# Provenance study of the Lubok Antu Mélange from the Lupar valley, West Sarawak, Borneo: Implications for the closure of eastern Meso-Tethys.

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**Abstract**

The Lubok Antu M´elange is exposed along one of the most important tectonic lineaments, the Lupar Line in Sarawak, Borneo. However, the depositional age of the Lubok Antu M´elange is poorly known, and no provenance studies have been conducted so far. Here, we use geochemical, Nd isotopic and detrital zircon U–Pb analyses of samples from the Lubok Antu M´elange to constrain provenance and routing in order to better understand Borneo's evolution history. Bulk rock geochemistry reveals that the Lubok Antu M´elange was deposited in a continental arc setting related to the Paleo-Pacific subduction margin. New U–Pb detrital zircon data suggest that the maximum depositional age for the Lubok Antu M´elange is ca. 115 to 105 Ma. The Lubok Antu M´elange with a strongest Jurassic peak is interpreted to be sourced from the Mesozoic continental arc related to the Paleo-Pacific subduction, with contributions from West Borneo, the Malay Peninsula and possibly Sumatra. Compared with the detrital zircon data of the uppermost Cretaceous sedimentary rocks in Sarawak, our study records a change in source in the latest Cretaceous from erosion of basement magmatic rocks of the Paleo-Pacific subduction-related arc that was probably located offshore of what is now South Vietnam and West Borneo, to the Schwaner Mountains arc of SW Borneo. This indicates that the rapid uplift and exhumation of the Schwaner Mountains could have initiated in the latest Cretaceous, which may imply the arrival of SW Borneo and the closure of the eastern Meso-Tethys at that time.

## 1. Introduction

Borneo formed from several tectonic blocks (West Borneo, SW Borneo, East Java-West Sulawesi and NW Sulawesi-East Sabah, Hall, 2012; Fig. 1a, b). From the Triassic West Borneo was a part of the Southeast margin of Sundaland based on studies of magmatic and metamorphic rocks in West Sarawak (Breitfeld et al., 2017;

Hennig et al., 2017) and was located in the transition zone between the Meso-Tethys and Paleo- Pacific by the late Mesozoic (Hall, 2012; Metcalfe, 2011). SW Borneo (Banda), NW Sulawesi-East Sabah, and East Java-West Sulawesi (Argo) had rifted from the Australian margin of Gondwana by the Late Jurassic, opening the Ceno-Tethys Ocean (Hall, 2012; Metcalfe, 2011). The eastern Meso-Tethys Ocean thus gradually closed when these fragments drifted to the north in the Late Cretaceous (Metcalfe, 2011). The process by which these fragments accreted to the present-day southeast margin of Sundaland is linked to the demise of the eastern Meso-Tethys with potential impacts on the paleobiogeographical evolution and the continent-ocean configuration. The timing of collision between SW Borneo and West Borneo remains poorly defined, but was constrained to ca. 130–90 Ma (Breitfeld et al., 2020; Davies et al., 2014; Hall, 2012; Hennig et al., 2017). Paleomagnetic data from the Jurassic–Cretaceous sedimentary rocks in West Sarawak also show that West Borneo was rotated about 90◦ _anti-clockwise since the Jurassic–Cretaceous (Fuller et al., 1999), possibly caused by the closure of the eastern Meso-Tethys, the subsequent collision of West Borneo with SW Borneo, or the collision between the eastern side of SW Borneo with East Java-West Sulawesi and Northwest Sulawesi-East Sabah. Thus, a significant tectonic transition in response to the above tectonic events might have occurred in the Late Cretaceous.

Provenance analysis is a useful and direct way to track changes in paleogeography caused by regional tectonics such as collision (e.g., Hu et al., 2016), although it may also be complicated by drainage reorganization or changes in erosion pattern caused by climate change. Several geochronology and provenance researches in Sarawak have mainly focused on the uppermost Cretaceous–Eocene Rajang Group, Kayan Group and younger formations (e.g., Breitfeld and Hall, 2018; Breitfeld et al., 2018; Galin et al., 2017; Hennig et al., 2017). These studies found that contributions from the Schwaner Mountains, the Malay Tin Belt and West Borneo varied through time.

However, no provenance studies have been conducted on possible Upper Cretaceous sedimentary rocks (e.g., Lubok Antu M´elange, Serabang, Sejingkat and Sebangan Formation) in West Sarawak. Strata of the Lubok Antu M´elange, which occurs along the Lupar Line, a possible suture (Hutchison, 1996, 2005, 2010; Tan, 1979, 1982) or a major strike-slip fault which active during the Cenozoic (Breitfeld et al., 2017; Haile, 1974; Hall, 2012; Hall and Breitfeld, 2017; Hall and Sevastjanova, 2012), in West Borneo could provide a window into the geodynamic history of this region. Geochemical analysis of sedimentary rocks, especially mudstone, has been successfully applied to constrain potential provenance and tectonic setting (Bhatia and Crook, 1986; McLennan et al., 1993). Thus, in this study we applied geochemical methods coupled with detrital zircon geochronology to define the provenance of sedimentary rocks in the Lubok Antu M´elange. Results are compared with complementary published data to better define the tectonic evolution history of Borneo.

## 2. Geological setting

Borneo now lies in an area of dynamic tectonics influenced by relative motions of the Indian-Australian, Pacific and Philippine Sea plates (Hamilton, 1979; Hall, 2012; Fig. 1a). The tectonic provinces of Borneo now can be divided into five zones—SW Borneo, Triassic Sundaland of Borneo (western part of the Kuching Zone), Mesozoic accretionary complex (or a remnant ocean basin suggested by Moss, 1998), Northwest Sulawesi-East Sabah and East Java-West Sulawesi (Fig. 1b; Breitfeld et al., 2017). SW Borneo is dominated by Cretaceous magmatic rocks and meta-igneous rocks with some Triassic–Jurassic meta-igneous rocks in the NW Schwaner Mountains (Breitfeld et al., 2017, 2020; Haile, 1974). The Lupar fault zone is the boundary between the Kuching Zone and the Sibu Zone (Haile, 1974; Tan, 1982; Fig. 1b), and is a narrow zone comprising the Lubok Antu M´elange, Lupar Formation and associated Pakong

Mafic Complex. The Lubok Antu M´elange is bounded to the southwest by the Eocene Silantek Formation deposited in a nearshore to terrestrial environment, and to the northeast by the uppermost Cretaceous Lupar Formation, the oldest rocks of Rajang Group (Fig. 1c). The Lupar Formation is composed of sandstone interbedded with shale, siltstone and mudstone and represent turbidite deposits within a submarine fan. The Lupar Formation was intruded by rocks of the Pakong Mafic Complex (Fig. 1c; Tan, 1982). The maximum depositional age (MDA) of the Lupar Formation is Maastrichtian based on the youngest (70 ± _1 Ma) zircon U–Pb age (Galin et al., 2017) and the few published paleontological ages presented by Liechti et al. (1960) and Wolfenden (1960). The boundary between the Lupar Formation and the Lubok Antu M´elange is not exposed, and has been assumed to be a faulted contact (Tan, 1982). The base of the Silantek Formation is dominated by upper Eocene steeply-dipping to vertical sandstone and conglomerate sequence, which is also in faulted contact with the Lubok Antu M´elange (Tan, 1982).

