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# Nature of the Paleo-Pacific Subduction Along the East Asian Continental Margin in the Mesozoic: Insights From the Sedimentary Record of West Sarawak, Borneo

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**Key Points:**

- Triassic sediments in West Sarawak were mainly sourced from the craton erosion
- Paleo-Pacific slab underwent the Early Jurassic shallowing subduction, followed by slab steepening after the Middle Jurassic in West Borneo
- The subduction of Paleo-Pacific plate had variable slab dip histories from West Borneo to northeast China during the Mesozoic

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Abstract** The Mesozoic subduction history of the Paleo-Pacific plate below the East Asian margin remains contentious, in part because the southern part is poorly understood. To address this, we conducted a sediment provenance study to constrain Mesozoic subduction history below West Sarawak, Borneo. A combination of detrital zircon U-Pb geochronology, heavy minerals, trace element, and bulk rock Nd isotope data were used to identify the tectonic events. The overall maturity of mineral assemblages, dominantly felsic sources, abundant Precambrian-aged zircons, and low εNd(0) values (average −13.07) seen in Late Triassic sedimentary rocks suggest a period of inactive subduction near Borneo. Slab shallowing subduction occurred between 200 and 170 Ma based on subdued magmatism and tectonic compression across West Sarawak. From c. 170 to 70 Ma there was widespread magmatism and we interpret the Paleo-Pacific slab steepened. Collectively, we show the Paleo-Pacific plate subduction had variable slab dip histories in Borneo.

**Plain Language Summary** Modeling studies have shown that the ocean slab underwent periodic shallowing and steepening in the long-term subduction system. To know the Mesozoic Paleo-Pacific subduction history of the southern section, we established the subduction process of West Sarawak by studying the provenance of Mesozoic sedimentary rocks. Based on it, we subsequently deduce that west dipping subduction of the Paleo-Pacific slab underwent periodic shallowing and steepening of slab dip from north to south.

## 1. Introduction

The nature of Mesozoic tectono-magmatic evolution within East Asia and their links to the subduction history of tectonic plates that existed prior to the current Pacific realm (i.e., Paleo-Pacific) remains a controversial topic (Jahn, 1974; Li & Li, 2007; Wu et al., 2019; Zhou & Li, 2000). Extensive magmatism took place in northeast China (Tang et al., 2016; W. L. Xu et al., 2013; Z. J. Xu et al., 2013), Japan (Pastor-Galán et al., 2021), the North China Block (Wu et al., 2019), southeast China (Li & Li, 2007), Pearl River Mouth Basin (Xu et al., 2017; Yan et al., 2014), Indochina Peninsula (Nguyen et al., 2004), and Borneo (Breitfeld et al., 2017; Wang et al., 2022), forming a NNE-trending volcanic-intrusive complex belt (Figure 1a). It is thought that subduction and rollback of the Paleo-Pacific plate are the main dynamic factors responsible for the destruction of the North China Craton (Hao et al., 2020; Li et al., 2019), Yanshan movement (or Orogeny) (Wang et al., 2011; Wu et al., 2019) and a flare-up in magmatic activity along the East Asian continental margin (Li & Li, 2007; Zhou et al., 2021).

Numerous studies reveal variable subduction timing of the Paleo-Pacific plate beneath different parts of the East Asian continental margin. In the Korean Peninsula, the Paleo-Pacific plate subduction initiated in the Late Triassic (232–226 Ma) (Kim et al., 2015). For the North China Craton, westward subduction of the Paleo-Pacific plate is inferred to have commenced at least in the Early Jurassic (Wu et al., 2019; Zhu & Xu, 2019). For South China, the earliest record of subduction of the Paleo-Pacific plate can be traced back to 500 Ma (Gao et al., 2022; Isozaki et al., 2010; Pastor-Galán et al., 2021), whereas Li and Li (2007) proposed that subduction started in the Permian.

