Interaction between the Tethyan and Paleo-Pacific tectonic domains in Southeast Asia: Late Triassic initiation of an inward-dipping double subduction system

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Abstract

Interaction between Tethys and the Paleo-Pacific subduction zones in Southeast Asia during the Mesozoic remains poorly understood. Using new and published zircon U-Pb and Hf datasets from Borneo (Paleo-Pacific domain) and Sumatra (Tethyan domain), we propose that isotopically juvenile magmatism was active on both sides of Sundaland due to the initiation of inward-dipping double subduction during the latest Triassic when Indochina collided with Sibumasu, as evidenced by a pronounced positive shift in zircon εHf(t) values from both Cenozoic sedimentary successions and Mesozoic magmatic rocks in Sumatra and Borneo. From the latest Triassic to Cretaceous, the contrasting positive εHf(t) values ranges between Borneo and Sumatra, with Borneo showing a broad range and Sumatra a narrower variability, imply that the inward-dipping double subduction system evolved asymmetrically due to differences in slab dip angles between the subducting Meso-Tethys and Paleo-Pacific oceanic lithosphere. After 80 Ma, this asymmetric double subduction system was disrupted, marked by the complete cessation of arc magmatism in Borneo while isotopically juvenile magmatism continued on Sumatra. Our findings emphasize that, when compared to the contemporary single-sided subduction system of the western Meso-Tethyan domain and the northern Paleo-Pacific domain, SE Asia developed more juvenile crust due to large-scale upper plate extension driven by inward-dipping double subduction.

Plain Language Summary (PLS)

The interaction between the Tethyan and Paleo-Pacific domains has shaped the formation of the present megacontinent Eurasia. However, how the two subduction zones (Tethyan and Paleo-Pacific domains) interacted and evolved, and how they impacted on the geology of Southeast Asia is not yet clear. Using radiometric ages and hafnium isotopes from magmatic and detrital zircon, we found that the interaction between the Tethyan and Paleo-Pacific domains in Southeast Asia can be explained by an inward-dipping double subduction model that began in the Late Triassic. Furthermore, our results highlight that the strengthened juvenile crustal signatures in Southeast Asia because the large-scale extension of upper plate in an inward-dipping double subduction system.

1. Introduction

The last supercontinent cycle was characterized by the breakup of Pangea, a process that began in the Triassic (Olsen, 1997; Golonka, 2007; De Min et al., 2020), leading to the formation of the present megacontinent Eurasia, regarded as a potential precursor to the future supercontinent Amasia (Wang et al., 2020). The assembly of Eurasia was driven by broadly E-W-trending Tethyan-style collisional orogens (Tethyan tectonic domain) and the approximately N-S-trending circum-Pacific-style accretionary orogens (Paleo-Pacific tectonic domain). These trends converge in Southeast Asia, influencing both mantle convection patterns and climate (Metcalfe, 2011; Li et al., 2019; Nance et al., 2014; Wang et al., 2020; Wang et al., 2024).

The post Triassic evolution of western Tethyan and the northern Paleo-Pacific tectonic domains have been extensively studied. The western Tethyan tectonic domains are characterized by closure of the Devonian-Triassic Paleo-Tethys in the Late Triassic (Hu et al., 2014; Fan et al., 2024), as well as the subduction and demise of the Permian–Cretaceous Meso-Tethys and Jurassic–Cretaceous Ceno-Tethys, between the Triassic and Paleogene (Hall, 2012; Metcalfe, 2013). These developments were accompanied by the accretion to Eurasia of continental blocks derived from the northern margin of Gondwana (e.g., the South Qiangtang and Lhasa terranes; **Fig.1A**; Metcalfe, 2017, 2021). In the Phanerozoic the Paleo-Pacific plate has been subducting along the East Asian continental margin in various stages, although the timing of its initial subduction remains debated. For South China,

proposed subduction initiation of Paleo-Pacific plate spans from 500 Ma to the Permian or Triassic (**Fig.1A**; Li and Li, 2007; Isozaki et al., 2010; Zhu et al., 2013; Pastor-Galán et al., 2021; Zhou et al., 2023), while the North China Craton records Early Jurassic onset of Paleo-Pacific plate subduction (Wu et al., 2019; Zhu & Xu, 2019; Qiu et al., 2022a, b).