The Lubok Antu M´elange is exposed along the Lupar Line, strikes west-northwest and dips steeply to the north (Tan, 1979; Tan, 1982; Fig. 1c). The Lubok Antu M´elange is a mappable unit of mixed rocks including blocks of different origin, randomly distributed in its tectonically sheared pelitic matrix (Tan, 1982). Clasts of shale, mudstone, sandstone, limestone, chert were probably derived from adjacent units or other probably distant sources according to whether it is correlated to any adjacent units (Tan, 1982). Rare blocks of mafic rock within the Lubok Antu M´elange were likely to have been derived from older oceanic crust, but could also be from the Pakong Mafic Complex within the Lupar Formation, as postulated by Tan (1978) and Haile et al. (1994). The m´elange has been tectonically sheared and probably undergone mild dynamic metamorphism. Tan (1982) and Zhao et al. (2021) interpreted the m´elange as a subduction complex which formed in an active subduction channel. Breitfeld et al. (2017), Hall and Breitfeld (2017) and Hennig et al. (2017) considered that the m´elange represents a part of the Mesozoic accretion complex related to the subduction of Paleo-Pacific, assuming there is a continuous plate boundary from Southeast Asian to Borneo caused by the Late Mesozoic subduction of Paleo-Pacific.

Up to now the depositional age of the Lubok Antu M´elange is still debated. The presence of characteristic Upper Cretaceous foraminifera from the m´elange was reported by Tan (1979, 1982). The Middle Eocene undeformed calcareous Engkilili Formation was also included in the m´elange (Tan, 1979, 1982). However, Haile (1996) excluded the Engkilili Formation based on the calcareous lithology and deformation differences. Breitfeld et al. (2017) considered that the Lubok Antu M´elange which contains Cretaceous sediments should be interpreted to be Cretaceous. The chert blocks in the m´elange represent deep marine deposits and show three distinct radiolarian assemblage ages: Late Tithonian, Middle Valanginian to Barremian and Late Albian to Cenomanian from Upper Jurassic to Upper Cretaceous (Basir, 1996). The ages of detrital mica/illite in the m´elange matrix were constrained at 145 ± _5.1 Ma and 96.2 ± _8.3 Ma, and the deformation age of the m´elange matrix cluster around ca.60 Ma by illite age analysis (Zhao et al., 2021). Thus, based on the available age data (Basir, 1996; Tan, 1979, 1982; Zhao et al., 2021), the depositional age of the m´elange is most likely to be Late Cretaceous, if the Engkilili Formation is excluded (e.g., Breitfeld et al., 2017).

## 3. Samples and analytical methods

### *3.1. Samples*

In this study, twenty-two samples (two sandstone blocks and twenty mudstone samples) were collected from the Lubok Antu valley in Sarawak at locations shown on Fig. 1c and are listed in Supplementary Table S1. Among them, twenty mudstone samples (Sixteen from the Lubok Antu M´elange matrix and four from the Lupar Formation) were selected for geochemical analysis and two sandstone blocks in the m´elange for zircon U–Pb dating. The mudstone samples of the m´elange matrix are pervasively sheared, grey to dark grey in color (Fig. 2a, b, c), non-calcareous and are generally composed of quartz and clay minerals with some chert detrital. The mudstone of the Lupar Formation rhythmically interbedded with sandstone and are dark-grey in color (Fig. 2d). There are no obvious differences in mineral compositions of the m´elange matrix and the Lupar Formation mudstone, and the clays of our samples consist primarily of 1*M*d illite, 2*M*1 illite/muscovite, chlorite and kaolinite (Zhao et al., 2021). Two sandstone blocks in the m´elange, which are characterized by necking and boudinaging, have been collected for zircon U–Pb dating (Fig. 2c). The detrital grains from the sandstone block samples are texturally immature with poorly sorted and mostly sub-angular detrital grains, and are primarily composed of quartz and lithic fragments (Fig. 2e, f).

### ***3.2. Bulk chemistry and Nd isotope analysis***

Sixteen mudstone samples of the Lubok Antu M´elange matrix and four of the Lupar Formation were collected for geochemical analysis (Fig. 1c). Samples were crushed and powdered to 200 mesh by agate mortars, and then leached with 2 N acetic acid to remove biogenic carbonates. The solid residue was cleaned three times using distilled water, centrifuged, oven dried at 90 ◦C, and ground to a powder <75 μm.

Major element compositions were analyzed by X-ray fluorescence on an ME-XRF26d instrument at Australia Laboratory Services (ALS) Chemex (Guangzhou) Co. Ltd. Analytical standard deviations are <5% and detection limits <0.01%. Trace element concentrations and Nd isotopes were measured at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Nebulized sample solutions were analyzed for trace element concentrations on a Perkin-Elmer Sciex ELAN 6000 inductively coupled plasma mass spectrometer (ICP-MS). A set of rock standards, including BHVO-2, G-2 and GSP-2, were chosen for calibrating element concentrations. Nd isotope composition were measured on a Micromass Isoprobe multicollector mass spectrometer (MC-ICP-MS). The Shin Etsu JNdi-1 standard 143Nd/144Nd value of 0.512115 was used for adjusting the reported ratios in this study. All results are provided in Table S1 in the Supporting Information.

### 3.2. Zircon U-Pb Analysis

Two sandstone clasts (LA-09S and LA-14S) of Lubok Antu Mélange have been collected for zircon U-Pb dating. U-Pb dating was performed by laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS) located in the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The instrumentation comprises a RESOlution M-50 LA system and an Agilent 7500a ICP-MS. The diameter of analytical spots is 24 μm. Isotope ratios were calculated using ICPMSDataCal 10.7 (Liu et al., 2010). Isoplot (Version 3.23) were used for calculating the relative age probability of detrital zircons (Ludwig, 2003). The $^{206}Pb/^{238}U$ ages for zircon grains younger than 1000 Ma and $^{207}Pb/^{206}Pb$ ages for those older than 1000 Ma with discordance <10% were used for analyzing. The results are compiled in Table S2 in the Supporting Information.

# 4. Results

## 4.1. Geochemistry

Results of the major and trace elements and Sr-Nd isotopic analyses of the mudstones samples of the Lubok Antu Mélange matrix and the Lupar Formation can be seen in Table S1.