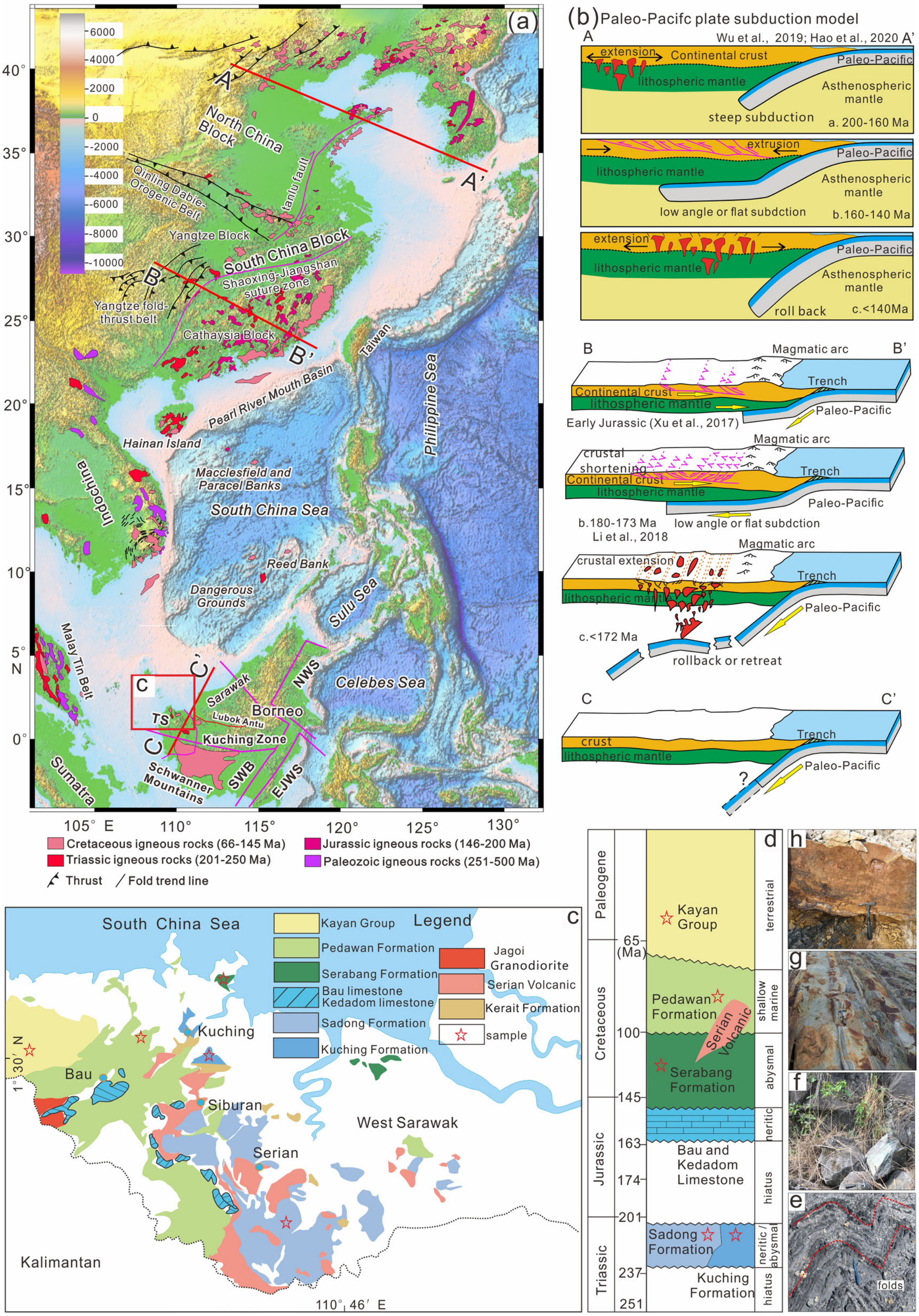



**Figure 1.** (a) Distribution of Mesozoic intrusive rocks in the East Asian continental margin (Li & Li, 2007; Wu et al., 2019; Zhou et al., 2020), NWS: Northwest Sulawesi; SWB: Southwest Borneo; EJWS: East Java-West Sulawesi; TS: Triassic Sundaland. (b) Cartoon showing the subduction of the Paleo-Pacific slab. (c) Sample locations from this study. (d) Stratigraphic column of the West Sarawak (Hutchison, 2005). (d–h) field photos of the Kuching, Serabang, Pedawan Formation and Kayan Group, respectively.

In contrast, other researchers suggested that subduction did not commence until the Triassic (Zhu et al., 2013), Early Jurassic (Xu et al., 2017).

Another controversy is related to how subduction accounted for Mesozoic magmatism parallel to the Paleo-Pacific plate subduction zone with proponents arguing for: (a) prolonged flat slab subduction (Li & Li, 2007), (b) slab steepening from gentle dip in the Jurassic to a moderate dip in the Cretaceous (Zhou & Li, 2000), and (c) oblique subduction (Xu et al., 2017). These different interpretations, in part, stem from a lack of integrated understanding of subduction histories along the entire East Asian continental margin, from north to south. The North and South China Blocks have been well-studied (Li & Li, 2007; Wu et al., 2019; Zhou & Li, 2000; Zhu & Xu, 2019) but the subduction history of the southern section is less understood, especially for Borneo (Figure 1b). To address this shortfall, we investigated the subduction history of West Sarawak, Borneo by studying the provenance of Mesozoic sedimentary rocks. We expanded on published datasets by adding detrital zircon U-Pb analyses, heavy mineral composition, major, trace element, and Nd isotope data. Specific aims are to define: (a) the magmatic pulses characteristic of this southernmost part of the Paleo-Pacific subduction zone; (b) the regional tectonic setting for northwest Borneo during the Triassic to Cretaceous; (c) how the Paleo-Pacific plate subducted along the different parts of East Asian continental margin in the Mesozoic, with the discussion of possible implications for the Paleo-Pacific slab dip histories from the inferred magmatism and subduction process.

## 2. Geological Background

Borneo is the largest island in Asia and is located in the southern part of the Paleo-Pacific plate subduction zone (Breitfeld et al., 2017; Hall, 2012). It formed by the accretion of small blocks to the Triassic-aged Sundaland core of Borneo (TS in Figure 1a), including Southwest Borneo, Northwest Sulawesi and East Java-West Sulawesi (Breitfeld et al., 2017) (Figure 1a). Within a west-directed subduction margin setting, Mesozoic magmatism and volcaniclastics are preserved in West Sarawak, especially within the Kuching zone.

