Subduction history of the Proto-South China Sea: Evidence from the Cretaceous - Miocene strata records of Borneo

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Key Points

More than 60% of the sediments in Northwest Borneo came from a magmatic belt during the Late Cretaceous to Early Paleocene.

Diachronism of provenance and tectonic setting from southwest to northeast related to the scissor closure of the residual basin.

Ocean basin in Sarawak closed in Early Paleocene whereas subduction in Sabah continued during Late Eocene to Miocene.

Abstract

Cretaceous - Miocene sedimentary rocks of northern Borneo preserve records of subduction of the Paleo-Pacific and Proto-South China Sea, providing important evidence for reconstructing the tectonic evolution of Southeast Asia since the Mesozoic. However, the genesis and tectonic setting of these sediments remain controversial. In this study, new Sr isotope, combined with Nd isotope data were used to determine the provenance contribution of the Cretaceous – Late Eocene Lubok Antu mélange and the Rajang Group. Detrital zircon ages and sedimentary geochemistry data of the Cretaceous - Miocene strata are also used to better understand the tectonic evolution of Borneo. Results show that more than 60% of the sediments came from a magmatic belt during the Late Cretaceous to Early Paleocene, and more than 50% from the Malay Peninsula during the Paleocene to the Late Eocene. The proportion of different detrital zircon ages and sedimentary geochemical characteristics in Borneo changed from west to east during the Cretaceous to the Miocene, which may be related to drainage changes caused by the gradual closure of an ocean basin. Subduction ceased in central Borneo during the Early Paleocene, slightly later than Late Cretaceous cessation in western Borneo. The collapse of magmatic belt lead river drainages from the Malay Peninsula to flow into Borneo. Whereas subduction continued in Eastern Borneo until the Miocene. Opening of the South China Sea cut off the drainage from the Malay Peninsula, and the inner rocks in Borneo once again became the main source of sediments.

Plain Language Summary:

The Paleo-Pacific and Proto-South Sea left a huge set of sediments in Borneo, providing a window into how these two oceans disappeared. However, the question of where these sediments came from and how they formed remains unclear. In this study, we studied the chemical elements of these sediments, combine with the ages of the zircon minerals in sediments to reconstruct the disappearance of these two oceans. Results show that more than 60% of the sediments came from a magmatic belt during the Cretaceous to Early Paleocene, and more than 50% from the Malay Peninsula during the Paleocene to the Late Eocene. In addition, we found that the characteristics of these sediments varied regularly from southwest to northeast in Borneo. We suggest this change is related to the gradual disappearance of the Paleo-Pacific and Proto-South China Sea from west to east in Borneo. The Paleo-Pacific disappeared during the Late Cretaceous in the western Borneo, then disappeared in the Early Paleocene in central Borneo. Rivers carried sediment from the Malay Peninsula into Borneo. The Proto-South China Sea gradually disappeared beneath the Sabah region of northeastern Borneo until the Miocene, and the inner rocks of Borneo became the main source of sediment.

Keywords: Proto-South China Sea, Paleo-Pacific Ocean, Borneo, Geochemistry, Sedimentary provenance

1. Introduction

As the predecessor of the South China Sea, the Proto-South China Sea was bounded by Indochina and South China to the north and Borneo to the south (Holloway, 1982; Taylor & Hayes, 1983). Although the term Proto-South China Sea has been used by many researchers, it is difficult to observe remnants of the Proto-South China Sea on the surface due to subduction and opening of the modern South China Sea. A clear understanding of the process from formation to extinction of the Proto-South China Sea is not only instructive for the expansion mechanism of the modern South China Sea, but can also add to our understanding of the evolution of how Southeast Asia developed.

During the Triassic to Late Cretaceous, the margins of the South China block and Sundaland experienced subduction of the Paleo-Pacific Ocean, forming a Late Mesozoic magmatic belt stretching thousands of kilometers from Japan to Sumatra (Hutchison, 2010; Xu et al., 2016; Li et al., 2018; Breitfeld et al., 2020a; Wang et al., 2021). Southeast Asia experienced extensional and rifting events due to the retreat and cessation of Paleo-Pacific subduction (Shellnutt et al., 2013; Liu et al., 2016; Li et al., 2019b). The shift from compressional to extensional tectonic setting led to opening and expansion of the South China Sea in a broadly north-south direction, accompanied by subduction of the Proto-South China Sea beneath Borneo-Palawan (Cullen et al., 2010; Li et al., 2020). The geology of Borneo records the Late Cretaceous Paleo-Pacific Ocean subduction and Proto-South China Sea subduction in Cenozoic, but existing data leave open questions regarding the timing of subduction events and whether they overlapped in space and time, and which events link and/or distinguish the two subductions? Hutchison (1996, 2005) suggested that the subduction of the Paleo-Pacific/Proto-South China Sea along Sarawak, North Borneo, began in Late Cretaceous and ceased in Late Eocene, and the continental island arc of the Schwaner Mountains (Hutchison 2005), the forearc basin of the Kuching Supergroup (Williams et al., 1988), the suture of the Lupar Line and the accretion prism of the Rajang Group (Hutchison, 2005) formed a completed "Trench-Arc-Basin" system. In this model, the end of subduction is marked by the shift of the sedimentary environment from the deep-sea Rajang Group to the terrestrial Tatau Formation, and that a major unconformity within the Rajang Group represented collision between Luconia, which rifted from South China, with Borneo. However, this model has been questioned. Magmatism of the Schwaner Mountains ceased before ~72-80 Ma (Moss, 1998; Davies et al., 2014; Breitfeld et al., 2020a), and Hennig et al. (2017) pointed out that the magmatic rocks of the Schwaner Mountains and contemporaneous magmatic rocks in West Borneo have a similar geochemistry formed by subduction of the Paleo-Pacific Ocean. The youngest age of ophiolites outcrop near the Lupar Line are Late Cretaceous (Wang et al., 2016; Hennig et al., 2017), which are consistent with the maximum sedimentary age of tectonic mélange formed by subduction (Zhao et al., 2022). U-Pb ages of detrital zircons and the composition of heavy minerals showed that the Kuching Supergroup were not part of a forearc basin, and that the Rajang Group was deposited in passive continental margin setting, separated from the Kuching Supergroup by the srike-slip fault of the Lupar Line (Breitfeld & Hall, 2018; Breitfeld et al., 2018; Galin et al., 2017). Thus, Hall and Breitfeld (2017) suggested that the crust subducted under Northwest Borneo before the Late Cretaceous belonged to the Paleo-Pacific Ocean, and that the Proto-South China Sea subducted under North Borneo after the Paleocene, and that a regional plate reorganization driven by northward motion of the Australia Plate, rather than subduction affected Borneo during Paleocene – Late Eocene. Other researchers proposed that the subduction ceased in the Paleocene (Moss, 1998; Hutchison, 2010; Madon et al., 2013; Wang et al., 2016). Zhao et al. (2022) considered that deformation ages of the mélange based on authigenic illite, recorded the cessation of subduction at c. 60 Ma and uplift of the Sibu Zone at 36 Ma,. Sedimentary geochemistry also recorded significant difference in strata before and after the Paleocene (Zhu et al., 2021). As for the subduction along Sabah, Northeast Borneo in the Eocene, geophysical data have identified lithospheric residues of the Proto-South China Sea beneath Sabah and

Philippine (Hall & Spakman, 2015; Wu & Suppe, 2018). The transition of the Middle/Late Eocene depositional environment from deep-sea to terrestrial facies and the large amount of pyroclastic material in Oligocene strata also support the beginning of the subduction at this time (Hall & Breitfeld, 2017), until Miocene collision between the Dangerous Ground block with Borneo.

A complete Cretaceous - Miocene sequence is preserved in Borneo (Liechi et al., 1960; Haile, 1974; Hutchison, 2005), which provides an excellent geological window into the evolution history of the Paleo-Pacific Ocean and Proto-South China Sea. These strata are extensive thick and strongly deformed. Due to the location near the equator, most outcrops are covered by vegetation and strongly weathered, hence geological work in Borneo is patchy. The Cretaceous - Miocene sedimentary sequence extends from the Kuching Zone in northwestern Borneo to the Sabah region in the northeast, and comprise the Kuching Supergroup in the Kuching Zone, the Rajang Group in Sibu Zone, and the Crocker Formations in Sabah. The Rajang Group and the contemporaneous formation in Sabah are also known as the Rajang-Crocker Group (Figure 1; van Hattum et al., 2006). Hamilton (1979) suggested that these sedimentary rocks were sourced from Indochina based on limited datasets centered on fission track analysis and paleocurrents. Moss (1998, 1999) commented that the sedimentary environment and scale of the Rajang-Crocker Group were similar to that of the present Bengal Fan, and that the source area comprised South China, Indochina and the Malay Peninsula. Researchers further suggested that sediments were transported from older terranes to the Sunda shelf via major rivers draining Southern China and Indochina, such as the Proto-Mekong (Hutchison, 1996; Hall, 1996; Métivier et al., 1999). However, Hennig et al. (2018) found that the Proto-Mekong flowed from south to north, which was quite different from the current flow of the Mekong River. A recent provenance study found that the Late Cretaceous and Permian-Triassic detrital zircon age peaks, and heavy mineral indicated a source area near Schwaner Mountains and the Malay Peninsula (van Hattum et al., 2006, 2013; Galin et al., 2017; Breitfeld et al., 2018). More basic-intermediate materials were found near the base of the Rajang Group (Zhu et al., 2021), and mass balance studies identified inconsistencies between the depositional volumes of the Rajang Group and the amount of denudation of the Malay Peninsula and the Schwaner Mountains (Zhao et al., 2021; Zhu et al., 2021). Oligocene - Miocene sediments deposited in the Miri Zone and Sabah region sit unconformably on the underlying Rajang-Crocker Group. This unconformity represents a collision event (Hutchison, 2005; Madon et al., 2013) or a regional reorganization event (Hall & Breitfeld, 2017) that uplifted the Sarawak region, where it is known as the Sarawak Orogeny. The Tatau Formation and Nyalau Formation in the Southwest Miri Zone were deposited in terrane environment, and geochemical data implied the sediments came from the erosion of the Rajang Group (Hennig-Breitfeld et al., 2019; Breitfeld et al., 2020b; Zhu et al., 2021), while the Setap Shale Formation in the northeast Miri Zone, the Temburong Formation and the Crocker Formation in Sabah were still in a deep-sea environment setting. The Early Miocene and overlying Neogene strata are separated by two unconformities. There are many different names for these unconformities in the literature, we use Top Crocker unconformity (TCU) and Deep Regional unconformity (DRU). The age difference between these two unconformities is less than 5 Myr. TCU was suggested to be caused by collision between the Dangerous Grounds and the Sabah–Cagayan Arc at about 17 Ma (Hall, 2013), and this angular unconformity at the bottom of the Meligan Formation can be observed at outcrop in both Sabah and Sarawak (Levell, 1987). By contrast, the tectonic event represented by DRU is not universally understood (Hutchison, 1996; Balaguru & Nichols, 2004; van Hattum et al., 2013; Hall, 2013). The transition of the sedimentary environment above the unconformity to continental facies, mark the end of the bathyal environments in the Sabah area.