### 4.1.1. Major and trace elements

Mudstone samples of the Lubok Antu M´elange matrix show a SiO2 content of between 58.0 wt% and 71.2 wt%. Contents of Al2O3 (17.6–23.5 wt%) have an average value (19.6 wt%) higher than that of the Post Archaean Australian Shales (PAAS) (18.9 wt%; McLennan et al., 1993; Table S1), indicating that these samples contain abundant clay minerals (e.g., Zhao et al., 2021). The low contents of CaO (0.0–0.1 wt %) and Na2O (0.1–0.7 wt%) imply that these elements have been leached by intense alteration. There is no significant variation between the major element compositions of mudstone from the Lupar Formation and the matrix of the Lubok Antu M´elange. Except for very few samples where the total rare earth element contents (ΣREE) are abnormally low (Sample LA-5E, 75.4 ppm) or abnormally high (Sample LA-5B, 332.8 ppm), the contents of ΣREE in the Lubok Antu M´elange matrix samples are between 125.1 ppm and 241.4 ppm, with average values of 168.0 ppm, which are comparable with that in the upper continental crust (UCC) and PAAS (Table. S1). All the samples show similar REE distribution, where light REE (LREE) are abundant, but heavy REE (HREE) are relatively flat when normalized to chondritic values, and these samples are marked by negative Eu anomalies (δEu = 0.56–0.88), with average values of 0.67 (Fig. 3a). Samples from the Lupar Formation yield similar chondrite-normalized rare earth element patterns with samples from the matrix of the Lubok Antu M´elange (Fig. 3a). Most samples in this study show slightly lower concentrations of large ion lithosphere elements (LILEs, e.g., Rb, Ba, K, Pb and Sr) and high field strength elements (HFSEs, e.g., Nb, Ta, Zr, Hf, Th and U) when compared with PAAS (Fig. 3b). Sr concentrations are variable but strongly depleted in the upper continental crust-normalized spider diagrams (Fig. 3b).

*4.1.2. Nd isotopic values*

The samples of matrix from the Lubok Antu M´elange have a relative narrow range of $\varepsilon Nd(0)$ values (ranging from -5.8 to -2.7) with average values of -4.5, and the $\varepsilon Nd(0)$ values of the Lupar Formation samples range from -4.3 to -2.5 with average values of -3.5 (Table S1).

## 4.2. Detrital Zircon Geochronology

Zircon grains extracted from the two samples range in length from 40 μm to 160 μm with aspect ratios of 1:1 to 3:1(Fig. 4). Their shapes range from subrounded to angular, with more than half of the grains being angular (Fig. 4). Most zircons have Th/U > 0.3, suggesting an igneous origin, and only two grains show Th/U < 0.1 consistent with a metamorphic origin (Corfu et al., 2003, Table S2).

A total of 207 zircon grains from the two sandstone samples of Lubok Antu M´elange clasts yield a wide range of U–Pb ages from 3461 to 104 Ma, with main peaks at ca. 150 Ma and ca. 1850 Ma, accompanied by some minor peaks at 250 Ma, 460 Ma and 2500 Ma. The samples yielded relatively abundant younger grains (<500 Ma, representing 61% of the total population). The zircon U–Pb age distribution of Sample LA-14S from the southern m´elange zone shows a similar trend to Sample LA- 09S from northern m´elange zone. The youngest zircon U–Pb ages from Samples LA-14S and LA-09S are 114.7 ± _1.6 Ma and 104.9 ± _1.6 Ma, respectively.

# 5. Discussion

*5.1. Provenance tracing*

### *5.1.1. Provenance tracing using geochemistry data*

Although the elements of the source rocks could be modified by complex physicochemical processes during weathering, transportation, and deposition, the major and trace element compositions and REE data of fine-grained siliciclastic rocks have been widely used to determine provenance (e.g., Lim et al., 2014; McLennan, 1989; Yang et al., 2002). The Al2O3/TiO2 ratios (21.2–27.9) and REEs (103.0–332.7 ppm; Table S1) with clear negative Eu anomalies (0.56–0.88) in our samples indicate that the source rocks were likely intermediate to felsic igneous rocks (Cullers et al., 1997; Hayashi et al., 1997). Most samples from the Lubok Antu M´elange and the Lupar Formation fall into the continental arc field (Fig. 5a, b and c), which may also imply a significant contribution from nearby Mesozoic granites. *εNd*(0) values (ranging from □ _5.8 to □ _2.5; Fig. 6a) of our samples fall within the overlapped range of *εNd*(0) values of the nearby Mesozoic magmatic rocks from the Malay Peninsula, the eastern margin of Indochina and the Dangerous Grounds (Fig. 6b), implying that the above Mesozoic magmatic rocks could have contributed significantly to the Lubok Antu M´elange and the Lupar Formation. More negative *εNd*(0) values of the river sands (Fig. 6b), the greater transport distances to Borneo and the reconstruction of the paleo-drainage pattern of Indochina (Clark et al., 2004; Hennig et al., 2018) indicate that the hinterland of Indochina did not provide materials or contributed little to Borneo.

### *5.1.2. Provenance tracing using detrital zircon ages*

Sandstone blocks in tectonic m´elanges formed in a subduction-accretion setting generally represent broken beds of turbidites, and formed by layer subparallel extension characterized by necking and boudinaging (Hashimoto et al., 2006; Fig. 2b, c). Thus, the sandstone blocks for zircon U–Pb dating in the Lubok Antu M´elange could represent contemporaneous turbidite blocks (Fig. 2b, c), with a depositional age similar to the m´elange matrix. The detrital zircon data in the sandstone blocks therefore offer useful insight for provenance tracing.

The maximum depositional age for the sandstone blocks in the Lubok Antu M´elange is ca. 115 to 105 Ma based on zircons in samples LA-14S and LA-09S. The zircon U–Pb results from the sandstone blocks in the Lubok Antu M´elange are dominated by Late Jurassic and Early Cretaceous ages with a strongest peak between 140 and 160 Ma (Fig. 7f). There are also scattered Paleozoic ages with several Permian-Triassic sub-peaks, and the Proterozoic peaks at 1.8 Ga are accompanied by other scattered Precambrian ages from 541 Ma to 2.5 Ga (Fig. 7f). A similar age distribution is seen in the Upper Cretaceous Pedawan Formation of the forearc basin units in the Kuching Zone (Fig. 1b), although Proterozoic zircons are fewer in that case (Breitfeld et al., 2017; Fig. 7e).