The oldest clastic sedimentary rocks exposed in the West Sarawak have been assigned to the Triassic Sadong and Kuching Formations (Figure 1d). The Late Triassic Sadong Formation is interpreted as an estuarine to neritic deposit. The Kuching Formation is a deep marine turbidite lateral equivalent of the shallow marine Sadong Formation, comprising an alternation of graded sandstones, siltstones, and mudstones (Breitfeld et al., 2017). The Upper Jurassic to Lower Cretaceous Serabang, Sejingkat, Sebangan Formations and Lubok Antu Melange are similar in lithology and age (Hutchison, 2005), and so are grouped and named the Serabang Formation in this paper. The Kuching Formation was folded prior to the deposition of the Serabang Formation (Figures 1e and 1f). The deep marine Pedawan Formation contains sandstone, pebbly mudstones, argillaceous limestone, and is overlain by the terrestrial uppermost Cretaceous to Eocene Kayan Group (Figures 1g and 1h).

## 3. Sampling and Methodology

Fresh samples of sandstones and siltstones from the Sadong, Kuching, Serabang, Pedawan Formations, and the Kayan Group were collected for heavy mineral analyses in the Langfang Chengxin Geological Service Co., Ltd, China. Detrital zircon U-Pb dating and geochemistry analyses of the samples were performed at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The major and trace elements of the mudstones were analyzed by whole-rock X-ray fluorescence (XRF) spectrometry and the Thermo Scientific iCAP Qc instrument respectively. The Nd isotopic ratios of the samples were analyzed on a MicroMass Isoprobe multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) in the Institute of Geology and Geophysics, Chinese Academy of Sciences. $(^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$ was used to calculate the εNd value recalculated at time $T = 0$.

## 4. Results

A wide range of heavy minerals was detected and summarized in Figure 2b. The heavy mineral assemblage of Triassic sediments is dominated by zircon-tourmaline-rutile (ZTR). Serabang sandstones contain abundant ilmenite, garnet, and some augite, consistent with metamorphic and basic igneous sources. Chrome spinel is widely found in the Pedawan Formation and Kayan Group, indicating ultrabasic input (Figure 2b). The ZTR index reflects the maturity of the heavy mineral assemblage (Morton & Hallsworth, 1994). Triassic sediments'