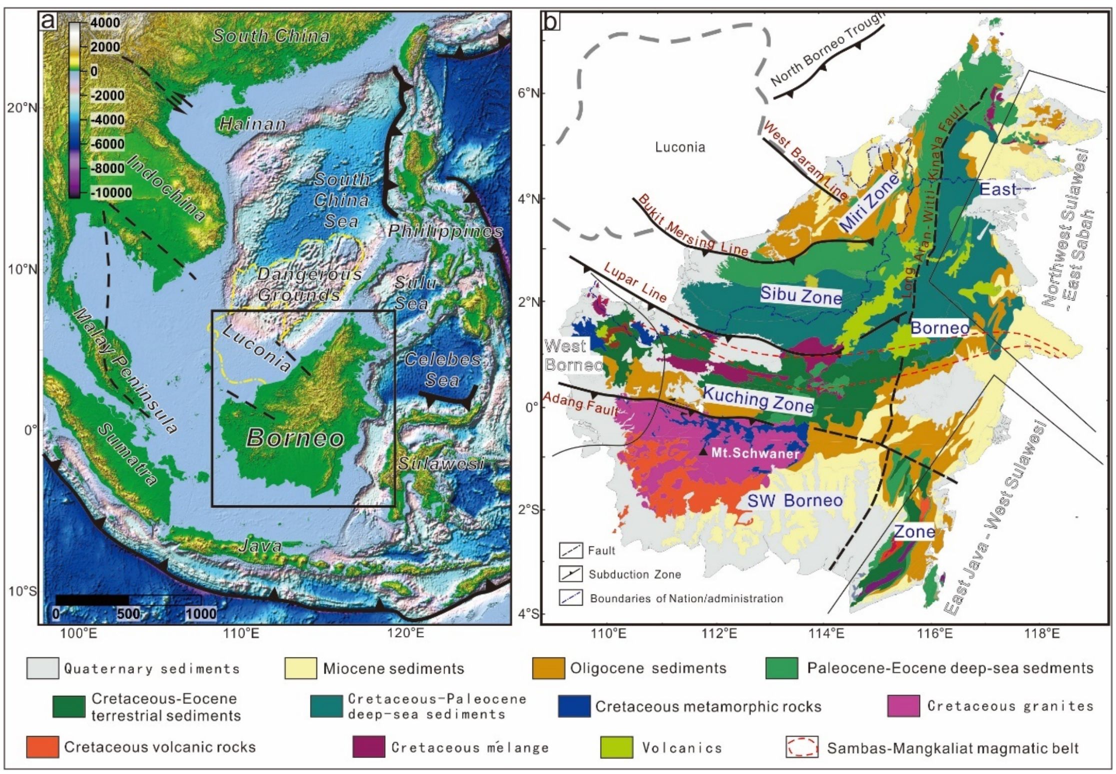

Figure 1. Geological map of Borneo (modified after Haile, 1974; Wang et al., 2016; Breitfeld et al., 2017; Hennig et al., 2017).

Previous studies on the Late Cretaceous - Miocene strata in Borneo have mainly focused on qualitative sedimentary provenance analysis and interpretations lacked a continuous spatial and temporal framework. In this study we: 1) locate the potential source area of the Rajang Group ; 2) attempt to semi-quantitatively calculate the contribution of the potential provenance areas of the Rajang Group using Sr-Nd isotope and 3) reconstruct the Cretaceous to

Miocene paleogeography of Borneo and closure of the Proto-South China Sea.

1. **Regional Geology**

Borneo, in the southern part of the South China Sea, is a complex patchwork of fragments. Previous work has divided Borneo into five parts. SW Borneo rifted from Gondwana in the Jurassic and collided with SE Sundaland in the Early Cretaceous and then experienced subduction of ocean crust. These events were recorded in the Schwaner Mountains. Northern Schwaner is mainly composed of Cretaceous subduction-related magmatic rocks and metamorphic rocks (Davies et al., 2014; Breitfeld et al., 2020a). Triassic - Jurassic and Cretaceous subduction-related rocks outcrop in the Northwestern Schwaner, and the Southern Schwaner comprise of Cretaceous and Jurassic post-collisional granitiod rocks (Davies et al., 2014; Setiawan et al., 2013; Hennig et al., 2017; Breitfeld et al., 2020a). North of the Schwaner Mountains is the Kuching Zone. The basement of Sundaland, Triassic igneous rocks and Mesozoic sedimentary rocks that outcrop in western Kuching. Most of the eastern area is covered by the Late Cretaceous - Eocene Kuching Supergroup that was deposited in a terrestrial setting. It is divided into the Kayan Group and the Ketungau Group (Breitfeld et al., 2018; Breitfeld & Hall, 2018). These strata are mainly sandstones, mud rocks and conglomerates, plus occasional volcanic material. The Lubok Antu mélange and Sambas-Mangkaliat granite belt are distributed along the Lupar Line, north of the Kuching Zone (Tan, 1982; William, 1988; Hutchison, 1996; Amiruddin, 2009). U-Pb ages of detrital zircon record a maximum depositional age for the Lubok Antu mélange of 105-115 Ma (Zhao et al., 2022). Ages of Sambas-Mangkaliat magmatic rocks are 74.9-80.6 Ma, considered a result of subduction roll back (Amiruddin, 2009). North of the Lupar Line is the Sibu Zone, which is covered by the Rajang Group. The nature of the basement is poorly known because of the thick sediment cover. Stratigraphic age control of the cover rocks, based on micro-palaeontology spans the Late Cretaceous to Late Eocene. There is a general younging trend from south to north (Liechti et al., 1960; Hutchison, 2005). The Rajang Group are divided into the Lupar Formation and the Belaga Formation. The Belaga Formation comprises of the Layar, Kapit, Pelagus, Metah and Bawang Member. Galin et al. (2017) and Hennig-Breitfeld et al. (2019) separated the Rajang Group into four Units based on detrital zircon ages and heavy minerals, among which the Lupar Formation, the Layar Member and the lower Kapait Member were grouped into Unit 1. The upper Kapit Member and the Pelagus Member were Unit 2, and the Metah Member and the Bawang Member were divided into Unit 3 and Unit 4 respectively (Fig. 3). Oligocene - Miocene sediments were deposited in the Miri Zone, which is separated from the Sibu Zone by Bukit-Mersing Line. The Oligocene Tatau Formation and Oligocene-Early Miocene Nyalau Formation unconformably overly the Rajang Group (Breitfeld et al., 2020b). The base of the Tatau Formation is conglomerate and this gradually changes upsection to sandstone with coal seams, reflecting a change in sedimentary environment from abyssal facies to marsh facies. The Nyalau Formation and the Setap Shale Formation cover most of the Miri Zone. The Nyalau Formation is located southwest of the Miri Zone and has a tide-influenced delta sedimentary facies and huge thickness. The Setap Shale Formation in the northeast has the same sedimentary age as the Nyalau Formation is but is a deep-sea black shale. The unconformity is overlain by post-Miocene sedimentary strata, such as the Tukau Formation, Belait Formation and Lambir Formation. Sabah is an area in the northeast of the Miri Zone and in northern of East Borneo Zone. It contains Late Mesozoic to Cenozoic sedimentary strata, which overlying the basement of hornblende schist, gneiss and ultramafics. These basement rocks outcrop in the Mount Kinabalu and Darvel Bay area and have ages concentrated in the Middle Jurassic to Early Cretaceous (Hutchison, 1989; Rangin et al., 1990; Macpherson et al., 2010). The Upper Cretaceous - Middle Eocene consists of deep-sea turbidites (Trusmadi Formation and Sapulut Formation, corresponding to the Rajang Group in the Sarawak) unconformable on the Sabah basement (Hutchison, 1996). Hutchison (1996) split the Crocker Formation into the "Lower Crocker Group", and the "Upper Crocker Group". The age of the Upper Crocker Group is Eocene - Early Miocene. Before the Middle Miocene, the Sabah area was in a deep-sea environment setting, that changed to a river delta and shallow-marine environment (van Hattum et al., 2006, 2013). The southern part of the East Borneo has outcrops of Cretaceous mafic and deep-sea sediments thought to be associated with the subduction of Sulawesi Sea, while much of the rest of the area is covered by less studied Miocene-Quaternary sediments.

