alkaline	calc-alkaline	calc-alkaline	high-K calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline	calc-alkaline		
SiO_2	77.22	75.47	75.44	74.34	61.09	70.42	69.72	59.87	55.57	69.67	67.49	69.47	70.04	70.51	71.36	69.59	68.73	71.84	69.52	69.44	70.24	69.85	0.25	
Al_2O_3	15.40	14.48	14.97	15.18	16.72	15.74	16.38	16.57	17.76	15.78	16.38	15.68	14.96	15.81	14.91	15.70	15.99	15.24	15.58	16.00	15.87	15.69	0.12	
Fe_2O_3	0.44	0.26	1.38	1.01	5.65	2.33	2.94	7.56	7.28	2.91	3.19	3.37	3.08	2.63	0.83	2.88	3.30	2.44	3.18	3.04	2.74	3.01	0.05	
MgO	0.09	0.06	0.21	0.22	3.90	0.87	0.95	2.84	5.13	1.13	1.51	1.56	1.27	1.13	1.13	1.27	1.50	0.74	1.41	1.43	1.28	1.30	0.04	
CaO	0.03	0.32	0.35	1.22	2.18	2.88	2.36	4.44	7.91	4.58	4.41	4.09	3.67	4.83	4.77	4.28	4.30	3.24	4.18	3.95	4.20	4.49	0.03	
Na_2O	2.90	4.99	4.34	3.35	7.87	3.99	4.36	4.75	3.51	3.61	3.98	3.89	3.91	3.34	3.72	3.75	3.65	3.92	3.76	3.83	3.76	3.58	0.05	1.0
K_2O	3.42	3.18	2.52	3.53	1.02	2.65	2.10	1.30	1.28	1.41	1.83	1.43	1.97	1.33	2.94	1.78	1.56	1.53	1.57	1.80	1.52	1.51	0.005	0.3
TiO_2	0.102	0.081	0.129	0.091	0.903	0.327	0.306	1.527	0.844	0.393	0.520	0.362	0.434	0.300	0.382	0.347	0.419	0.265	0.369	0.363	0.323	0.386	0.004	0.5
MnO	0.008	0.011	0.083	0.073	0.119	0.029	0.098	0.145	0.121	0.051	0.046	0.061	0.061	0.063	0.038	0.071	0.064	0.044	0.074	0.062	0.062	0.058	0.003	
P_2O_5	0.036	0.068	0.131	0.076	0.281	0.142	0.128	0.326	0.199	0.105	0.175	0.121	0.122	0.105	0.121	0.125	0.131	0.102	0.125	0.137	0.105	0.149	0.003	
SO_3	0.014	0.014	0.010	0.014	0.017	0.030	0.017	0.034	0.018	0.014	0.024												0.005	
Total	**99.65**	**98.93**	**99.57**	**99.12**	**99.75**	**99.41**	**99.36**	**99.36**	**99.62**	**99.65**	**99.55**	**100.04**	**99.52**	**100.05**	**100.20**	**99.79**	**99.65**	**99.36**	**99.77**	**100.05**	**100.10**	**100.02**		
LOI	1.91	0.69	1.98	1.51	1.67	0.78	1.48	2.63	0.64	4.03	2.35	1.81	4.46	4.87	0.89	3.40	1.79	1.30	1.24	2.73	0.98	4.27	0.1	
Ni	2.1	1.6	1.8	1.6	55.2	4.5	7.9	22.4	43.1	8.3	19.9	26.3	22.5	17.9	22.50	14.50	18.9	24.0	26.5	17.7	14.7	14.0	0.5	2.0
Co	<1	7	9	2	27	8	7	19	31	9	10												1.0	5.0
Cr	<2	<2	<2	3	90	6	6	21	58	13	32	25	21	16	17	13	11	3	21	19	15	8	1.0	2.5
V	2	<2	2	3	136	26	26	199	180	47	57	49	40	39	33	38	54	22	41	45	37	42	1.0	1.5
Sc	<1.2	1.3	<1.2	2.2	15.2	3.7	3.2	21.9	22.4	7.8	7.4	8.6	6.4	6.6	5.8	6.7	8.4	3.3	7.9	7.1	6.8	6.7	0.5	4.0
Cu	2	1	2	2	24	37	4	74	26	12	36	22	15	9	3	11	8	7	17	20	14	15	0.5	1.0