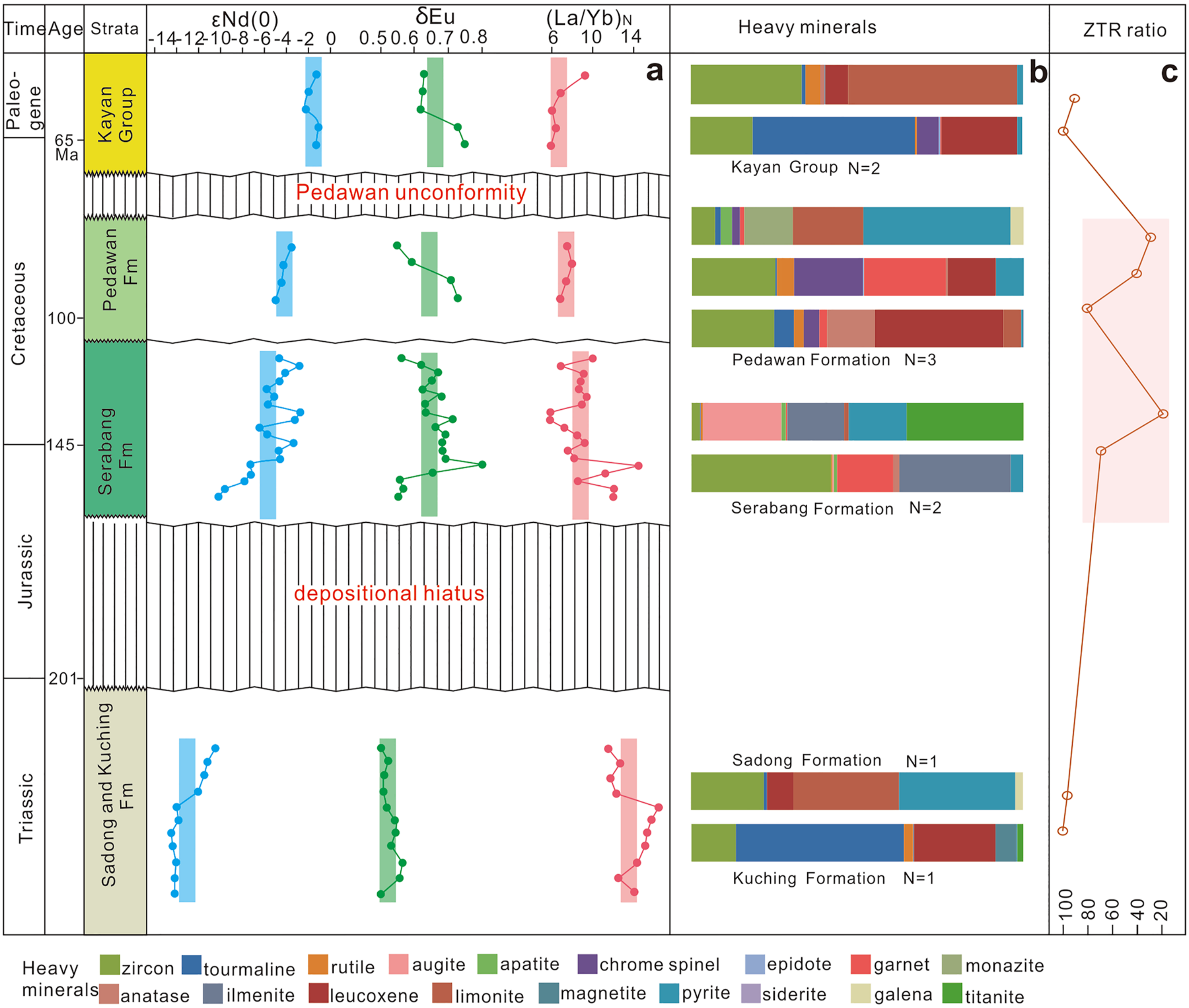



**Figure 2.** (a) Plot of εNd(0), δEu and $(La/Yb)_N$ values of mudstone samples. Part of the Serabang Formation (Lubok Antu Melange) is from Zhao et al. (2021). (b) Heavy mineral abundance in the sediments. (c) Sample ZTR ratio.

ZTR values are very high (>85%), indicating maturity (Figure 2c) whereas the Serabang Formation and Pedawan Formation have a very low ZTR (average ~ 50%) indicative of immaturity. The Late Triassic samples are on the whole characterized by abundant $SiO_2$ content ($Al_2O_3/SiO_2$, average 0.33), high Th/Sc (average 1.52), La/Sc (average 4.15), Th/Sc (average 1.52) ratios, and low δEu (average 0.52) content, suggesting dominantly felsic source rocks (Gu et al., 2002). From the Triassic to Eocene, the younger sediments have lower $Al_2O_3/TiO_2$, La/Sc, Th/Sc values and higher concentrations of ferromagnesian trace elements Sc (average 14.12–18.11 ppm), V (average 102.75–150.20 ppm), Ni (average 22.82–27.65 ppm), V (average 60.47–71.26 ppm) values, reflecting more mafic components in the provenance (Table S1 in Supporting Information S1) (Armstrong–Altrin et al., 2004). The εNd(0) values of the samples range from −14.29 to −1.09 (Figure 2a). Triassic sediments have the lowest εNd(0) values, ranging from −14.29 to −10.49 (average of −13.07). The εNd(0) values increase rapidly in Late Jurassic to Early Cretaceous Serabang sediments (average of −5.57) and the uppermost Jurassic to Cretaceous Pedawan Formation (average of −4.33). In the Kayan Group, the εNd(0) values are concentrated in the range of −1.09 to −2.22 (average of −1.57). In general, the εNd(0) values of the mudstone gradually increase from the Triassic to Eocene. Detrital zircon U-Pb analyses from the three samples are presented in the Table S4 in Supporting Information S1.