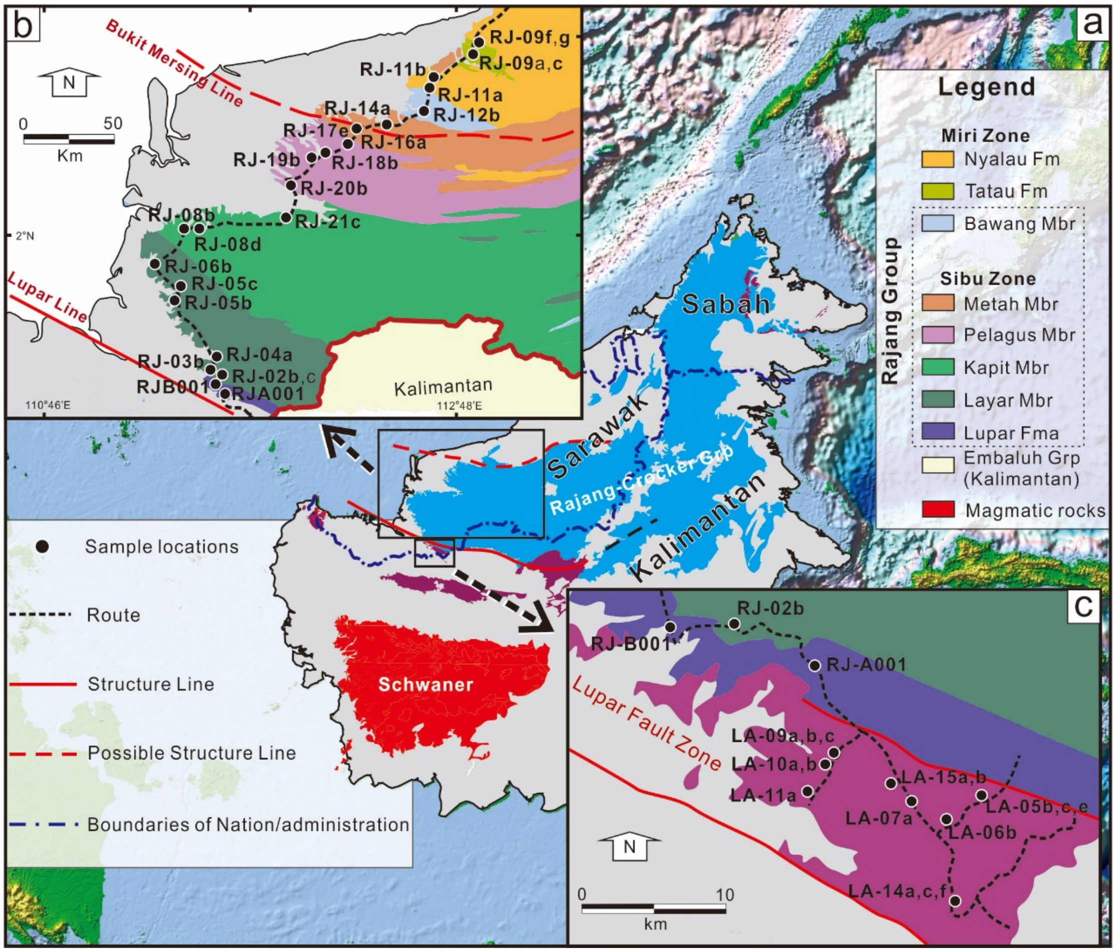

Figure 2. (a) Distribution of the Schwaner Mountains, Rajang-Crocker Group and mélange. (b) Geological map of Sibu Zone (c) Geological map of the Lupar Fault Zone. Modified after Liechti et al. (1960), Haile (1974), Hall (2013), Galin et al. (2017), Breitfeld et al. (2020b), Zhao et al. (2022).

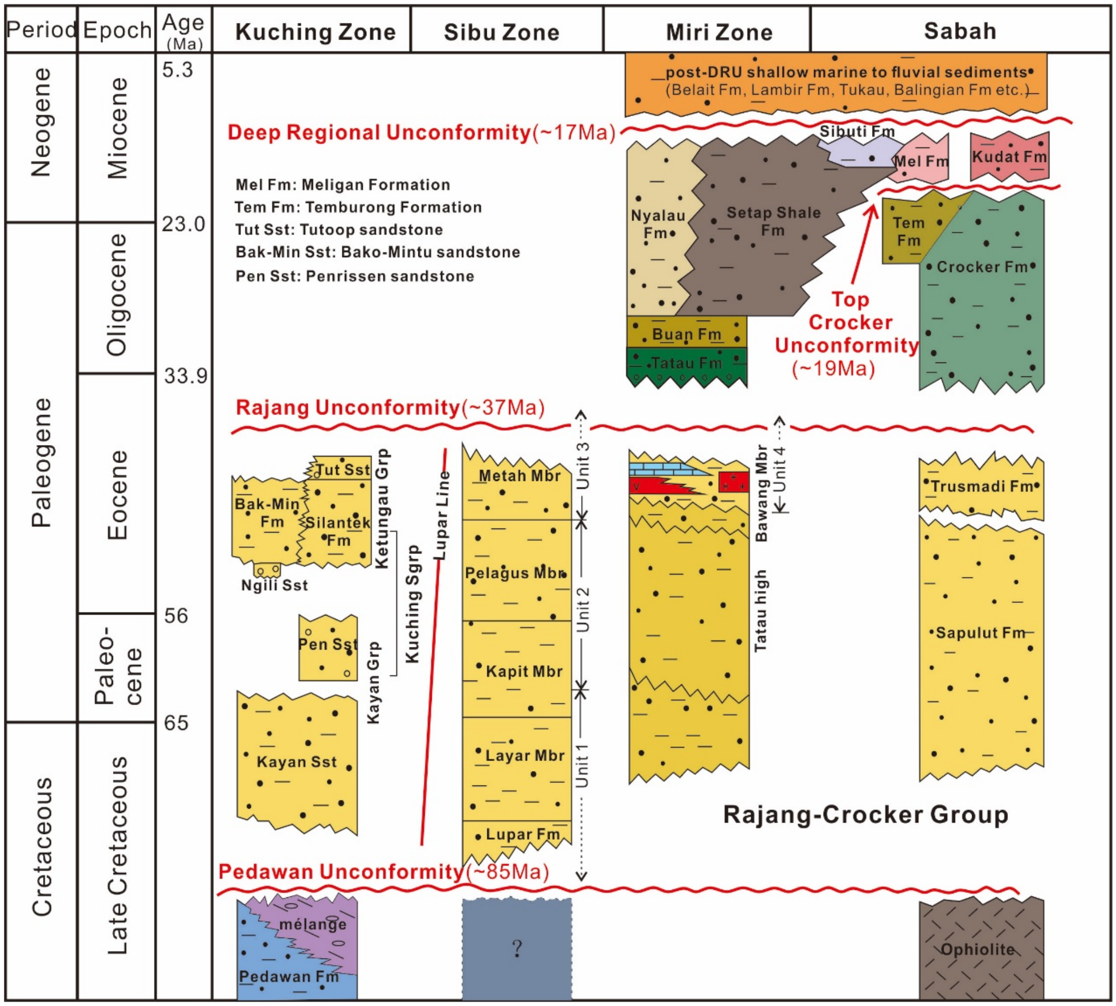

Figure 3. Simplified stratigraphy of northern Borneo based on Balaguru and Nichols (2004), Hall and Breitfeld (2017), Zhao et al. (2020a), Breitfeld et al. (2020b) and Burley et al. (2021).

1. **Sampling and analysis methods**

To better understand the geology, fieldwork was carried out in Lubok Antu valley, Sibu Zone and Miri Zone, of western Borneo. Samples were collected mainly along the Pan-Borneo Highway from the Lupar valley to Tatau (Fig. 2b, 2c). Seventy-four surface sediment samples were collected in Sarawak, of which 36 were selected for Sr and Nd isotope determination. Of the tested samples, 16 were collected from the Lubok Antu mélange, 17 from the Rajang Group and 3 from the Tatau Formation (Fig. 2). Sr and Nd isotopic analyse followed procedures similar to those described by Li et al. (2019a). Whole rock powders for Sr isotopic analyses were dissolved in Savillex Teflon screw-top capsule prior to HF

+ HNO_3 + $HClO_4$ dissolution. Sr was separated using the classical two-step ion exchange chromatographic method and measured using a Thermo Fisher Scientific Triton Plus multi-collector thermal ionization mass spectrometer at IGGCAS. The whole procedure blank was lower than 260pg for Sr. The isotopic ratio was corrected for mass fractionation by normalizing to $^{88}Sr/^{86}Sr$=8.375209. The international standard, NBS-987 and JNdi-1, were employed to evaluate instrument stability during data collection. Measured values for the NBS-987 Sr standard and JNdi-1 Nd standard were $^{87}Sr/^{86}Sr$ =0.710260 ± 0.000020 (n=4, 2 SD). USGS reference material BCR-2 was measured to monitor the accuracy of the analytical procedures, with the $^{87}Sr/^{86}Sr$ = 0.705012 ±0.000012. The $^{87}Sr/^{86}Sr$ data of BCR-2 show good agreement with previously published TIMS data (Li et al., 2016; Li et al., 2019a).