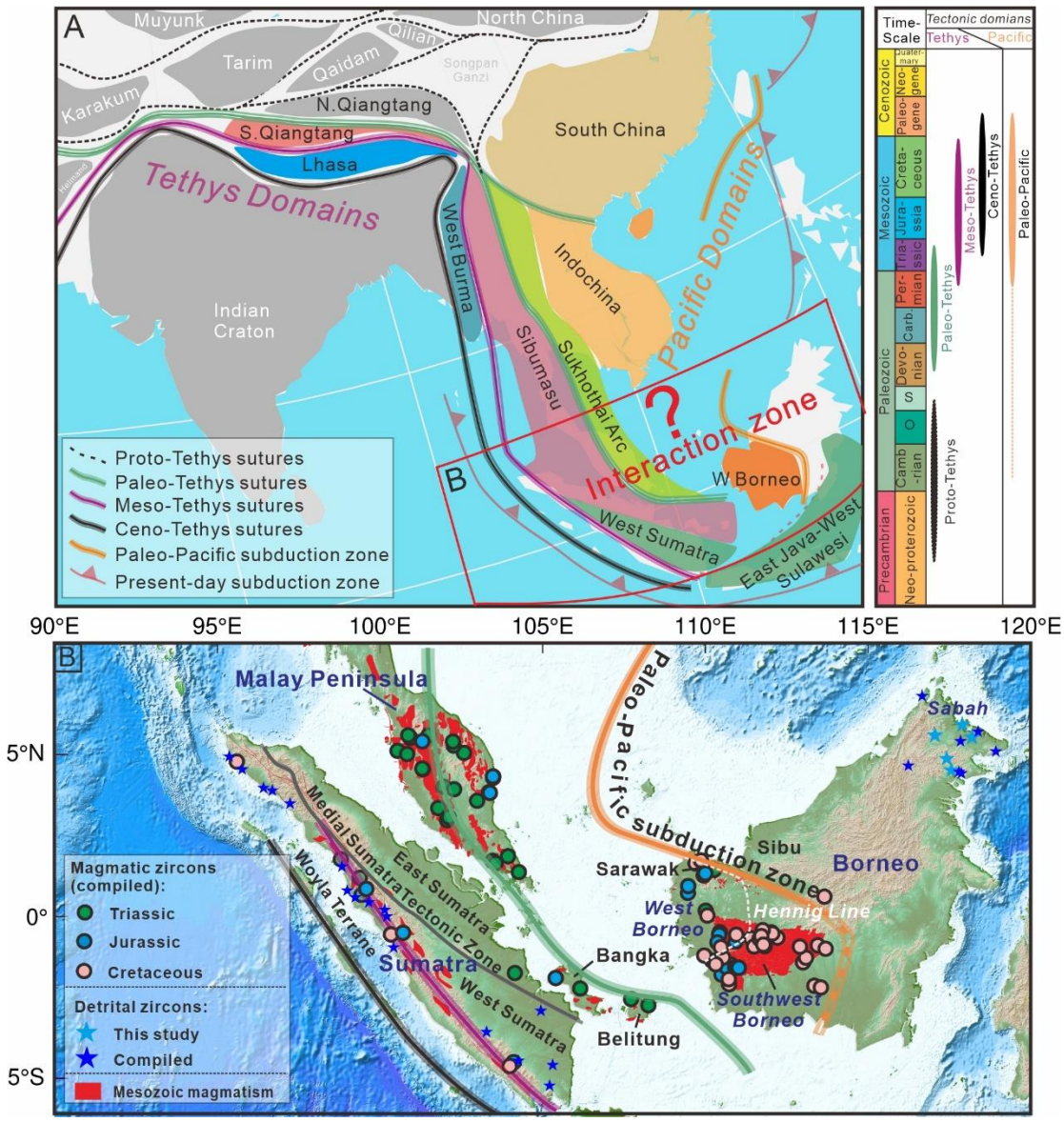


Figure 1. (A) Simplified tectonic map illustrating the Tethys tectonic domains and the Pacific tectonic domains, along with the temporal evolution of the ocean basins (refer

to Metcalfe 2021; Zhou et al., 2023 and reference therein). (B) Location of compiled Mesozoic magmatic and detrital zircons, as well as the new detrital zircons in the interaction zone. Further details are provided in **Table S3**.

However, the interaction and evolution of these two subduction zones (Tethyan and Paleo-Pacific domains), as well as their impact on the geology of Southeast Asia, remain unclear. Present-day West Sumatra and West and Southwest Borneo, which are separated from the Malay Peninsula by the Sunda Shelf, and the Bangka and Belitung islands, represent the easternmost extent of the Tethyan domain (**Fig 1B**; Metcalfe, 2017, 2021; Zhang et al., 2019; Li et al., 2020) and the southernmost extent of the Paleo-Pacific domain (Metcalfe, 1996: Hennig et al., 2017; Breitfeld et al., 2020; Wang et al., 2022a, 2023, 2024). Two principal models have been proposed regarding the origin of Southwest Borneo: (1) it represents an allochthonous terrane that accreted to SE Asia during the Late Jurassic or Early Cretaceous (Metcalfe, 2009; Hall, 2012; Hennig et al., 2017; Breitfeld et al., 2020), or (2) it was autochthonous, undergoing accretion linked to Paleo-Pacific plate subduction since the Earliest Jurassic or possibly earlier (Wang et al., 2022a, 2023, 2024). Nevertheless, Southwest Borneo—or at least its northwestern portion (the Northwest Schwaner zone, termed West Borneo in Hennig et al., 2017)—was situated along the southeastern margin of the Sundaland continent since the Late Triassic. Tectonic reconstructions constrain accretion of the West Sumatra block onto the Sundaland margin to the Late Triassic,