Jurassic magmatism, ranging from 144 to 158 Ma, has been reported by Xiu et al. (2016) from the basement of Paracel Islands (Fig. 8a). Granitic rocks encountered by drilling in the Dangerous Grounds also indicate significant magmatism from 127 to 159 Ma (Fig. 8a; Yan et al., 2010). These ages indicate that there was a Late Jurassic to Early Cretaceous magmatic arc across the submarine continental basement of present-day South Vietnam and West Borneo (Fig. 8a; e.g., Hutchison, 1996; Li et al., 2018; Metcalfe, 2013; Shellnutt et al., 2013; Taylor and Hayes, 1983; Williams et al., 1988; Zhou et al., 2008). This Mesozoic magmatic arc could have supplied Late Jurassic to Early Cretaceous zircons to the Upper Cretaceous sedimentary rocks in Sarawak, Borneo (Fig. 8a). Samples from the modern river sands draining the Malay Peninsula show a small number of Jurassic zircon grains which were most likely reworked from the Upper Jurassic “redbeds” _of Indochina and the Malay Peninsula (Fig. 7b; Sevastjanova et al., 2011), implying Indochina and the Malay Peninsula are also possible sources.

In addition to the main Jurassic and Cretaceous zircons, the Upper Cretaceous Pedawan Formation and the Lubok Antu m´elange contain Permian-Triassic sub-peaks which may be derived from West Borneo or East Malaya (Fig. 8b; e.g., Breitfeld and Hall, 2018; Breitfeld et al., 2017; Galin et al., 2017; Hennig et al., 2017; Setiawan et al., 2013). Paleozoic and Precambrian zircons suggests that the possible sources of recycled material were Indochina, East Malaya, and possibly Sumatra (e.g., Breitfeld and Hall, 2018; Galin et al., 2017).

In contrast, compiled zircon age data of the uppermost Cretaceous to Eocene sedimentary rocks in Sarawak dominated by Cretaceous and Permian-Triassic zircons with an increase in the number of Precambrian zircons, and the populations of Jurassic zircons are much smaller (Fig. 7c, d). West Borneo, SW Borneo, East Malaya, and possibly Sumatra, with reworking of sediment from Sibumasu and Indochina have been suggested as sources for the uppermost Cretaceous to Eocene sedimentary rocks in Sarawak based on heavy minerals and zircon ages (Breitfeld and Hall, 2018; Galin et al., 2017; van Hattum et al., 2006). The uppermost Cretaceous sedimentary rocks in Sarawak, which have the same bimodal Cretaceous zircon peaks as the modern river sands in SW Borneo (Fig. 7a, d), reveal a significant contribution from the Schwaner Mountains in SW Borneo (e.g., Breitfeld and Hall, 2018; Galin et al., 2017). The loss of the Jurassic zircon peak is probably related to the continental margin dissection, which has broken the Mesozoic arc area (Li et al., 2018).

*5.2. Implication for tectonic reconstruction*

The Upper Cretaceous sedimentary rocks in West Borneo, that record relatively high $\varepsilon Nd(0)$ values and strongest Jurassic peaks between 140 and 160 Ma, were derived from the Late Jurassic to Early Cretaceous magmatic arc, with contributions from West Borneo, the Malay Peninsula and possibly Sumatra. The Cretaceous granitoids in the east margin of the Malay Peninsula and Singapore could be a part of a granite belt related to the Paleo-Pacific subduction (Fig. 9a; Breitfeld et al., 2020; Hennig et al., 2017). Although very little is known about the paleo-drainage network offshore of what is now Vietnam and West Borneo, this long-lived Mesozoic subduction margin between Vietnam and East Malaya (Breitfeld et al., 2017; Hennig et al., 2017; Williams et al., 1988), the arc rocks that were located offshore of what is now West Borneo could have contributed significantly to the Upper Cretaceous sedimentary rocks in Sarawak, Borneo (Fig. 9a).

Jurassic zircons, which are much less abundant in the uppermost Cretaceous to Eocene sedimentary rocks in Sarawak, may imply the rifting and collapse of the Mesozoic magmatic arc (e.g., Li et al., 2018). In addition, significant increase of bimodal Cretaceous zircons in the uppermost Cretaceous sedimentary rocks in West Borneo indicates the rapid uplift and exhumation of the Schwaner Mountains in SW Borneo at that time, which may be related to the arrival of SW Borneo. This implies that SW Borneo gradually drifted northward followed by the demise of the eastern Meso-Tethys in the latest Cretaceous, if the granites of the Schwaner Mountains were the products of subduction during opening of the Ceno-Tethys and northward movement of SW Borneo (Davies et al., 2014; Hall, 2012). Since then the fluvial system named proto-Sarawak River became a major drainage system of eastern Sundaland (Fig. 9b, Breitfeld and Hall, 2018).

## 6. Conclusions

The Late Mesozoic sedimentary records from West Borneo can provide important clues to changes in the tectonic evolution history of Borneo. Our results suggest that the maximum depositional age of the Lubok Antu m´elange is ca. 115 to 105 Ma and that detrital sources of Upper Cretaceous sedimentary rocks in West Borneo are consistent with a continental arc setting related to Paleo-Pacific subduction. The Lubok Antu M´elange was sourced from the Late Jurassic to Early Cretaceous magmatic arc, with contributions from West Borneo, the Malay Peninsula and possibly Sumatra. Early extension and rifting of this margin prior to opening of the South China Sea, together with the uplift of the Schwaner Mountains led to a change in sediment sources. This change may be related to the arrival of SW Borneo, implying the demise of the eastern Meso-Tethys in the latest Cretaceous.