1. **Results**

The $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ values of the clay-sized samples are shown on Figure 4 and Table 1. From previously published Nd isotope data (Zhao et al., 2021; Zhu et al., 2021), the $^{143}Nd/^{144}Nd$ values of Lubok Antu mélange range from 0.512306 to 0.512498, and the corresponding Nd values range from -2 — -6. While the $^{143}Nd/^{144}Nd$ ratios of the Rajang Group vary widely from 0.512139 to 0.512457, with the corresponding Nd values ranging from -3 — -9. The Lupar Formation, the Layar Member and the Lower Kapit Member of the Lower Rajang Group have higher Nd isotopic values similar to those of the Lubok Antu mélange. With the decrease of stratigraphic age of Rajang Group, Nd isotope values also tend to decrease. The Nd isotope values of the sediments in the Tatau Formation fluctuate within a very small range. The $^{143}Nd/^{144}Nd$ ratios of the three samples in the Tatau Formation are 0.512233, 0.512239 and 0.512236, respectively. The difference between the Nd values of the three samples is less than 0.12, and the average value is -7.8418.

$^{87}Sr/^{86}Sr$ ratios range from 0.710427 to 0.0.727511 in Lubok Antu Mélange, and between 0.713772 and 0.734629 in the Rajang Group. The Sr isotope values of the Lupar Formation and the Layar Member of the Lower part of the Rajang Group are less stable than those from the upper part. The $^{87}Sr/^{86}Sr$ ratios of the three samples in the Tatau Formation are 0.725830, 0.711878 and 0.718905 respectively, with an average of 0.718871.

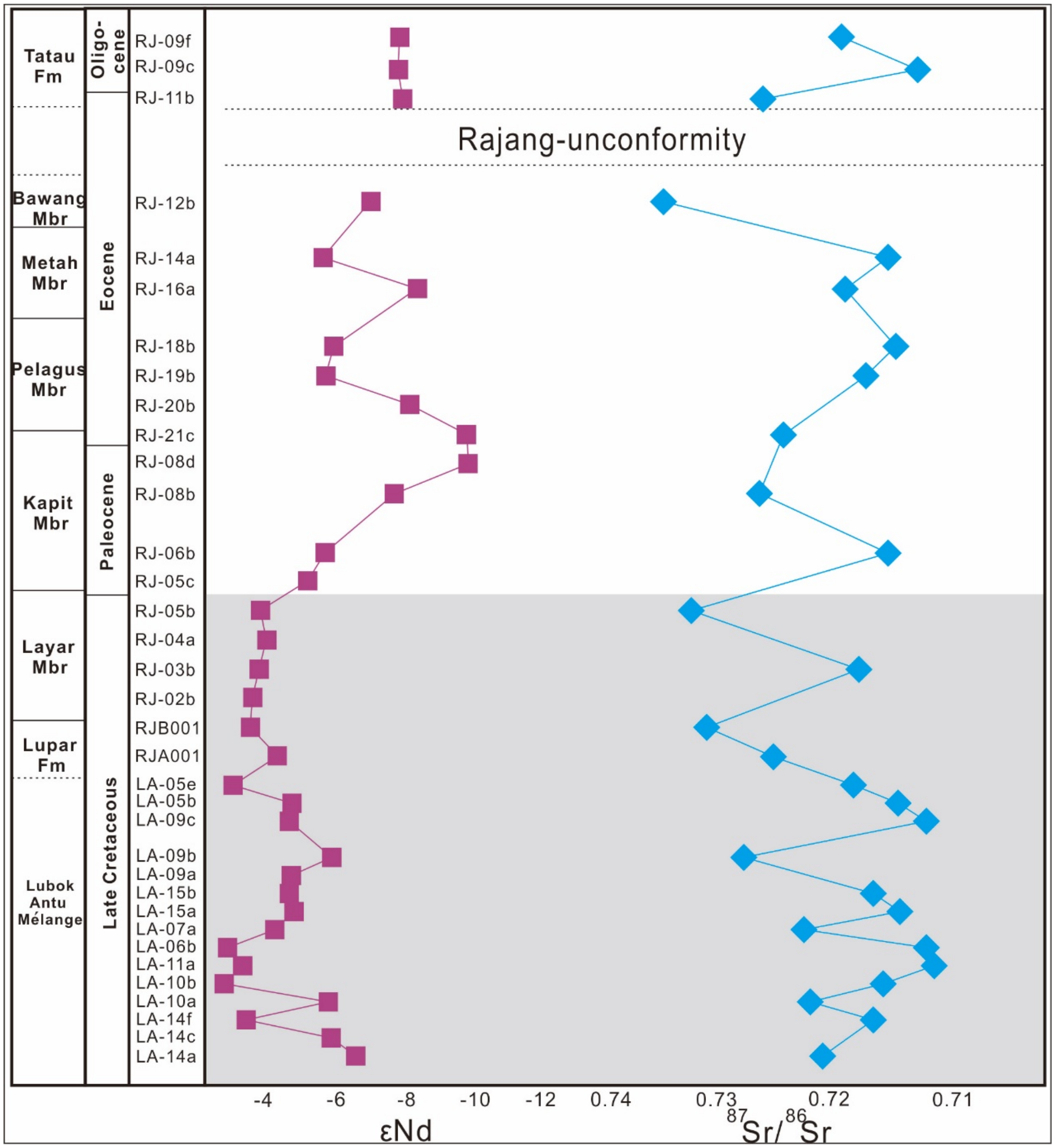

Figure 4. Profiles of Sr isotopic ratios and Nd values plotted against the sedimentary rock samples from the Lubok Antu mélange and the Rajang Group (the Nd values were from Zhao et al. (2021) and Zhu et al. (2021)).

1. **Discussion**

5.1 Semi-quantify the provenance contribution of the Rajang Group by the Sr-Nd isotope

The Sr-Nd isotopes generally show good correspondence, high Nd and low Sr values represent relatively juvenile material input (Li et al., 2003; Yan et al., 2007; Wei et al., 2012). The Lupar Formation, the Layar Member and the Lower Kapit Member have a higher Nd values, more similar to the Lubok Antu Mélange, than that of the Upper Rajang Group. However, the Sr isotope values show oscillatory characteristics at the bottom of the Rajang Group. Compared to the Nd isotope data, Sr isotope results are more easily influenced by weathering, diagenesis and other factors. Thus, we suggest that the Lower part of the Rajang Group before Early Paleocene and the Lubok Antu Mélange have similar sources, and then there was a change to older crustal material. The Sr-Nd ratios of Late Mesozoic granites in Southern Vietnam and Permian - Triassic granites in the Malay Peninsula were plotted as two end-Members in a provenance discrimination diagram (Fig. 5). The results show that the Lubok Antu Mélange, the Lupar Formation and the Layar Member sedimentary rock samples are close to granites of Southern Vietnam, Hainan and West Kalimantan, and the contribution of the Malay Peninsula is about 40%. Samples from the Kapit Member, Pelagus Member, Metah Member and Bawang Member are closer to the end-member of the Malay Peninsula, and the contribution of Malay Peninsula material increases to 60-80% (Fig. 5). The results are roughly consistent with the calculated results of deposition and denudation of Zhu et al. (2021).

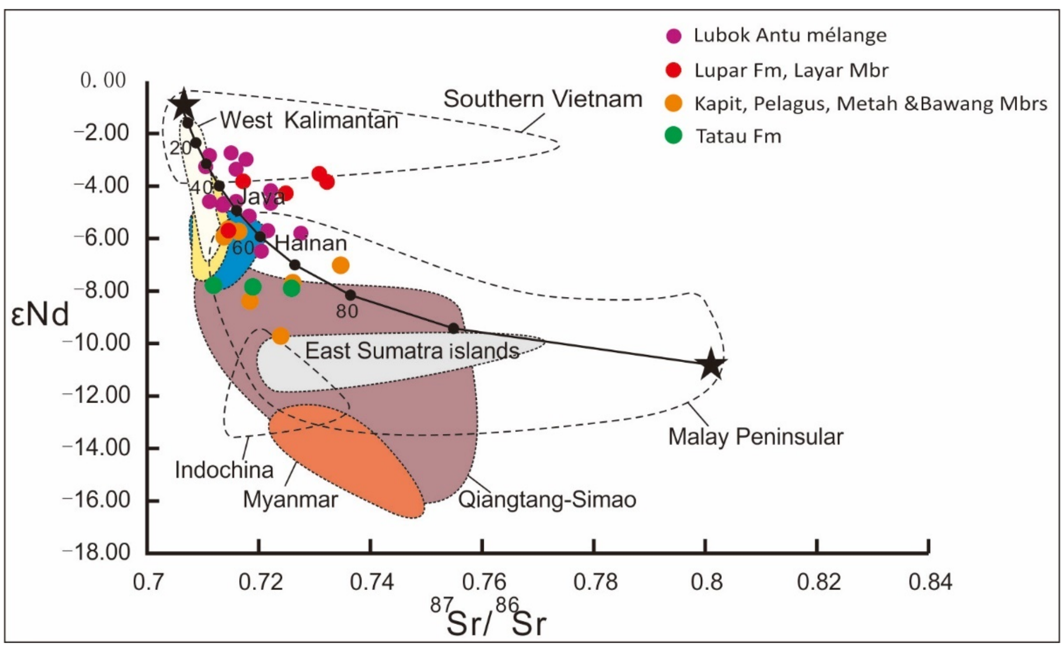

Figure 5. $^{87}Sr/^{86}Sr$ versus Nd plots for sedimentary rocks from the Lubok Antu mélange and the Rajang Group.