after which a Mesozoic subduction-related arc developed within a narrow belt throughout West Sumatra (Barber et al., 2005; Cobbing, 2005; Barber & Crow, 2009; Li et al., 2020; Metcalfe, 2021). Thus, the Mesozoic magmatic rocks in West Sumatra and West and/or Southwest Borneo record, respectively, continental accretion and growth related to the northeastward subduction of the Tethyan lithosphere (e.g., Li et al., 2020) and the westward subduction of the Paleo-Pacific plate (Breitfeld et al., 2017, 2020a; Hennig et al., 2017; Wang et al., 2024). These rocks provide an important record for understanding how these two subduction systems interacted.

In this study, we examined compiled regional magmatic and detrital zircon U-Pb data in the West and Southwest Borneo and West Sumatra, and integrated these results with new zircon U-Pb and Hf isotopic data obtained from samples collected across northern Borneo (Sabah). Zircon data from Mesozoic igneous rocks were used to track the spatial distribution of magmatism through time and Mesozoic detrital zircon ages from Upper Oligocene to Neogene sedimentary rocks capture temporal variations in magmatism across the sediment source regions. Collectively, these datasets capture regional temporal and spatial changes in Mesozoic magmatism providing fresh new insights into the tectono-magmatic evolution and underlying geodynamic processes across the interaction zone (**Fig 1A**) between the Tethyan and Pacific-Pacific domains.

2. Geological Background

Southeast Asia was formed by the successive assembly of different continental fragments that rifted from Gondwana since the Paleozoic (Metcalfe, 1988, 2017). During the Triassic, major continental blocks, such as Sibumasu, Indochina, West and SW Borneo were positioned between the Tethyan and Paleo-Pacific domains (**Fig.1A**; e.g., Metcalfe, 2017), herein referred to as the interaction zone of both. The origin of Southwest Borneo remains debated. It may represent either a continental terrane rifted from northwestern Australia (e.g., Metcalfe, 2009; Hall, 2012; Hennig et al., 2017; Breitfeld et al., 2020a), or a Paleo-Pacific active continental margin similar or attached to West Borneo (e.g., Wang et al., 2022a, 2023, 2024). In contrast, West Borneo (containing the Northwest Schwaner Zone) was unambiguously situated at the western and southernmost part of the Paleo-Pacific subduction zone in the Triassic, where most of the subduction-related Mesozoic igneous and metamorphic rocks were developed (**Fig. 1B**; Haile et al., 1977; Williams et al., 1988; Hennig et al., 2017; Breitfeld et al., 2020a). Upper Mesozoic to Paleogene fluvio-deltaic sedimentary rocks and deep-marine turbidites are mainly developed in Sarawak and Sabah, respectively. Sabah, situated at the northern tip of Borneo, is thereby dominated mainly by Paleogene-Neogene clastic sedimentary rocks deposited on the Mesozoic Chert-Spilite Formation/ophiolite basement (Hutchison, 2005). Cenozoic rifting of the Sunda Shelf caused by the propagating South China Sea, along with associated tectonic events in Borneo resulted in erosion and deposition of large volumes of Lower Oligocene to Neogene sediments in Sabah (Hutchison, 1996, 2005; Hall, 2013;

148 Hall & Breitfeld, 2017; Breitfeld et al., 2023a, b). Although Early Cenozoic drainage
149 reorganization in Borneo triggered dynamic sediment provenance fluctuations
150 between the Malay-Thai Peninsula and West and Southwest Borneo (e.g., Galin et al.,
151 2017; Hennig-Breitfeld et al., 2019; Breitfeld et al., 2020b), most Upper Oligocene to
152 Neogene sedimentary rocks in Sabah are dominated by Cretaceous zircons and were
153 mainly derived by multi-recycling from West and Southwest Borneo with minor
154 inputs from inland Sundaland (e.g., Malay Peninsula) or mainland Asia (van Hattum
155 et al., 2006, 2013; Galin et al., 2017; Hennig-Breitfeld et al., 2019; Breitfeld et al.,
156 2020b, 2023a, b; Quek et al., 2021b). As a result, these Cretaceous zircons-dominant
157 sedimentary successions represent an important archive of continental growth history
158 and magmatism related to subduction of the southernmost Paleo-Pacific oceanic slab
159 beneath Borneo in the Mesozoic.