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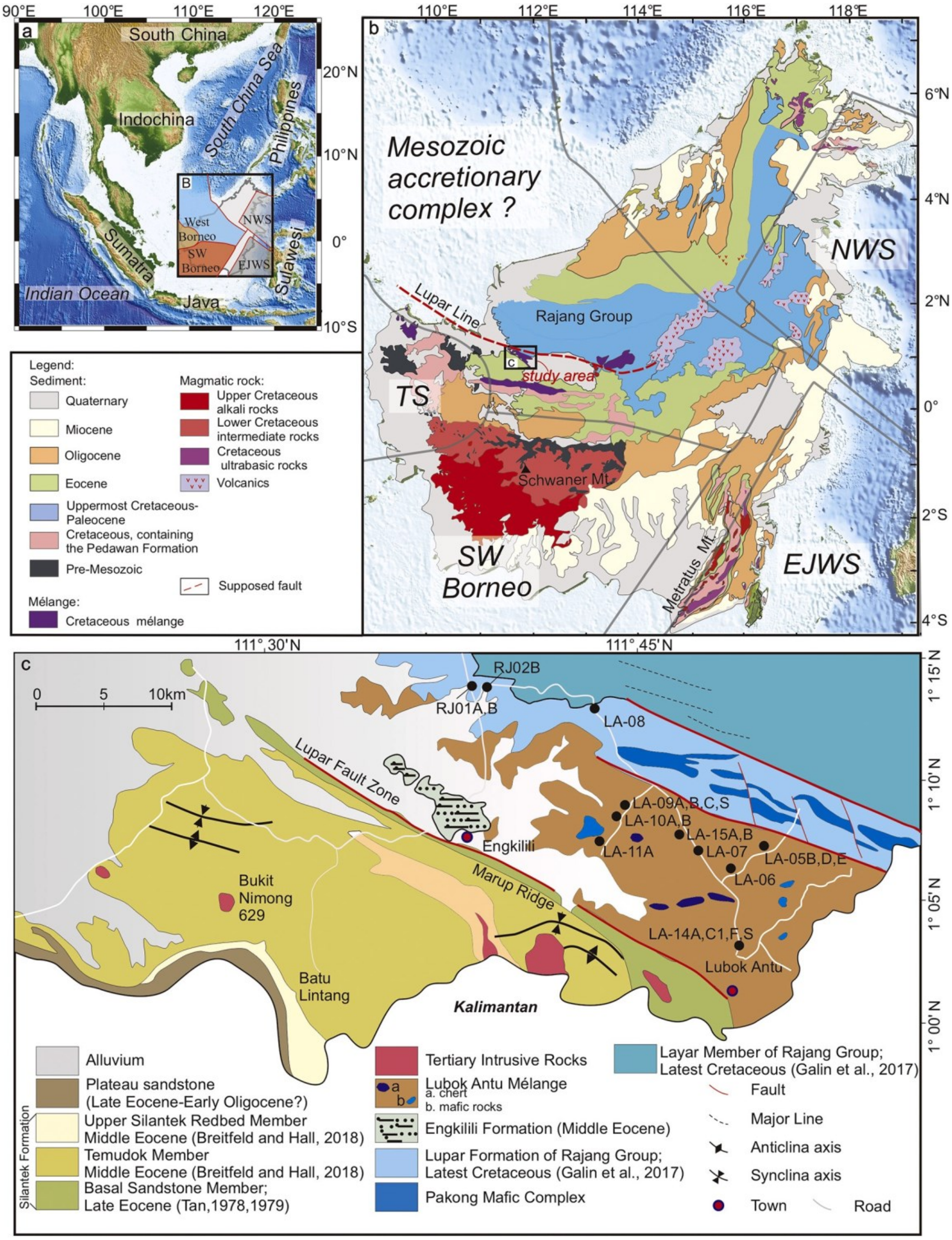

**Fig. 1.** (a) Location and main continental fragments of Borneo. (b) Simplified geology map and main tectonic provinces of Borneo after Haile (1974), Hutchison, 2010 and Breitfeld et al. (2017). (c) Simplified geological map of West Sarawak modified from Tan (1982), showing the sample locations. EJWS — East Java-West Sulawesi; NWS—Northwest Sulawesi and E Sabah; TS—Triassic Sundaland of Borneo.

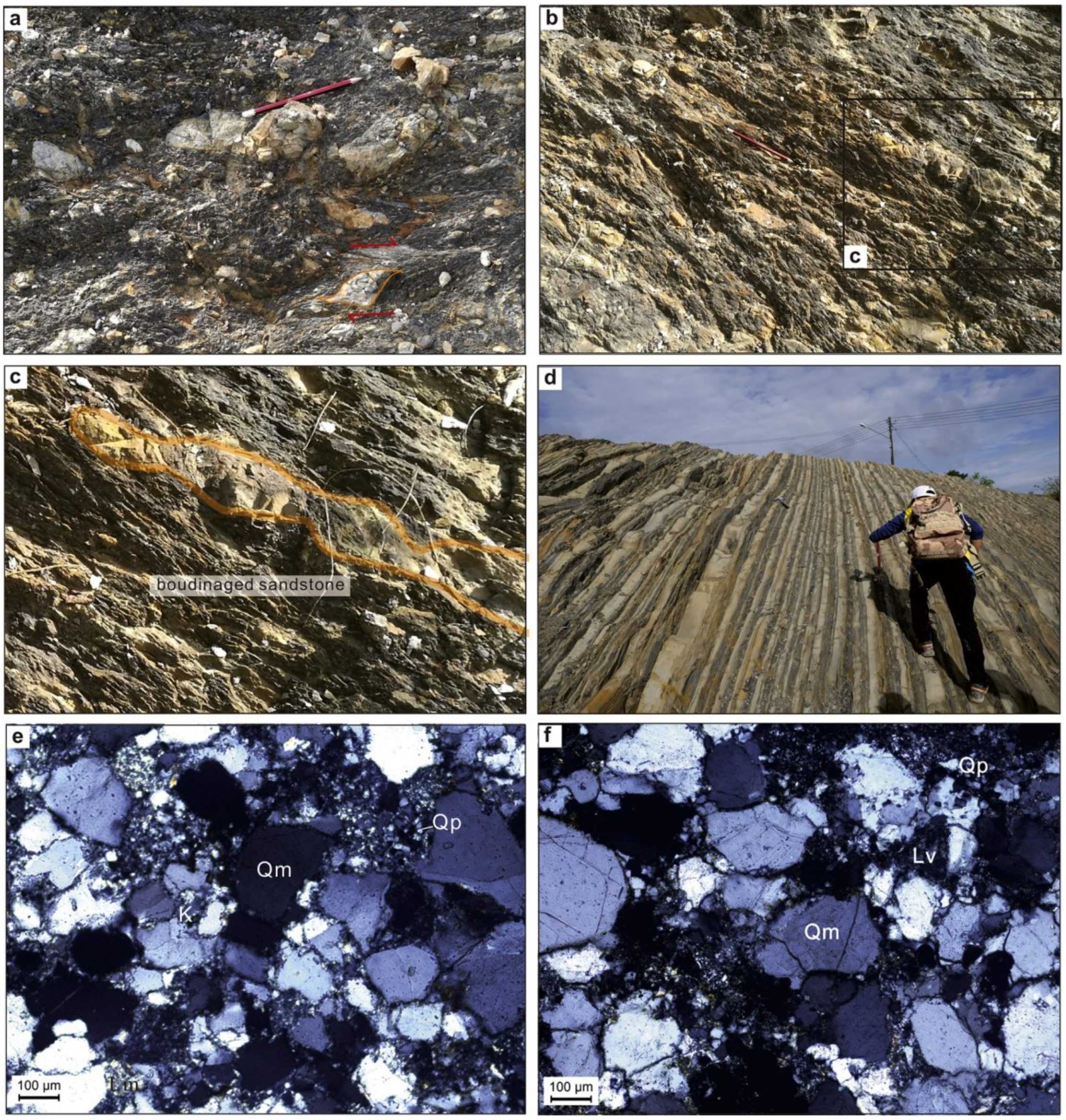


**Fig. 2.** Outcrops and photomicrographs of the collected samples. (a) Asymmetric flow deformation of the pelitic matrix in the Lubok Antu M´elange. (b) Boudinaged sandstone blocks in m´elange. (c) Close-up of the boudinaged sandstone blocks for zircon U–Pb dating (LA-09S). (d) field photograph of the Lupar Formation. (e) photomicrograph of the sandstone block sample (LA-09S). (f) photomicrograph of the sandstone block sample (LA-14S). K for K-feldspar; Qm for monocrystalline quartz, Qp for polycrystalline quartz, Lm for metamorphic lithic fragment; Lv for volcanic lithic fragment