Zn	26	7	32	50	47	26	42	80	100	45	53	52	47	46	23	43	47	38	52	50	44	51	0.7	1.0
As	0.3	0.2	<0.2	1.8	1.7	1.6	0.3	0.9	0.6	1.2	0.4												0.4	
S	38	7	75	33	315	1314	35	98	66	18	65												10.0	4.0
F	274	335	327	129	329	249	158	289	383	196	352												20.0	
Cl	59	37	95	71	4798	511	93	312	715	69	52				161								10.0	4.0
Br	0.4	0.4	0.3	0.4	6.2	0.9	0.4	0.5	0.5	0.3	0.1												0.2	5.0
Ga	16.4	15.0	16.3	15.6	21.2	14.6	16.7	19.6	18.2	15.6	19.0	16.6	15.9	15.3	14.8	17.2	16.8	15.4	17.2	16.2	15.8	16.5	0.4	
Pb	23.7	11.6	10.9	30.4	6.1	15.0	9.3	10.8	6.2	12.1	10.2	9	7.1	8.7	7.7	10.2	6.8	8.1	9.0	8.2	10.2	7.3	0.3	1.5
Sr	96.1	190.6	186.4	213.3	577.3	326.8	666.7	382.8	680.3	606.3	587.2	397.6	222.6	472.8	372.5	380.4	237.1	289.2	320.2	488.7	546.1	267	0.2	0.4
Rb	130	76	72	148	21	93	54	43	31	48	49	38	64	44	68	55	43	52	45	56	51	39	0.1	0.4
Ba	464	639	526	586	237	350	628	359	340	452	307	404	265	369	457	402	300	388	361	317	414	436	2.0	0.8
Zr	103.5	70.0	114.6	67.1	149.0	151.0	173.7	195.6	117.2	99.6	154.1	118.7	165.2	90.6	142.5	124.1	143.8	110.9	128.4	135.7	93.1	178.4	0.2	0.5
Nb	8.4	15.0	11.5	7.8	6.7	6.3	9.0	6.8	3.9	4.8	8.9	6.0	9.3	4.4	7.5	6.7	6.6	5.8	6.8	6.2	5.3	8.1	0.1	
Ta	2.6	2.1	1.8	1.8	<0.7	1.1	1.1	<0.7	<0.7	<0.7	1.1	0.54[a]	0.87[a]	0.40[a]	0.79[a]	0.63[a]	0.63[a]	0.56[a]	0.62[a]	0.57[a]	0.51[a]	0.70[a]	0.4	
Mo	0.5	0.8	1.9	<0.2	0.3	1.2	0.5	0.7	0.9	0.6	0.9												0.2	
Th	11.4	5.1	6.2	8.6	5.2	7.7	10.3	4.7	5.5	4.3	6.1	4.5	7.7	3.2	7.4	5.7	5.2	3.2	5.5	4.7	3.7	5.8	0.2	
U	4.4	2.9	2.0	3.2	1.6	3.2	2.6	1.0	0.9	1.2	1.2	1.17[a]	1.84[a]	0.90[a]	1.50[a]	1.31[a]	0.77[a]	0.94[a]	1.21[a]	0.80[a]	0.89[a]	1.56[a]	0.5	
Y	17.9	27.8	16.8	12.4	20.3	12.6	17.4	30.2	20.0	8.9	11.0	9.7	15.1	9	13.1	11	12.6	8.3	10.7	9.7	8.9	13.3	0.3	
La	21.4	9.0	20.5	15.8	22.2	15.0	30.2	15.2	20.5	12.1	21.9	18.30[a]	20.78[a]	13.23[a]	16.74[a]	18.56[a]	18.07[a]	15.90[a]	20.28[a]	18.88[a]	12.82[a]	17.72[a]	2.0	
Ce	46	24	46	33	46	32	61	34	42	25	44	30.90[a]	35.79[a]	22.51[a]	28.45[a]	32.40[a]	31.43[a]	27.56[a]	34.35[a]	33.10[a]	21.75[a]	31.11[a]	3.0	
Nd	18.2	10.1	18.4	13.9	21.1	12.6	23.6	19.3	20.9	11.1	18.1	12.14[a]	14.68[a]	9.48[a]	11.67[a]	13.22[a]	13.40[a]	10.85[a]	13.30[a]	13.58[a]	9.10[a]	13.17[a]	2.0	
Sm	4	4	4	3	5	4	3	4	4	3	3	2.12[a]	2.74[a]	1.73[a]	2.19[a]	2.38[a]	2.48[a]	1.88[a]	2.36[a]	2.31[a]	1.67[a]	2.48[a]	2.0	