1. **Provenance evolution of the Cretaceous – Miocene strata in Bor-**

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5.2.1 Geochemical characteristics of the Lubok Antu mélange, the Rajang Group and the Kuching Supergroup

Geochemical data from Late Cretaceous - Miocene sedimentary strata in Borneo were collected to examine their provenance. Late Cretaceous - Late Eocene mudstones of the Rajang Group, Kuching Supergroup and the Lubok Antu mélange are characterized by Chondrite-normalized LREE-enriched REE patterns and negative Eu anomalies, and the UCC-normalized trace element patterns show a Sr negative (Fig. 6a, 6b; Ferdous & Farazi, 2016; Ramasamy et al., 2021; Ahmed et al., 2021; Baioumy et al., 2021; Zhao et al., 2021; Zhu et al., 2021). In the Zr-TiO_2 provenance discrimination diagram, samples from the Kayan and Ketungau Groups of the Kuching Supergroup plot in the felsic region, and Lubok Antu Mélange samples and the Lower Rajang Group (Lupar Formation, Layar Member and Lower Kapit Member) are closer to the intermediate region, while samples from the Upper part of the Rajang Group mostly fall into the felsic region (Fig. 6c). The Al_2O_3-TiO_2 discriminant plot shows that samples from the Lubok Antu Mélange and the Lower part of the Rajang Group are concentrated at the junction of granodiorite and granite fields, whereas the samples from the Upper part of the Rajang Group are more dispersed within the granodiorite and granite areas (Fig. 6d). The geochemical characteristics of the Rajang Group are seen to vary with time, whereby Late Cretaceous samples, such as from the Lupar Formation, and Layar Member contain more intermediate-basic materials than the overlying younger strata. Contributions from acidic sources also increase gradually with decreasing deposition age. The Kuching Supergroup is similar with the Rajang Group with sources from granite and granodiorite, but the former contain lower TiO_2 and Al_2O_3 values than Rajang Group (Fig. 6d).

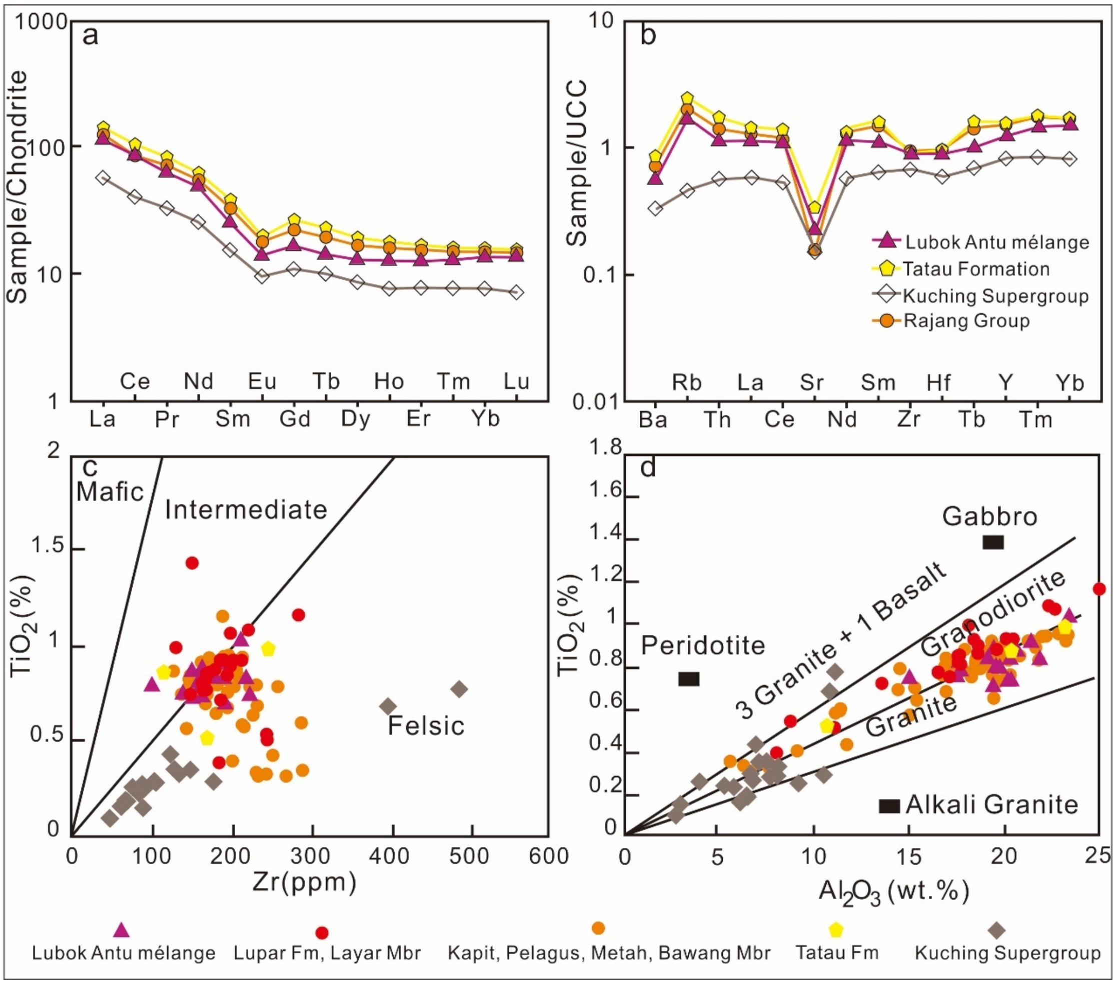

Figure 6. Comparison of elements of the Lubok Antu Mélange, the Rajang Group, the Kuching Supergroup and the Tatau Formation. (a) Chondrite – normalized REE patterns (Sun & McDonough, 1989), (b) UCC – normalized trace elements patterns (Rudnick & Gao, 2003), (c) Binary discriminant diagram of TiO_2 – Zr (McLennan et al., 1989), (d) TiO_2 – Al_2O_3 binary discriminant diagram (McLennan et al., 1989).

5.2.2 Detrital zircon geochronology of the Cretaceous – Miocene strata

Detrital zircon ages data from Late Cretaceous - Miocene sedimentary strata were collected to further constrain sample provenance (van Hattum et al., 2013; Galin et al., 2017; Breitfeld & Hall, 2018; Hennig-Breitfeld et al., 2019; Breitfeld et al., 2020b; Zhu et al., 2021). Peak ages of detrital zircons from Late

Cretaceous - Miocene strata are mainly concentrated in the Late Cretaceous and Permian - Triassic. Zircon age composition changes regularly, both spatially and temporally from the Kuching Zone, Sibu Zone, Miri Zone and Sabah region (Fig. 7).

In terms of time, Late Cretaceous - Miocene strata show a decrease in abundance of Cretaceous ages upsection and then increase for the youngest samples, while Permian - Triassic zircon show the opposite trend. Abundances of Cretaceous zircon ages in the Late Cretaceous - Early Eocene strata (Kayan Group, Lupar Formation, Layar Member and Sapulut Formation) reach as high as 44% - 59% and drop to 23% - 38% in the Early Eocene - Late Eocene strata (Ketungau Group, Kapit Member, Pelagus Member, Metah Member, Bawang Member and Trusmadi Formation), whereas Permian - Triassic zircon ages increased from 4% - 17% to 19% - 38%, and the content of the pre-Permian zircon slightly increased from 11% - 40% to 28% - 43% (Fig. 7). In the Oligocene to Middle Miocene strata, Cretaceous zircons decreased to 9% - 13% of all analysed sample ages, while the content of the Permian - Triassic and pre-Permian zircon ages increased significantly to 30% and 50%, respectively, of which the highest contribution was an increase of detrital zircon around 240 Ma and 1800 Ma (Fig. 7). After the Middle Miocene, the content of the Cretaceous zircons recovered to between 30% - 41%, and the proportion of zircon ages between 202-1000 Ma decreased. Changes in proportions of detrital zircon ages in the Kuching Zone and Sibu Zone are consistent. Samples from the Pedawan Formation, the Kayan Group in Kuching Supergroup, and Lupar Formation and the Layar Member of the Rajang Group are dominated by Cretaceous detrital zircons with large numbers of zircons with ages around 80 Ma and 120 Ma. For Middle - Late Eocene samples, the proportion of Cretaceous detrital zircons in the Ketungau Group of the Kuching Supergroup, the Kapit Member, Pelagus Member, Metah Member and the Bawang Member of the Rajang Group decreased, while detrital zircon ages around 240 Ma and 1800 Ma increased. A significant increase of Permian - Triassic detrital zircon occurred in Oligocene - Middle Miocene strata, in which the Permian - Triassic zircons and older grains accounted for more than 75% of the analyzed grains, indicating a significant increase in sources from older rocks. After the Middle Miocene, the main age peak of detrital zircons in the Miri Zone and Sabah switched from Permian - Triassic to the Cretaceous.

Spatial changes in abundances of Cretaceous and Permian - Triassic zircon ages show a diachronous trend from southwest to northeast. The first change is that the proportion of Permian - Triassic detrital zircons increased significantly. This change occurred in Ketungau Formation of Kuching Zone first where numbers of Permian - Triassic zircon ages in the Upper Rajang Group and Trusmadi Formation in Sabah, which has the same deposition age as the Ketungau Formation, increased but did not become the main age peak. The proportion of Permian - Triassic detrital zircons in samples from the Miri Zone and Sabah increased in the Oligocene Tatau Formation and Crocker Formation. The next change involved a significant decrease of Permian - Triassic detrital zircons and increase in Cretaceous zircons. Permian - Triassic zircons decreased significantly in Middle Miocene strata of Balingian Formation and Belait Formation in Miri Zone and Sabah (Fig. 7).