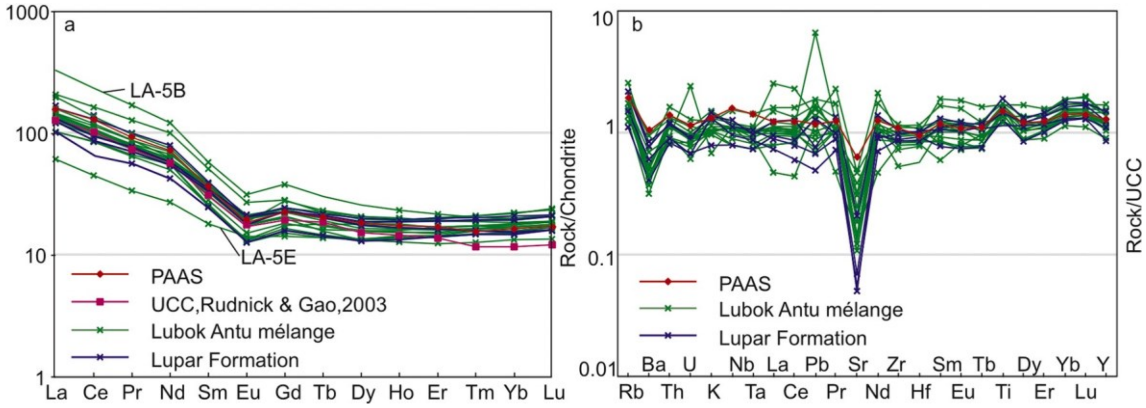


**Fig. 3.** (a) Chondrite-normalized REEs patterns and (b) upper continental crust-normalized spider diagrams of the Lubok Antu M´elange matrix and Lupar Formation shales. The PAAS values are from McLennan et al. (1993), the chondrite values are from Sun and McDonough (1989), and the upper continental crust values are from Rudnick and Gao (2003).

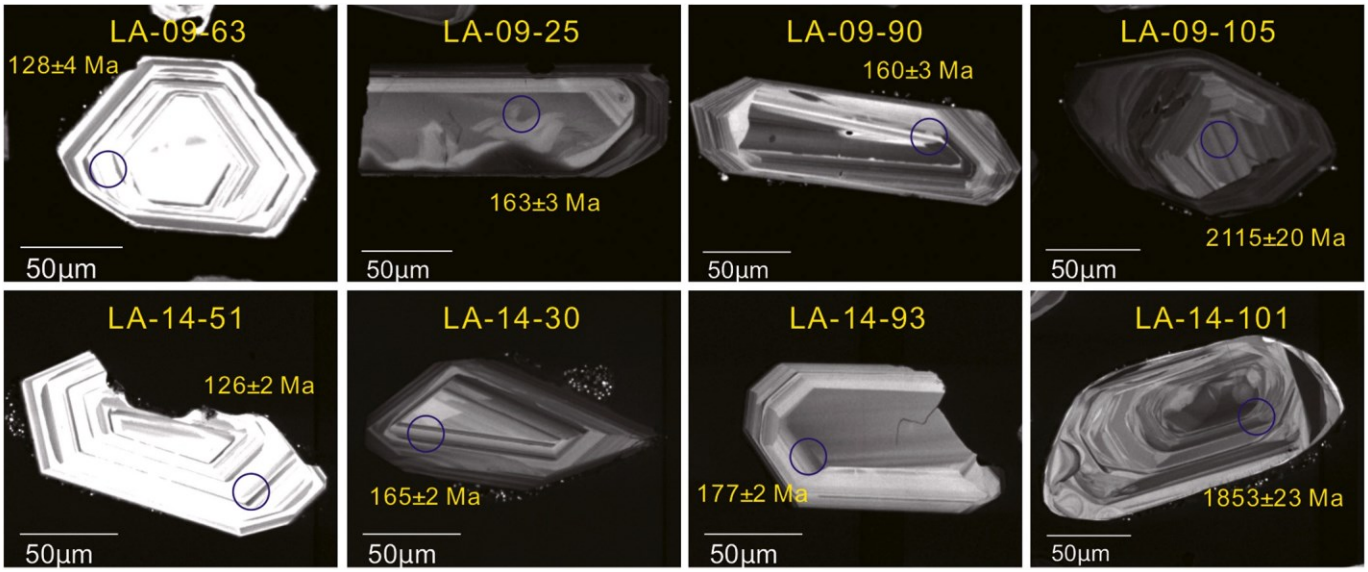


**Fig. 4.** Cathodoluminescent images of zircons from the sandstone blocks of the Lubok Antu M´elange.

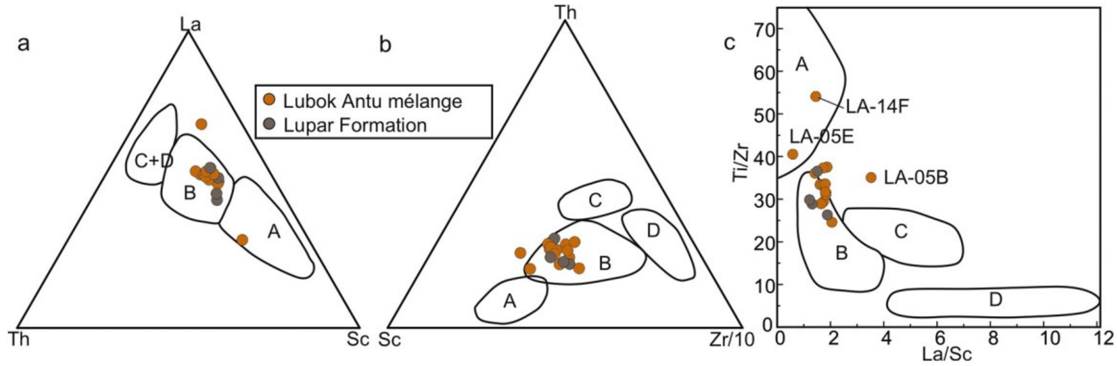


**Fig. 5.** (a) La-Th-Sc plot, (b) Th-Sc-Zr/10 plot and (c) La/Sc–Ti/Zr ratio diagram for tectonic setting discrimination (after Bhatia and Crook, 1986). A: Oceanic Island Arc; B: Continental Island Arc; C: Active Continental Margin; D: Passive Margin.