Yb	2.0	2.8	1.7	1.1	2.4	2.1	2.0	3.3	2.3	1.7	1.5	0.89[a]	1.31[a]	0.60[a]	1.18[a]	0.85[a]	0.80[a]	0.45[a]	0.87[a]	0.53[a]	0.60[a]	1.14[a]	0.7	
Hf	4.4	3.5	4.6	3.0	3.6	4.3	5.2	5.2	2.5	3.3	4.7	1.75[a]	2.93[a]	1.43[a]	2.14[a]	1.44[a]	0.93[a]	0.39[a]	1.92[a]	0.87[a]	1.31[a]	3.12[a]	0.5	
Cs	6	<1.5	3	10	<1.5	5	<1.5	3	<1.5	5	<1.5	1.10[a]	5.21[a]	1.90[a]	2.51[a]	2.72[a]	1.39[a]	1.82[a]	1.98[a]	2.76[a]	2.56[a]	9.77[a]	1.0	
Eu												0.69[a]	0.73[a]	0.57[a]	0.50[a]	0.72[a]	0.76[a]	0.64[a]	0.72[a]	0.72[a]	0.59[a]	0.82[a]		
Gd												1.87[a]	2.57[a]	1.57[a]	2.08[a]	2.05[a]	2.26[a]	1.53[a]	1.98[a]	1.86[a]	1.50[a]	2.31[a]		
Tb												0.28[a]	0.40[a]	0.22[a]	0.32[a]	0.29[a]	0.34[a]	0.22[a]	0.30[a]	0.26[a]	0.22[a]	0.35[a]		
Dy												1.52[a]	2.27[a]	1.25[a]	1.86[a]	1.68[a]	1.87[a]	1.19[a]	1.68[a]	1.35[a]	1.25[a]	1.97[a]		
Ho												0.30[a]	0.46[a]	0.24[a]	0.39[a]	0.33[a]	0.36[a]	0.22[a]	0.33[a]	0.25[a]	0.24[a]	0.41[a]		
Er												0.79[a]	1.25[a]	0.63[a]	1.10[a]	0.86[a]	0.88[a]	0.54[a]	0.87[a]	0.60[a]	0.62[a]	1.10[a]		
Tm												0.12[a]	0.20[a]	0.09[a]	0.18[a]	0.13[a]	0.13[a]	0.08[a]	0.14[a]	0.09[a]	0.09[a]	0.17[a]		
Lu												0.13[a]	0.21[a]	0.10[a]	0.20[a]	0.14[a]	0.12[a]	0.06[a]	0.14[a]	0.08[a]	0.10[a]	0.19[a]		

Sample	Longitude	Latitude	Sample type	Lithology	Location	Number of analysed zircons	Number of zircons ages used for mean age calculation	Weighted mean age (Ma)	Error (Ma)	MSWD
Bau Suite										
TB61	110.29019	1.50809	outcrop	granodiorite	Bt. Stapok (quarry)	10	3	12.4	0.9	1.4
TB9	110.37502	1.44329	outcrop	granodiorite	Bt. Stigang (quarry)	25	16	14.1	0.1	0.5
West Sarawak Sintang Suite - volcanic										
TB209a	111.69209	1.05622	float	rhyolite	Bt. Buwaya	41	25	18.6	0.2	2
TB141	110.18510	1.64817	outcrop	rhyolite	Kampung Matang	42	15	19.8	0.3	1.3
West Sarawak Sintang Suite - intrusive										
TB33	110.18631	1.60456	outcrop	micro-granodiorite	G. Bawang	66	57	20.1	0.2	2.1
TB58	111.39105	1.09237	float	granodiorite	Bt. Kelambi (Klambi)	51	36	20.3	0.2	3
TB63b	110.32163	1.72548	outcrop	granitic sill	Tanjung Santubong	86	70	21.1	0.2	3.5



Supplementary Fig. 1: a) R1-R2 classification for plutonic rocks (De La Roche et al., 1980). b) R1-R2 classification for volcanic rocks (De La Roche et al., 1980). c) Classification of Peccerillo & Taylor (1979). d) Geotectonic classification of granitoids (Pearce et al., 1984; Pearce, 1996). e) Granite classification by Frost et al. (2001).