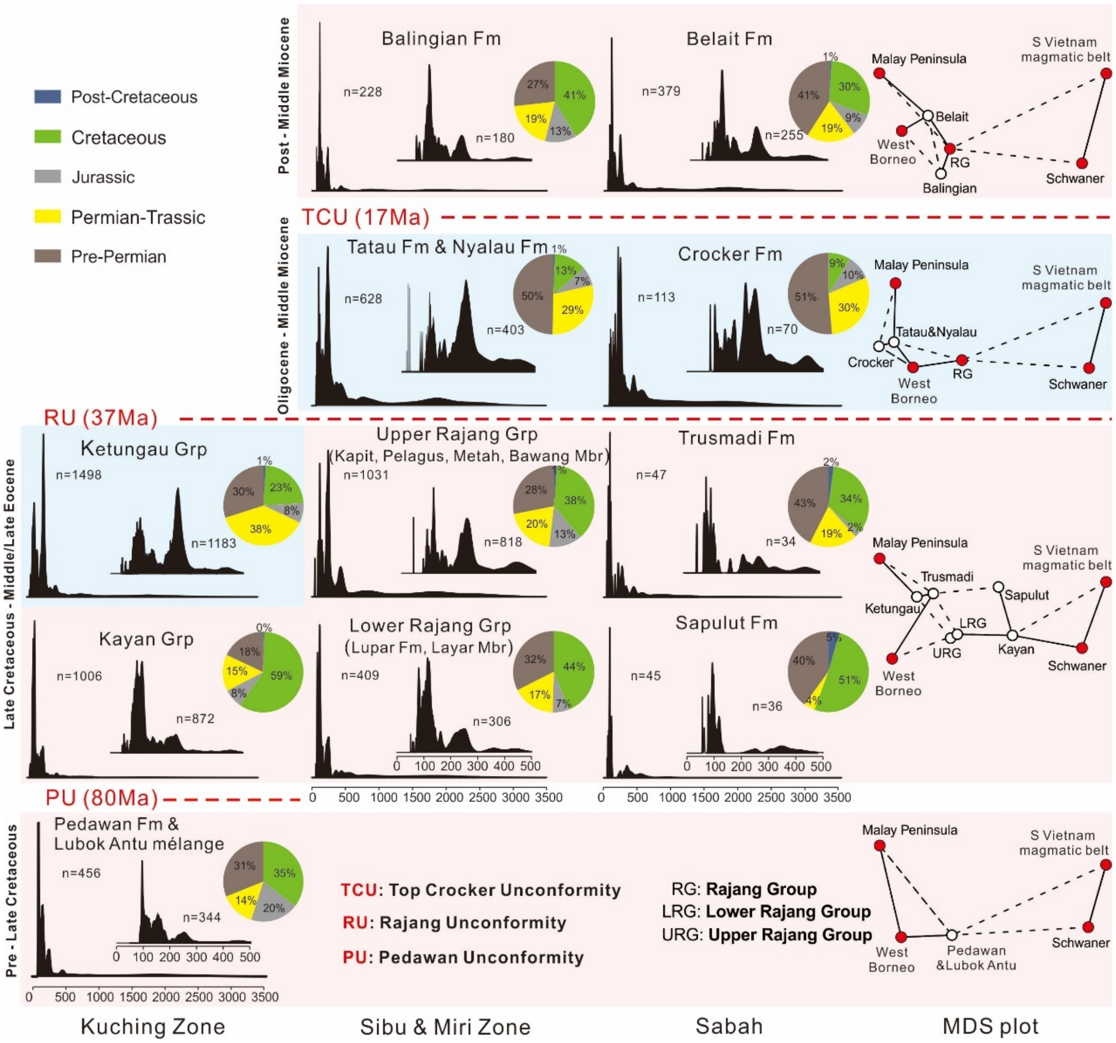

Figure 7. Zircon U-Pb age spectra and Multi-dimensional scaling (MDS) plot of samples from the Kuching Zone (Breitfeld et al., 2017; Breitfeld & Hall, 2018), Sibu Zone (Galin et al., 2017; Zhao et al., 2021; Zhu et al., 2020), Miri Zone (Hennig-Breitfeld et al., 2019; Breitfeld et al., 2020b) and Sabah (van Hattum et al., 2013).

5.2.3 Provenance evolution during the Cretaceous to the Miocene

The observed temporal variation recorded by our sample geochemical data and detrital zircon ages can be explained by the changes in the contributions of different source areas. Previous studies on paleocurrent, detrital zircon and heavy minerals suggested that the Late Cretaceous - Miocene sediments were mainly from the Schwaner Mountains and the Malay Peninsula (Tan, 1982; Hutchison, 2005; Galin et al., 2017; Breitfeld & Hall, 2018; Breitfeld et al., 2018; van Hattum et al., 2006, 2013). Galin et al. (2017) and Breitfeld and Hall (2018) proposed that sediments of the Rajang Group and the Kuching Supergroup were sourced from the Schwaner Mountains and the Malay Peninsula during the Late Cretaceous to Paleocene, and the Paleocene to Early/Middle Eocene sediments were almost entirely derived from the Schwaner Mountains, but then changed to the Schwaner Mountains and the Malay Peninsula during the Middle Eocene to Late Eocene.

According to our Sr-Nd isotope geochemical and detrital zircon data, the first significant change occurred in the Early Paleocene. We suggest that the Late Cretaceous - Early Paleocene sediments were sourced mainly from young magmatic rocks and that the provenance gradually shifted to older continental rocks during the Paleocene to Late Eocene. Considering previous mass balance studies, erosion of the Schwaner Mountains and the Malay Peninsula would not have not enough to provide the large amount of sediment for the Rajang Group and the Kuching Supergroup (Zhu et al., 2021). We suggest that the Late Mesozoic magmatic belt, which formed by the subduction of Paleo-Pacific Ocean, played an important role in sediments supply during the Late Cretaceous to Early Paleocene. Both outcrop and borehole evidences show that granites of the Magmatic belt have similar ages and geochemical characteristics (Katili, 1973; Li & Li, 2007; Hutchison, 2010; Shellnutt et al., 2013; Hennig et al., 2017; Li et al., 2018; Breitfeld et al., 2020a; Hennig-Breitfeld et al., 2021), and have undergone rapid weathering and denudation during the Late Cretaceous to Paleocene (Cuong & Warren, 2009; Areshev et al., 1992).

After the Early Paleocene, the river system draining the Malay Peninsula flowed across the Sunda Shelf into the Sarawak region of Borneo. With this change Nd isotope values began to decrease, Sr isotope values increased, and the proportion of Permian - Triassic detrital zircons increased. However, this change occurred much later in the Sabah region where Eocene strata remain dominated by Cretaceous detrital zircons (Fig. 7). van Hattum et al. (2013) suggested that the source area of Eocene sediments in Sabah were the Schwaner Mountains, and then changed to the Malay Peninsula in the Oligocene. Breitfeld et al., (2020b) suggested that two river systems supplied basins across Borneo during the Paleocene - Middle/Late Eocene, one from the Malay Peninsula, flowed across the Sunda Shelf to Sarawak, but did not penetrate far into NE Borneo. Another river system from the Schwaner Mountains flowed through the Sarawak and Sabah (Fig. 9b).

The second major change occurred in the Late Eocene, Large numbers of Permian - Triassic detrital zircons are found in the Oligocene - Middle Miocene sediment rocks from Sarawak and Sabah (Fig. 7), which means river draining older crust in the Malay Peninsula delivered sediment across the entire northern region of Borneo. The geochemical signals show that Oligocene strata in

Sarawak contains abundant recycled material (Zhu et al., 2021), and that the timing of this change followed the Sarawak uplift event in Middle/Late Eocene (Hutchison, 2005; Zhao et al., 2022). This uplift of the Sarawak region likely obstructed the rivers draining from the Schwaner Mountains, enabling the Malay Peninsula to become the main source area (Fig 9c).

The third change occurred in the Middle Miocene. Detrital zircon age distributions show that Cretaceous detrital zircons dominate post-Middle Miocene strata once again (Fig. 7), at the expense of Permian-Triassic detrital zircon that decreased in abundance. Sediments were most likely derived by uplift and recycling of Rajang-Crocker Group/Kuching Supergroup sediments from Borneo (van Hattum et al., 2013; Breitfeld et al., 2020b). This change was thought to have resulted from the opening of the southwestern end of the South China Sea, which cut off the river system from the Malay Peninsula (Breitfeld et al., 2020b). Rivers within Borneo re-emerged as the main system transporting sediments to Sabah from the Schwaner Mountains and uplifted central Borneo (Fig. 9d).