## 5. Discussion

### 5.1. Provenance

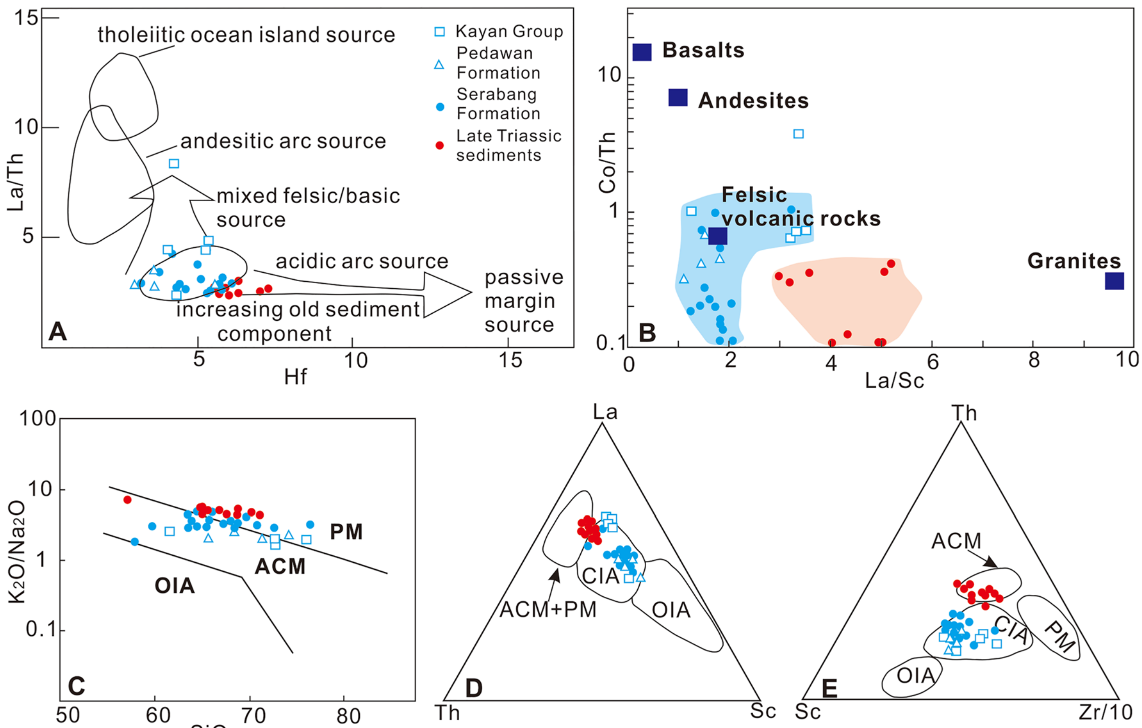
U–Pb ages of detrital zircon in the sediments can be used to identify the sources of detritus (Andersen, 2005; Liu et al., 2021). The detrital zircon from the Late Triassic-Late Cretaceous sediments yields a wide range of U–Pb ages, with main peaks at ca. 102, 110–120, 160, 250–260, 360, 440–460, and 1,800–1,900 Ma (Figure 4). The mid-Paleozoic Kwangsian Orogeny (460–400 Ma) in the Cathaysia (Xu et al., 2016) and coeval 460 to 400 Ma granitic rocks in the Indochina block (Wang et al., 2016) indicate the most possible source area for the 440–460 Ma detrital zircons. Detrital zircons with ages of ca. 360 Ma were found in all the samples, however, no magmatic rocks of similar age have been reported in the Vietnam and Malay Peninsula. Based on the presence of the, 360 ± 10 Ma tuffs in the Japan (Pastor-Galán et al., 2021) and the Late Devonian granite (368 ± 5 Ma) in southern Hainan, a Paleozoic magmatic arc existed along the southeastern margin of the South China in response to subduction of the Paleo-Pacific (Gao et al., 2022; Hu et al., 2015; Pastor-Galán et al., 2021). Thus, these detrital zircons were most likely derived from the Paleozoic magmatic arc. The Permian-Triassic zircons peak from the Triassic -Cretaceous sandstones in the West Sarawak may have multiple possible sources. The εNd(0) values (ranging from −10.49 to −14.29) fall within the range of εNd(0) values of nearby Middle Permian to Late Triassic magmatic rocks from the Malay Peninsula (−5.72 to −12.71), Vietnam (−7.14 to −15.98), and South China block (−6.20 to −18.38) (Table S2 in Supporting Information S1), indicating the possible sediment sources from the above areas. The Late Triassic zircons might be also derived from the Jagoi granodiorite in the West Sarawak (Breitfeld et al., 2017). From the Middle Jurassic onwards, evidence of widespread magmatism (170–70 Ma) is present with 102, 110–120, and 160 Ma peaks (Figure 4). The Late Jurassic to Cretaceous magmatic arc was widely exposed across the South China, South Vietnam, and West Borneo (Zhao et al., 2021). The εNd(0) values (ranging from −3.53 to −10.20) of the Jurassic-Cretaceous samples from the West Sarawak also fall within the overlapped range of εNd(0) values of the nearby Jurassic - Cretaceous magmatism from the Vietnam (−1.5 to −4.5) and the Dangerous Grounds (−1.8 to −11.9) (Table S2 in Supporting Information S1). Taken together, our new results confirm the existence of a Late Jurassic to Late Cretaceous magmatic arc across the western continental margin of the South China Sea, South Vietnam, and West Borneo. U-Pb data show the highest proportion of Late Jurassic-Late Cretaceous detrital zircon ages in the younger sediments (Table S3 in Supporting Information S1) (Figure 4). Hence, we suggest that Late Jurassic to Late Cretaceous sediments received more Jurassic to Cretaceous magmatic rocks denudation from its vicinity during its sedimentation.

In summary, such zircon production events (peaks at 430, 360, 250–270, 160, 110–120, 102 Ma) accompanied by a progressive disappearance of older sources Paleozoic populations disappeared in younger samples are similar to the observed in the South China block (Chen et al., 2021; Pastor-Galán et al., 2021). It may indicate that the West Sarawak experienced a similar tectonic evolution with South China block from 430 to 100 Ma.

### 5.2. Tectonic Evolution

The dominantly felsic source rocks (Figure 3), low εNd(0) values (average of −13.07) (Table S1 in Supporting Information S1), high ZTR values (>85%), large proportion of the Precambrian zircon population (78%), all indicate that the source rocks of the Triassic sediments were mainly formed by erosion within a relatively tectonically-inactive continental margin. In the $SiO_2$-$K_2O/Na_2O$, La-Th-Sc and Th-Sc-Zr/10 ternary diagrams (Roser & Korsch, 1986; Bhatia & Crook, 1986), the Late Triassic sedimentary rocks are plotted between tectonic settings of the active continental margin and passive continental margin (Figure 3), consistent with the tectonic settings reflected by the average abundances of La (42.73 ppm), Cr (81.96 ppm) and the ratios of Sc/Cr (0.21), ∑LREE/∑HREE (11.52), La/Yb (19.20), and δEu (0.52) (Figure 3). These observations are supported by the general scarcity of volcanic detritus among the Triassic sediments (Kirk, 1968). Hence, we infer the Triassic sediments were deposited in a marginal basin adjacent to the ancient craton, suggesting a period of limited to completely inactive subduction in the Late Triassic (Figure 5b).