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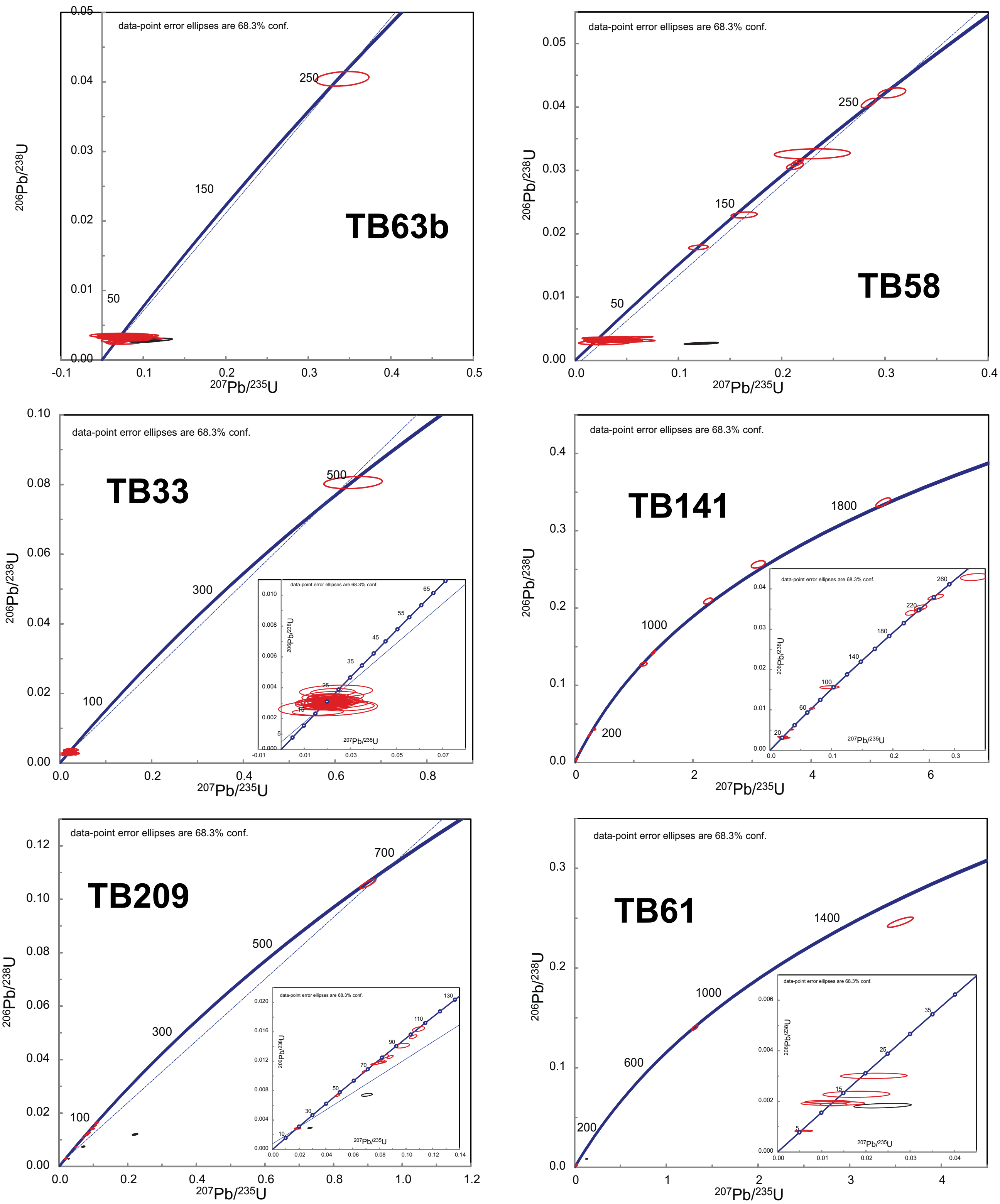
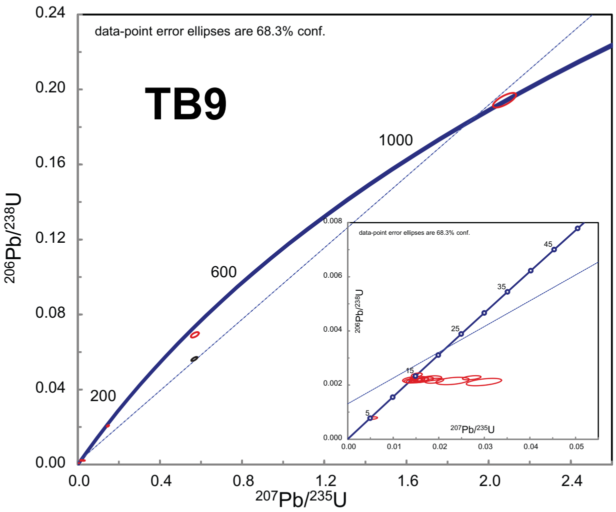
Peccerillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. Contributions to Mineralogy and Petrology, 58(1): 63-81.





Supplementary Fig. 2: Concordia plots of all ages of the West Sarawak Sintang intrusive (TB63b, TB58, TB33), volcanic (TB141, TB209) and Bau Suite (TB61, TB9) rocks. Black circles are discordant results.