5.3 Paleogeography and tectonic evolution of Borneo during Late Cretaceous to Miocene

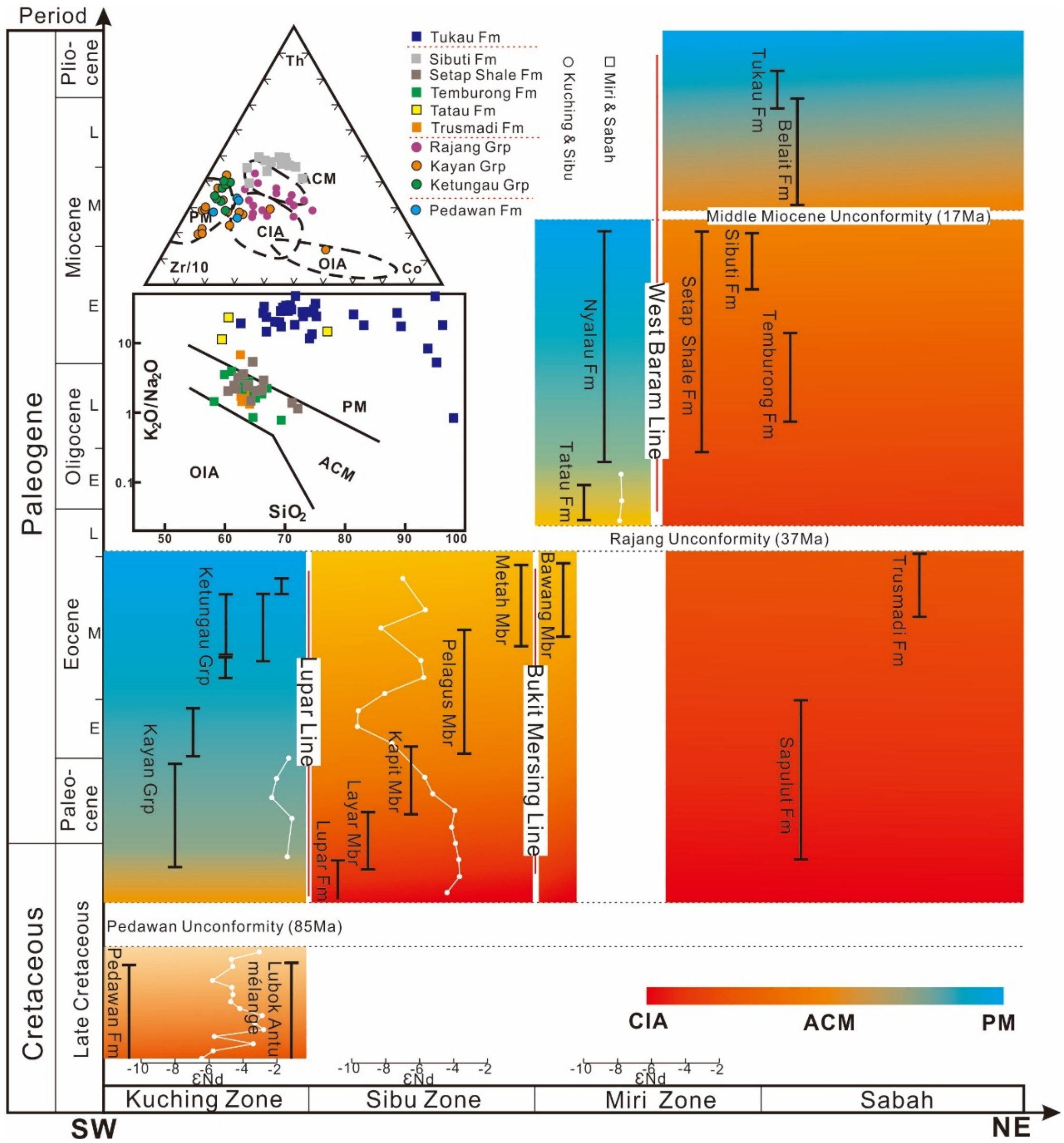

Figure 8. Tectonic setting and Nd isotope variation of Late Cretaceous-Miocene sedimentary rocks in Borneo from SW to NE. K_2O/Na_2O versus SiO_2/Al_2O_3 binary plot of Roser and Korsch (1986). The triangular plot of Th-Zr/10-Co after Bhatia and Crook (1986).

We collected geochemical data from the Late Cretaceous - Miocene sedimentary strata of Borneo (Burgan et al., 2008; Nagarajan et al., 2015, 2017; Ferdous & Farazi, 2016; Khan et al., 2017; Zhao et al., 2021; Zhu et al., 2021) to underlying tectonic regime. Results from the K_2O/Na_2O-SiO_2 and Th-Co-Zr/10 tectonic discrimination diagrams show that the tectonic settings of the Kuching Zone, Sibu Zone and Sabah also varied spatially (Fig. 8). Temporally, the geochemical signals of Cretaceous - Miocene sedimentary strata gradually change from continental island arc and active continental margin to passive continental margin, and are controlled by three unconformities (Fig. 8). The Pedawan Formation and Lubok Antu Mélange under the Pedawan unconformity in the Kuching Zone show clear active continental margin geochemical signal (Zhao et al., 2022). While the Kayan Group and Ketungau Groups of the Kuching Supergroup above the Pedawan unconformity developed passive continental margin signatures (Fig. 8). Similarly, the transformation of tectonic signatures for the Sibu Zone and Sabah area are controlled by the Rajang unconformity and Middle Miocene unconformity, respectively (Fig. 8).

At the spatial scale, differences in tectonic setting across Borneo from southwest to northeast are mainly distinguished by two tectonic lines, namely the Lupar Line and the West Baram Line (Fig. 8). The Lupar Line is the boundary between the Kuching Zone and the Sibu Zone, and the Kuching Supergroup in the southwest has passive continental margin geochemical characteristics, while the Rajang Group in the northeast with continental island arc and active continental margin signals (Fig. 8). The West Baram Line separates the Nyalau Formation, the Tatau Formation with a passive continental margin signature in the southwest whereas in the northeast the Setap Shale and Temburong formations record an active continental margin or even continental island arc setting (Fig. 8).

The Nd results (Zhao et al., 2021; Zhu et al., 2021) show relatively consistent changes with tectonic setting. In general, continental island arcs have more volcanic or magmatic materials. The entry of these mantle components into sedimentary rocks will cause an increase in the Nd value of sediments, such as seen in the Pedawan Formation and Lubok Antu Mélange which have Nd value of -2 — -6. The five samples from the Kayan Group fall into the active continental margin field and also have high Nd values, and the Lupar Formation and Layar Member at the bottom of the Rajang Group also have high Nd values of -3 — -6 (Fig. 8). However, the lack of young mantle material and the circulation of older crust or sediments in a passive continental margin setting will lead to a lower Nd value, similar to the decrease in Nd value to -10 that is seen in samples after the Paleocene when input from the Malay peninsula or Indochina increased, and later stabilized in the Tatau Formation at -7 (Fig. 8).

Changes in sediments provenance and tectonic setting can be used to improve understanding of the tectonic evolution of Borneo between the Late Cretaceous and Miocene. The Paleo-Pacific Ocean subducted along South China to Borneo margin to form an Andean-type island arc during the Triassic to Late Cretaceous (Xu et al., 2016; Li et al., 2018; Bretfeld et al., 2020a; Wang et al., 2021), and the Pedawan Formation in the Kuching Zone received sediments from the surrounding magmatic arc as a forearc basin (Breitfeld et al., 2017). Subduction-related magmatic activity in the Schwaner Mountains ceased at about 80 Ma. The sedimentary environment of the Kuching Zone changed from bathyal facies to continental facies, and deposition of the Kuching Supergroup began (Hutchison, 2005; Breitfeld et al., 2018). The region of the Sibu Zone was still in a deep-sea environment, and geochemical and isotopic evidence suggest that the Early Rajang Group sediments, deposited between the Late Cretaceous-Early Paleocene, and the Lubok Antu Mélange, were derived from younger intermediate-basic magmatic rocks compared to the Kuching Supergroup (Fig.4, 6; Zhu et al., 2021). The younger magmatic belts along the Lupar Line and the Paleocene age of mélange deformation (Zhao et al., 2022) seem to indicate that subduction ended in the Sibu Zone later than in the Kuching Zone. There are two possible reasons for these differences: 1) Retreat of Paleo-Pacific subduction during the Late Cretaceous and a new subduction location formed north of the Lupar Line to produce the Sambas - Mangkaliat granite belt (Amiruddin, 2009). The Rajang Group, first as an accretionary prism, changed to deposition within a a residual marine basin as subduction ceased at 60 Ma. 2) During the Late Mesozoic, the Sibu Zone, as an eastern extension of the Kuching Zone, formed a margin to subduction of the Paleo-Pacific Ocean along with the Kuching Zone and produced the Schwaner - Sambas - Mangaliat magmatic belt. Subduction in the Kuching Zone ceased first, while subduction in the Sibu Zone continued into the Early Paleocene (Fig. 9a). Strike-slip along the Lupar Line moved the Sibu Zone, along with the Sambas - Mangkaliat granite belt, to its present position during the Cenozoic.

The tectonic pattern of Southeast Asia changed significantly during the Paleocene - Middle/Late Eocene. Cessation of subduction produced a regional compressive regime which then transformed into an extensional setting, forming a series of extensional basins and structures (Li et al., 2019b). Collapse of the magmatic belt on the Sunda shelf, combined with the uplift of the Malay Peninsula, possibly due to the closure of the Ceno-Tethys (Fig. 9b), resulted in the increasing contribution of the Malay Peninsula and the Indochina to the Borneo sediments. There is no evidence of Paleocene - Middle Eocene subduction related magmatism in Sarawak (Wang et al., 2016; Hall & Breitfeld, 2017), while there appears to be Paleogene subduction in the Sabah region north of the West Baram Line. Detrital zircons in Paleogene sandstones indicate a maximum depositional age of 56 Ma for Sapulut Formation and 50 Ma for the Trusmadi Formation (van Hattum et al., 2006, 2013), and these show active continental margin geochemical signals (Fig. 8), confirming Eocene volcanic activity.

During the Oligocene to Middle Miocene, the deep-sea Rajang Group in Sibu Zone is unconformably covered by the terrestrial Tatau Formation and Nyalau Formation, and authigenic illite of the Rajang Group records a deformation age of about 37 Ma (Zhao et al., 2022), marking uplift of the Sibu Zone. The uplifted Rajang Group began to supply sediment to the northern basin (van Hattum et al., 2013; Breitfeld et al., 2020; Zhu et al., 2021) and partly blocked material supplied northward from the Schwaner Mountains. Northern Borneo received sediments mainly from the Malay Peninsula during this period (Fig. 9c). From the strata around the West Baram Line in the Miri Zone, the Tatau Formation and the Nyalau Formation in the south, were deposited in a stable tectonic setting (Breitfeld et al., 2020b; Zhu et al., 2021). A collision signal in the Tatau Formation and Sibuti Formation suggests that their sediments were derived from a passive to moderately active continental collision zone, and is likely related to collision between Luconia and Borneo (Hutchison, 1996; Nagarajan et al., 2015). The Setap Shale Formation and the Temburong Formation in the north show a strong active continental margin signal (Fig. 8) and the continental arc setting means that there was subduction north of the West Baram Line (Fig. 9c).