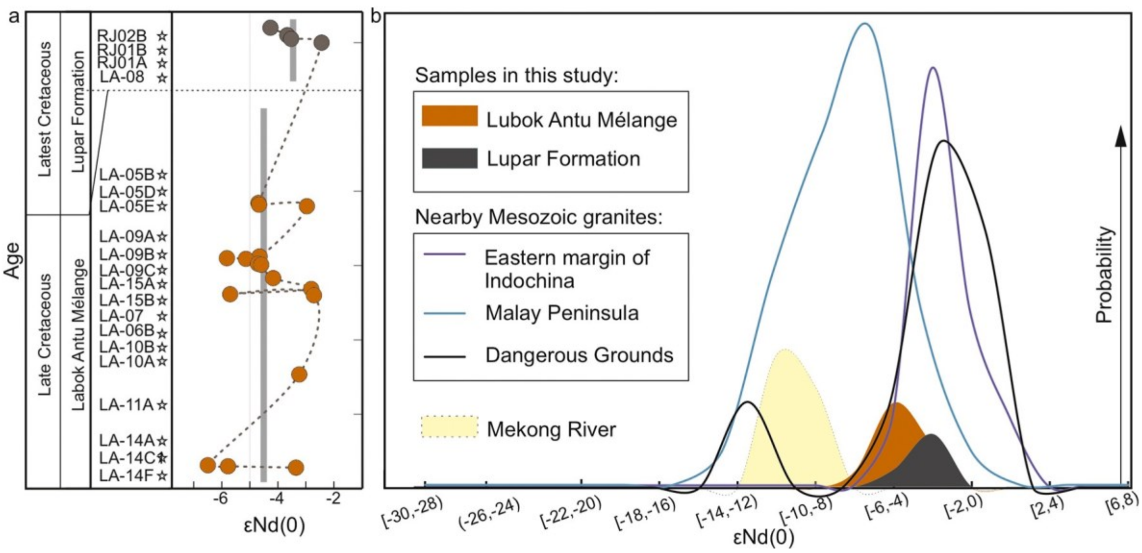


**Fig. 6.** (a) Plot of $\varepsilon_{Nd}(0)$ values of the mudstone samples from the Lubok Antu M´elange matrix and the Lupar Formation. (b) Relative probability plots of $\varepsilon_{Nd}(0)$ ranges. Published data for the Mesozoic granites include rocks from the eastern margin of Indochina (Chen et al., 2019; Lan et al., 2000; Owada et al., 2007; Thuy et al., 2004), the Malay Peninsula (Cao et al., 2020; Du et al., 2020; Ng et al., 2015a; Ng et al., 2017) and the Dangerous Grounds (Yan et al., 2010). Published data for the

present-day's Mekong River based on Goldstein et al. (1984) and Liu et al. (2007). See Table S3 for compiled $\varepsilon_{Nd}(0)$ values.

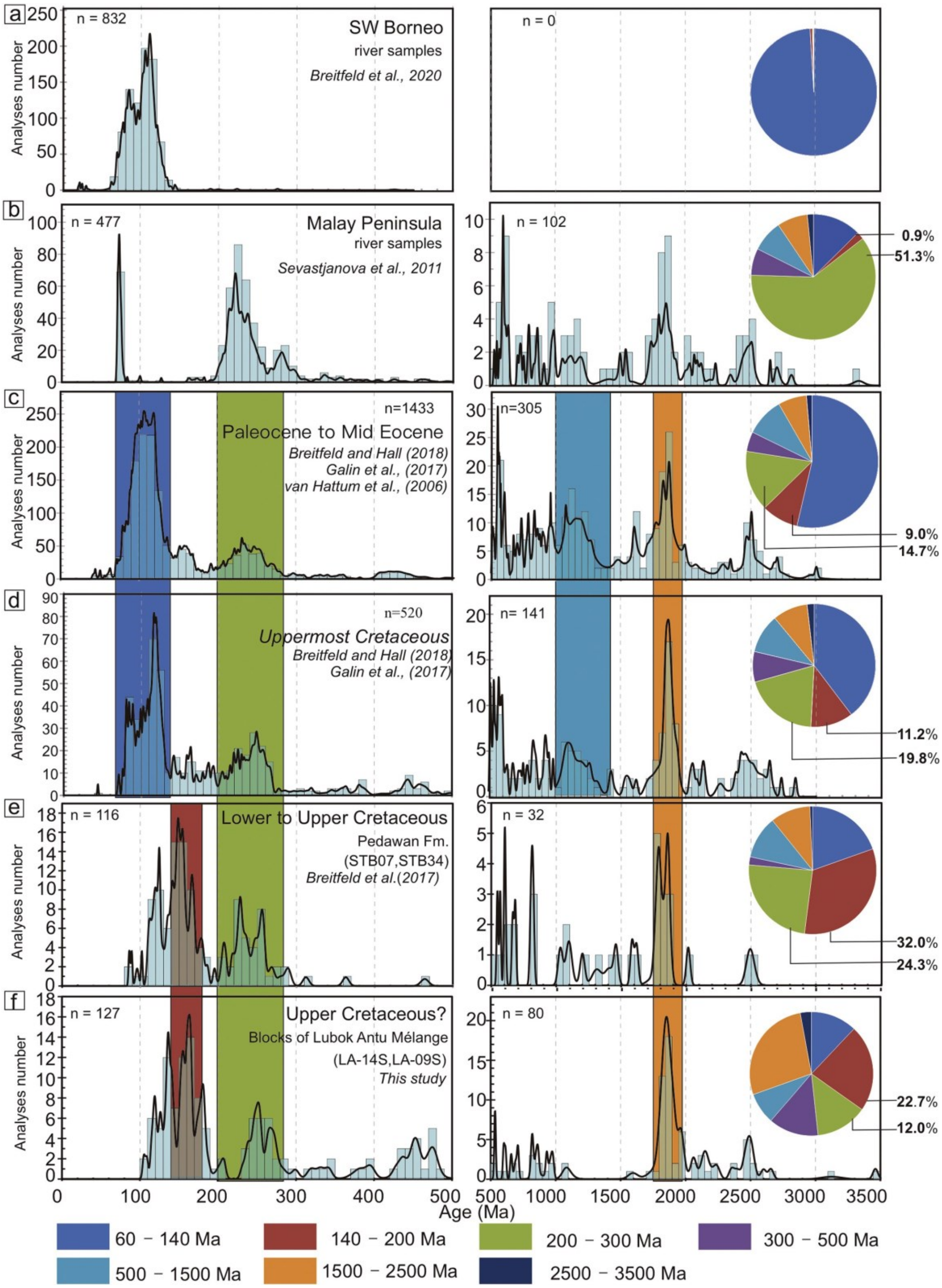


**Fig. 7.** (a–b) Detrital zircon U–Pb age histograms from modern river sands in potential sources. (c–f) Detrital zircon U–Pb age histograms from Upper Cretaceous

to Eocene sedimentary rocks in West Borneo. Published data for Cretaceous to Middle Eocene samples based on Breitfeld and Hall (2018), Galin et al. (2017) and van Hattum et al. (2006). Published data for modern river sands, including SW Borneo (Breitfeld et al., 2020) and the Malay Peninsula (Sevastjanova et al., 2011). See Table S2 for Compiled age data.