Early and Middle Jurassic rocks in West Sarawak are missing (Hutchison, 2005), presumably due to strong tectonic uplift. Early Jurassic granitoids in the Schwaner Mountains appear to reflect westward subduction of the Paleo-Pacific plate in the West Borneo (Wang et al., 2022). During this 200 to 170 Ma period of uplift and folding (Figures 1e and 1f), detrital zircon U–Pb age data show almost no record of magmatic activity in West Sarawak (magmatic lull in Table S3 in Supporting Information S1). Data from borehole samples from the Pearl

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| Tectonic settings | La | Ce | ΣLREE/ΣHREE | La/Yb | $(La/Yb)_N$ | Sc/Cr | δEu |
|---|---|---|---|---|---|---|---|
| Oceanic Island Arc | 8 ± 1.7 | 19 ± 3.7 | 3.8 ± 0.9 | 4.2 ± 1.3 | 2.8 ± 0.9 | 0.57 ± 0.16 | 1.04 ± 0.11 |
| Continental Island Arc | 27 ± 4.5 | 59 ± 8.2 | 7.7 ± 1.7 | 11.0 ± 3.6 | 7.5 ± 2.5 | 0.32 ± 0.06 | 0.79 ± 0.13 |
| Active Continental Margin | 37.00 | 78.00 | 9.10 | 12.50 | 8.50 | 0.30 ± 0.02 | 0.60 |
| Passive Margin | 39.00 | 85.00 | 8.50 | 15.90 | 10.80 | 0.16 ± 0.02 | 0.56 |
| Kayan Group | 32.70 | 72.20 | 6.50 | 9.56 | 6.86 | 0.24 | 0.67 |
| Padawan Formation | 18.78 | 37.04 | 7.45 | 10.32 | 7.40 | 0.25 | 0.65 |
| Serabang Foramtion | 29.74 | 58.92 | 8.44 | 12.18 | 8.74 | 0.28 | 0.65 |
| Triassic sediments | 42.73 | 81.96 | 11.52 | 19.20 | 13.78 | 0.21 | 0.52 |

**Figure 3.** (a) Hf-La/Th plot (Floyd & Leveridge, 1987), (b) La/Sc-Co/Th plot (Gu et al., 2002), (c) $K_2O/Na_2O-SiO_2$ plot (Roser & Korsch, 1986), (d) La-Th-Sc plot, (e) Th-Sc-Zr/10 plot (Bhatia & Crook, 1986). OIA: Oceanic Island Arc; CIA Continental Island Arc; ACM: Active Continental Margin; PM: Passive Margin. (f) Tectonic background of the sedimentary rocks from West Sarawak (Bhatia, 1985). The La, Ce value of the mudstone was divided by 1.2 to obtain the correction equivalent to that of the graywackes (W. L. Xu et al., 2013; Z. J. Xu et al., 2013). Part of the Serabang Formation (Lubok Antu Melange) is from Zhao et al. (2021).

River Mouth Basin, Reed Bank, and Dangerous Grounds also show intermittent magmatic activity during the Early Jurassic (Yan et al., 2010). This suggests that between ca. 200–170 Ma there probably was a magmatic lull across an extensive region stretching from the South China Sea to West Sarawak.

After the Middle Jurassic, abundant magmatism between 170 and ~70 Ma has been widely reported from the South China (Li & Li, 2007), Pearl River Mouth Basin (Xu et al., 2017), the southern Indochina Peninsula (Shellnutt et al., 2013), Dangerous Grounds (Yan et al., 2010), as well as Borneo (Wang et al., 2021; Zhao et al., 2021and this study). The immature heavy mineral assemblage, very low ZTRs (average ~ 50%), εNd(0) (average −5.57–4.33), progressive disappearance Precambrian zircon population and mixed felsic/basic source in the Hf-La/Th plot is consistent with the active continental margin to continental island arc tectonic setting from the La-Th-Sc and Th-Sc-Zr/10 ternary diagrams (Figure 3). All the observations suggest a period of active subduction with flare-ups of magmatism. The widespread Paleo-Pacific subduction and magmatism stretched from our West Borneo study area to northeast Asia (Wu et al., 2022).

### 5.3. Implication for Paleo-Pacific Slab Dip Angles

Modeling studies have shown that periodic shallowing and steepening of slab dips during long-term subduction (Guillaume et al., 2009; Yan et al., 2022). Slab shallowing subduction typically produce strong compression and