The Dangerous Ground block collided with Borneo in the Middle Miocene leading to uplift of central Borneo and the opening of the southwestern end of the South China Sea, which cut off the river system draining the Malay Peninsula (Fig. 9d). Sedimentary rocks in the Sabah region record a change from bathyal facies to terrestrial facies. The surrounding sedimentary basins were supplied by rivers draining the Schwaner Mountains and the uplifted Rajang-Crocker Group. Collision ended subduction in Sabah, and the tectonic background changed from an active setting to stable setting.

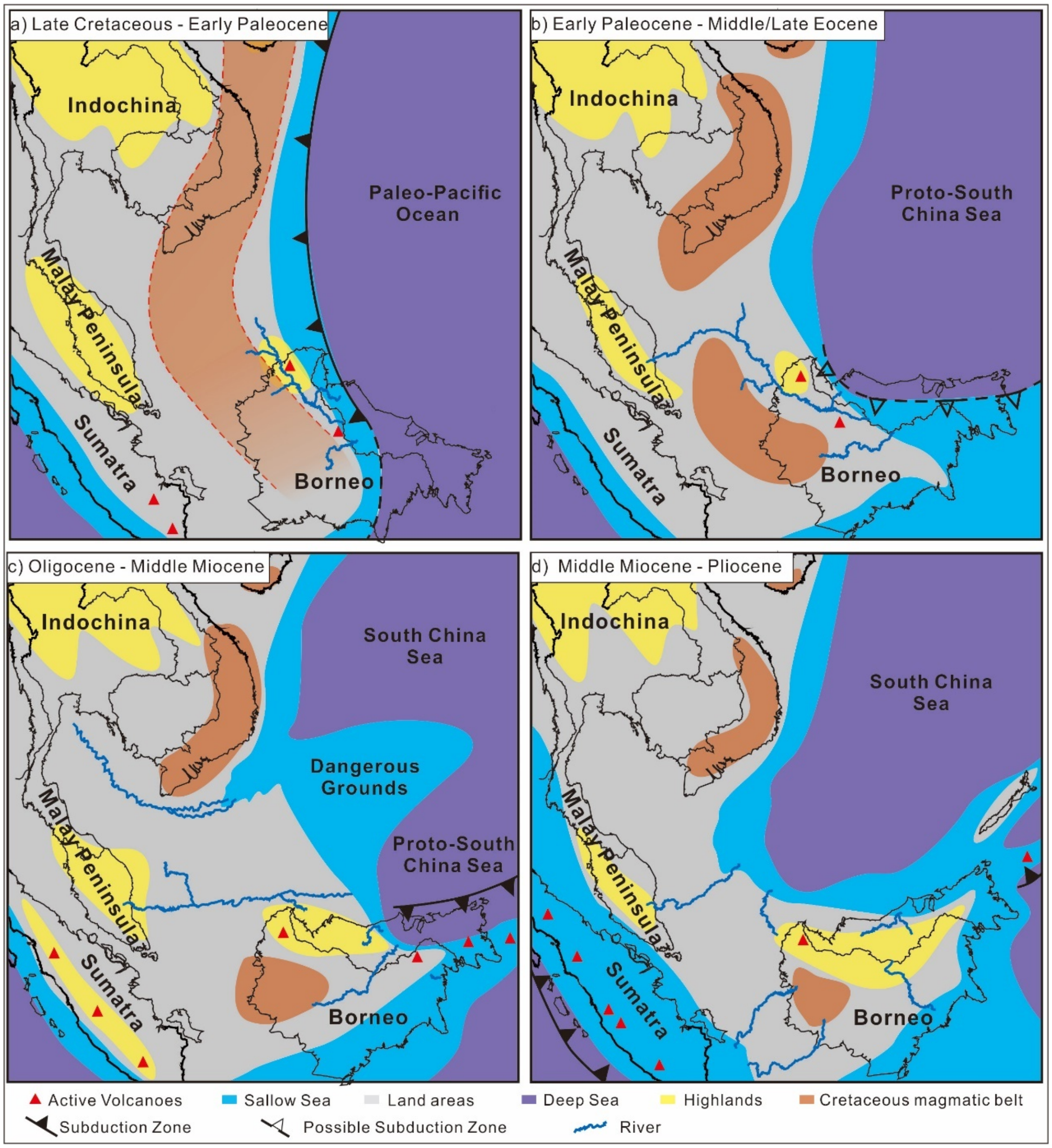

Figure 9. Paleogeography of NW Borneo during (a) Triassic to Early Cretaceous, (b) Late Cretaceous to Early Paleocene, (c) Paleocene to Middle Eocene and (d) Late Eocene to Middle Miocene (modified after Hall, 2012; Breitfeld et al., 2018, 2020b; Zhao et al., 2021; Zhu et al., 2021).

6. Conclusion

The Sr-Nd isotope results show that the Lupar Formation and the Layar Member of the Lower Rajang Group have similar characteristics to the Lubok Antu Mélange, and that their provenance is from a magmatic belt formed by subduction of the Paleo-Pacific Ocean. Cretaceous - Miocene sedimentary geochemical and detrital zircon data from Borneo indicate that the tectonic setting gradually changed from west to east. The Kuching Zone was in a stable tectonic setting during the Late Cretaceous, while subduction in the region of the Sibu Zone continued until the Early Paleocene. The West Baram Line of the Miri Zone was the tectonic boundary. Oligocene sedimentary rocks to the west were deposited in a stable continental setting, receiving sediments from NW Borneo, while east of the West Baram Line remained in a deep-sea sedimentary environment, with south directed subduction of the Proto-South China Sea continuing until the Middle Miocene.

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Table 1

Sr-Nd isotope compositions of the Lubok Antu mélange and the Rajang Group.

Sample No.	stratigraphy	Longitude	Latitute	$^{87}Sr/^{86}Sr$	2	$^{143}Nd/^{144}Nd$	2
RJ-09f	Tatau Fm	112.87°	2.92°	0.718905	0.000014	0.512236	0.0000
RJ-09c		112.87°	2.92°	0.711878	0.000012	0.512239	0.0000
RJ-11b		112.74°	2.8°	0.725830	0.000015	0.512233	0.0000
RJ-12b	Rajang Grp	Bawang Mbr	112.65°	2.62°	0.734629	0.000013	0.5122
RJ-14a		Metah Mbr	112.43°	2.56°	0.714552	0.000012	0.5123
RJ-16a			112.35°	2.54°	0.718392	0.000012	0.5122
RJ-18b		Pelagus Mbr	112.16°	2.41°	0.713772	0.000012	0.5123
RJ-19b			112.1°	2.36°	0.716372	0.000012	0.5123
RJ-20b			111.97°	2.25°			0.5122
RJ-21c		Kapit Mbr	112°	2.13°	0.723906	0.000012	0.5121
RJ-08d			111.45°	1.99°			0.5121
RJ-08b			111.45°	1.99°	0.726065	0.000012	0.5122
RJ-06b		Layar Mbr	111.34°	1.87°	0.714555	0.000012	0.5123
RJ-05c			111.43°	1.67°			0.5123
RJ-05b			111.43°	1.67°	0.732174	0.000012	0.5124
RJ-04a			111.87°	1.13°			0.5124
RJ-03b			111.64°	1.26°	0.717168	0.000013	0.5124
RJ-02b			111.65°	1.22°			0.5124
RJB001		Lupar Fm	111.25°	1.22°	0.730788	0.000013	0.5124
RJA001			111.06°	1.22°	0.724818	0.000015	0.5124
LA-05B	Lubok Antu Melange	111.83°	1.05°	0.711136	0.000014	0.512403	0.0000
LA-05D		111.83°	1.05°	0.713667	0.000012	0.512399	0.0000
LA-05E		111.83°	1.05°	0.717664	0.000012	0.512485	0.0000

Sample No.	stratigraphy	Longitude	Latitute	$^{87}Sr/^{86}Sr$	2	$^{143}Nd/^{144}Nd$	2
LA-06B		111.81°	1.09°	0.711137	0.000013	0.512493	0.0000
LA-07A		111.8°	1.1°	0.722113	0.000012	0.512424	0.0000
LA-09A		111.75°	1.14°	0.722084	0.000013	0.512400	0.0000
LA-09B		111.75°	1.14°	0.727511	0.000011	0.512341	0.0000
LA-09C		111.75°	1.14°	0.718218	0.000012	0.512375	0.0000
LA-10A		111.75°	1.13°	0.721552	0.000011	0.512346	0.0000
LA-10B		111.75°	1.13°	0.714999	0.000012	0.512498	0.0000
LA-11A		111.74°	1.12°	0.710427	0.000012	0.512471	0.0000
LA-14A		111.83°	1.05°	0.72044	0.000011	0.512306	0.0000
LA-14C		111.83°	1.05°			0.512342	0.0000
LA-14F		111.83°	1.05°	0.715894	0.000010	0.512466	0.0000
LA-15A		111.95°	1.14°	0.713505	0.000012	0.512396	0.0000
LA-15B		111.95°	1.14°	0.715887	0.000012	0.512403	0.0000