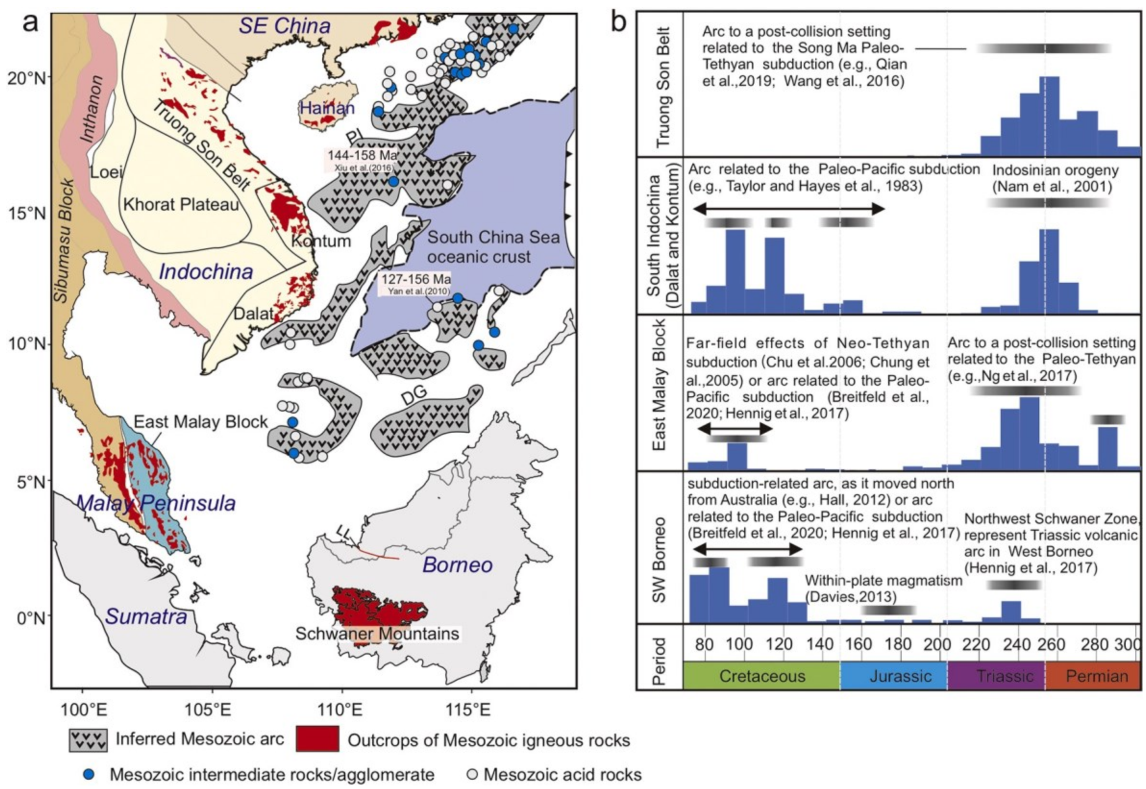


**Fig. 8.** (a) Map showing the outcrops of Mesozoic magmatic rocks and possible spatial distribution of Mesozoic arc in the present-day South China Sea margin (modified after Li et al., 2018). PI: Paracel Islands; DG: Dangerous Ground. (b) Mesozoic episodic tectono-magmatism in eastern margin of Indochina, SW Borneo, East Malay Peninsula. Published age data and locations for the Mesozoic tectono-magmatism surrounding the South China Sea are from Truong Son Belt (Hieu et al., 2016; Hou et al., 2019; Qian et al., 2019; Roger et al., 2012; Shao et al., 2017; Wang et al., 2016), South Indochina (Fyhn et al., 2010; Nam et al., 2001; Nguyen et al., 2004; Shellnutt et al., 2013),SW Borneo (Breitfeld et al., 2020; Hennig et al., 2017;

Setiawan et al., 2013; van Hattum et al., 2013) and East Malay block (Cao et al., 2020; Du et al., 2020; Gillespie et al., 2019; Ng et al., 2015b; Ng et al., 2017; Oliver et al., 2014; Searle et al., 2012) The data are provided in Table S4.

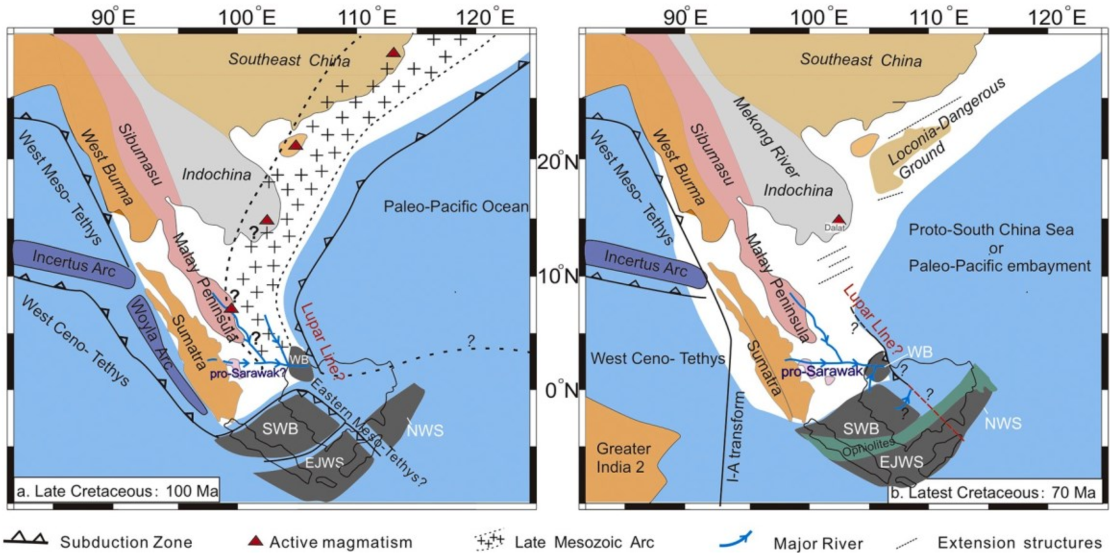


**Fig. 9.** Reconstruction of deposition and provenance of the Lubok Antu M´elange and the Lupar Formation in the (a). Late Cretaceous to (b). Latest Cretaceous. Positions of terranes, and sizes of main continental fragments of Borneo are modified from Breitfeld et al. (2017), Galin et al. (2017), Hall (2012) and Hennig et al. (2017). The reconstruction for Paleo-Pacific Ocean and Ceno/Meso-Tethys is modified from Metcalfe (2011), Incertus Arc and Woyla Arc are based on Hall (2012). The inferred pro-Sarawak river is based on Breitfeld et al. (2018). EJWS— East Java-West Sulawesi; NWS—Northwest Sulawesi and E Sabah.