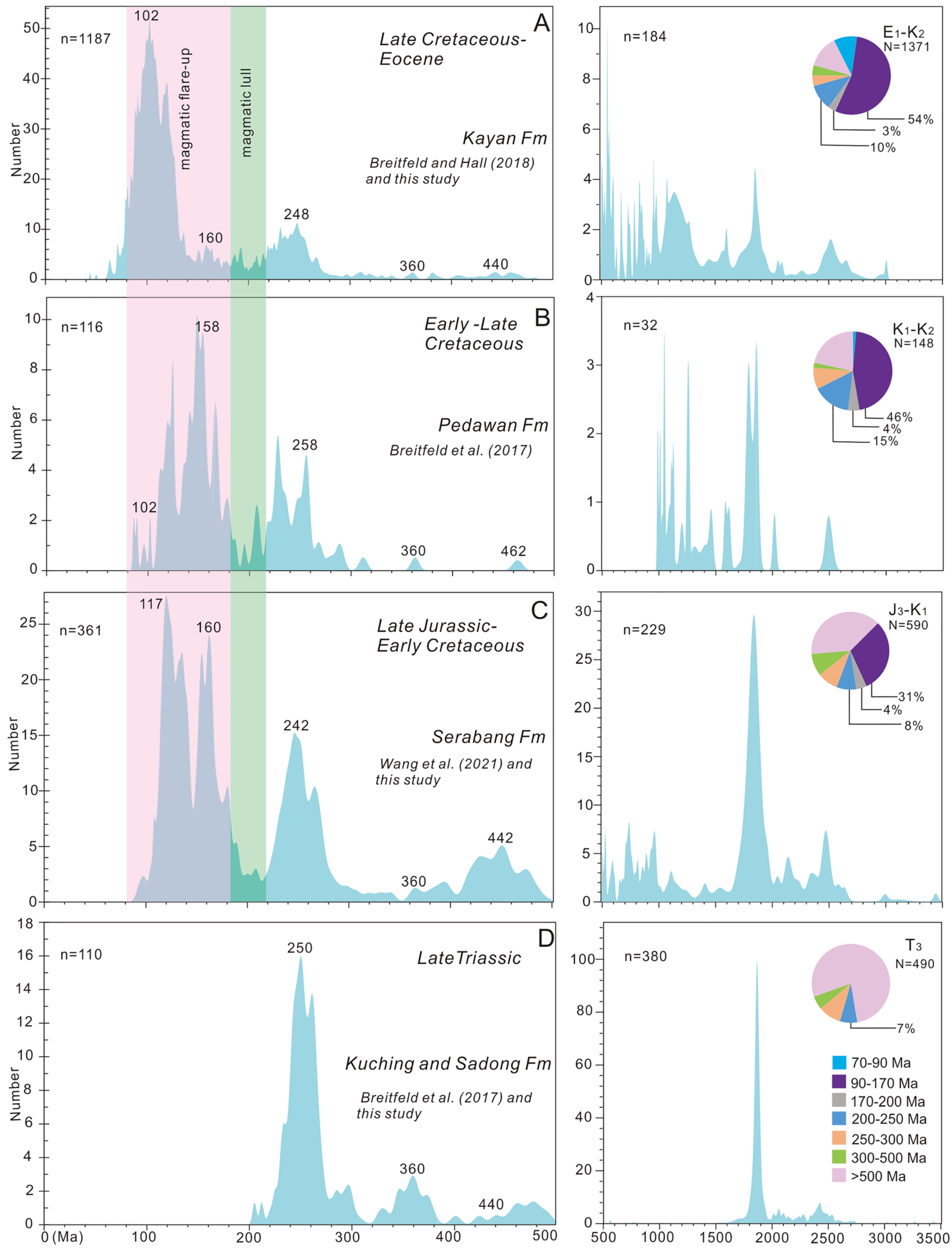


**Figure 4.** (a, b, c, d): Compilation of detrital zircon U–Pb age data of the Triassic to Cretaceous sedimentary rocks in West Borneo. Published data are from Breitfeld and Hall (2018), Breitfeld et al. (2017), Wang et al. (2021). See Table S3 in Supporting Information S1 for data.

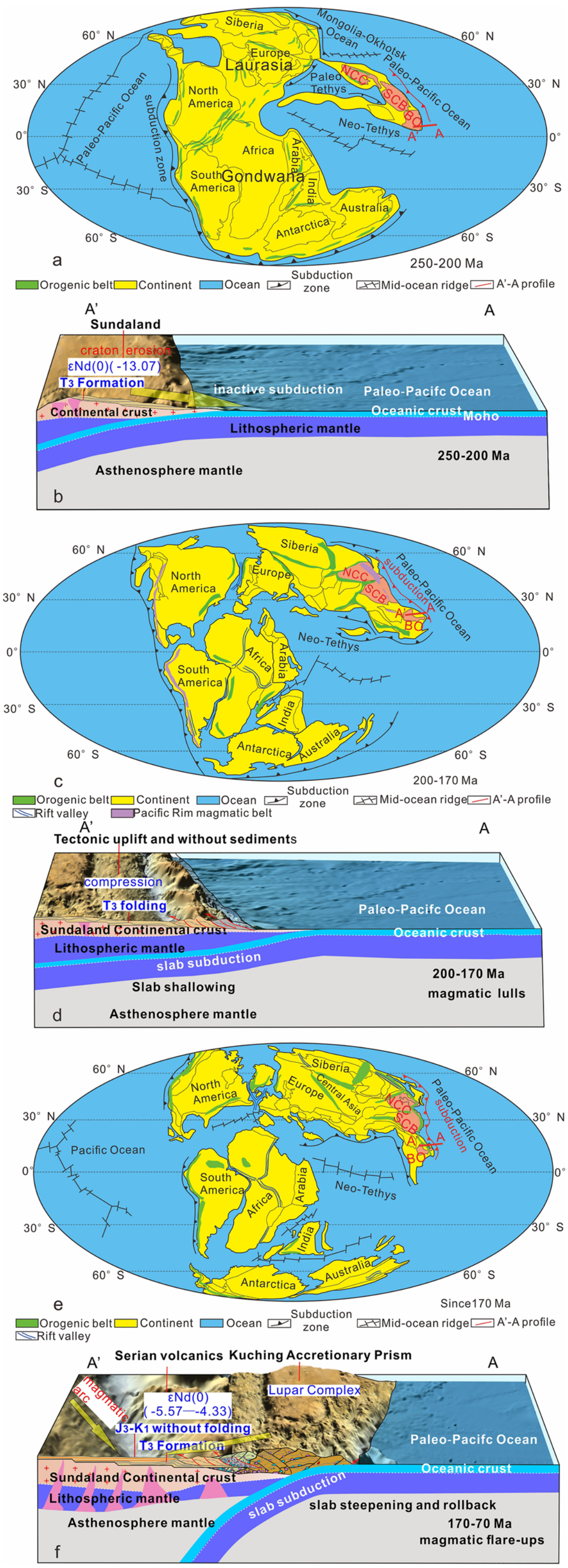


**Figure 5.** (a) Reconstructed map of Triassic Paleoplate (Li & Jiang, 2013). A'-A is the profile across Borneo. (b) Inactive subduction along the eastern margin of Sundaland. (c) Reconstructed map of 200–170 Ma Paleoplate (Li & Jiang, 2013). (d) The shallowing subduction of the Paleo-Pacific plate during 200–170 Ma. (e) Reconstructed map of Late Jurassic Paleoplate (Li & Jiang, 2013). (f) Increased magmatism due to slab steepening of the Paleo-Pacific plate. NCC—North China Craton, SCB—South China block, BO—Borneo.

magmatic quiescence in the overriding plate, whereas slab steepening (or rollback) typically results in the back-arc extension and increased magmatism (Lee & King, 2011; Zhang et al., 2019). In this context, detrital zircon U-Pb geochronology is especially useful since it can be used to track the evolution of magmatic arcs (Zhang et al., 2019) and thus infer changes in slab dip (Guillaume et al., 2009; Zhang et al., 2019). Evidence for such changes can be found across the former margin.

Within south-central Vietnam in the Middle Jurassic, a contractional fold belt developed with estimated shortening averaging 37% (Schmidt et al., 2021). Likewise, during Early-Middle Jurassic time the South China block experienced crustal shortening of up to 160 km across a 600 km wide fold belt (Li et al., 2018) coincident with a lull in magmatism (Table S3 in Supporting Information S1), also seen in West Borneo. Collectively, this evidence suggests a shallowing of the Paleo-Pacific slab beneath Southeast China and West Borneo ca. 200–170 Ma (Figure 5d). To the north it would appear that subduction at this time involved a more steeply dipping slab (Hao et al., 2020; Wu et al., 2019) since magmatism occurred across the eastern North China Craton.

In the Middle to Late Jurassic, eastern North China Craton was mostly subjected to compression with regional uplift from c. 167 Ma (Hao et al., 2020) and thrust-dominated deformation at 160–140 Ma (Wu et al., 2019). The structural reversal took place in the Early Cretaceous stage. There was an eastward younging trend of magmatism in the Cretaceous, accompanied by the extensional structures (Yang et al., 2007). This is consistent with a subduction model with a westerly dipping subduction of the Paleo-Pacific slab from the Middle–Late Jurassic flat or shallowing subduction, followed by the slab rolled back since the Early Cretaceous. After the Middle Jurassic (170–~70 Ma), West Borneo was possibly affected by back-arc extension and experienced increased magmatism associated with a seaward younging trend in the overriding plate (Figure S1 in Supporting Information S1), caused by slab steepening or rollback (Figure 5f).

The simplest explanation of our results in terms of periods of compression, breaks, and flare-ups of magmatism and changes in the younging direction of magmatism is that west dipping subduction of the Paleo-Pacific slab underwent periodic shallowing and steepening of slab dip, similar to that observed in other long-lived volcanic arcs including the Central Andes and Neo-Tethyan arc system from southern Tibet to Sumatra (Li et al., 2020; Zhang et al., 2019).

## 6. Conclusions

Sedimentary records from West Borneo analyzed in this study show Late Triassic sedimentary rocks that exhibit overall mature mineral assemblages, dominantly felsic and Precambrian-aged zircon population, and low εNd(0) values (average −13.07) that indicate craton erosion during a period of limited to completely inactive subduction. During the Early Jurassic, probable uplift and erosion are ascribed to flat subduction of the Paleo-Pacific slab that commenced during ca. 200–170 Ma. Starting in the Middle Jurassic, our results show abundant magmatism in West Borneo since ca. 170-70 Ma that implies the Paleo-Pacific subduction stretched from West Borneo to northeast China and the Russian Far East. We ascribe the West Borneo magmatism to a slab steepening event that was localized along the southernmost part of the East Asian continental margin.

## Data Availability Statement

Please use the link below to access the Tables S1, S2, S3, and S4 in the manuscript. https://doi.org/10.5281/zenodo.7724861.

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