160 By contrast, Sumatra lies at the easternmost Tethyan domain and was partly
161 formed from accretion of the Woyla Arc, and the West and East Sumatra blocks in the
162 Cretaceous (Advokaat et al., 2018; **Fig. 1B**). Rocks exposed in Sumatra record
163 subduction of Mesozoic Tethyan lithosphere following the closure of the
164 Paleo-Tethyan Ocean in the Middle to Late Triassic (Metcalfe, 1996; Barber and Crow,
165 2009). The Woyla Arc is mainly characterized by a Lower Cretaceous
166 volcanic-sedimentary succession, comprising basaltic to andesitic volcanic rocks
167 interbedded with clastic sedimentary units. It is interpreted as an intra-oceanic
168 subduction-related arc that accreted to Sundaland in the Middle-Late Cretaceous due

to the absence of continental rocks (Barber, 2000; Baber et al., 2005; Metcalfe, 2017, 2021). West and East Sumatra are separated by the Medial Sumatra Tectonic Zone, characterized as a major crustal shear zone/strike-slip fault system rather than a suture zone, given the complete absence of exposed ophiolitic components (e.g., Baber & Crow, 2009; Metcalfe 2013). West Sumatra was probably emplaced by the Medial Sumatra Tectonic Zone in the Late Triassic (Baber & Crow, 2009). Triassic-Jurassic and Cretaceous granitoids that represent a subduction-related arc magmatic suite are mainly distributed within a narrow belt in West Sumatra, representing the southeastern extension of the Meso-Tethyan arc system (Gasparon and Varne, 1995; Cobbing, 2005; Zhang et al., 2019; Li et al., 2020). Thus, detrital and magmatic zircon data in West Sumatra record the onset of crustal growth related to subduction of the easternmost Tethyan lithosphere after the Late Triassic (Zhang et al., 2019; Li et al., 2020).

3. Methods

3.1 Sampling and Analytical Methods

A total of five representative sandstones were collected from strata in Sabah (northern Borneo), which include the Cretaceous turbidite slice within the ophiolitic basement (TB-10B), Labang Formation (Late Oligocene, SK-06), Garinono Mélange (Early Miocene, SK-02), Kumaunt Formation (Early Miocene, K-01) and Tanjong Formation (Early-Middle Miocene, K-03). Zircon U-Pb-(Hf) isotopic analyses were

conducted on these samples to constrain temporal variations in magmatism along the southernmost segment of the Paleo-Pacific subduction zone.

Zircon grains were separated using standard density and magnetic techniques after Mange and Maurer (1992). U-Pb dating was performed by laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS) at Wuhan SampleSolution Analytical Technology Co., Ltd., Wuhan, China using the Agilent 7900 ICP-MS coupled with a GeolasPro laser ablation system. The diameter of the analytical spot is 32 μm. Zircon 91500 (1065 Ma; Wiedenbeck et al., 1995) and glass NIST610 (Pearce et al., 1997) served as external standards for U-Pb dating and trace element calibration. Data is provided in Supplementary Table S1.

From the 506 dated grains, 117 concordant zircons with ages younger than 500 Ma were selected for Lu-Hf isotopic analysis by LA-MC (multicollector) ICP-MS to track the Mesozoic tectono-magmatic evolution of Borneo. In-situe Lu-Hf isotopic measurements were performed at Wuhan SampleSolution Analytical Technology Co., Ltd employing a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany) coupled with a Geolas HD excimer ArF laser ablation system (Coherent, Göttingen). The diameter of the ablation spot is 44 μm. Analyses followed established Hu et al. (2012) operational frameworks. Plešovice, 91500 and GJ-1 are analyzed simultaneously with our samples to ensure the reliability of our data (Zhang et al. 2020). Their external precision (2SD) is better than 0.000020, with measured values showing concordance with published reference values within analytical uncertainty.

ICPMSDataCal was used to perform off-line selection and integration of analyzed signals and mass bias calibration (Liu et al., 2010). Data is provided in Supplementary Table S2.

3.2 Data Compilation

To determine the interaction and evolution of the two subduction zones (Paleo-Pacific and Tethyan domains), we compiled Neogene detrital zircon U-Pb-(Hf) data from Sabah (Breitfeld et al., 2023a; Zhang et al., 2023) and Sumatra (Hsu, 2016; Zhang et al., 2019). Zircon U-Pb(-Hf) data of Mesozoic magmatic rocks from Sumatra (Li et al., 2020), West Borneo and Southwest Borneo (Setiawan et al., 2013; van Hattum et al., 2013; Hennig et al., 2017; Breitfeld et al., 2017, 2020a; Gan et al., 2022; Qian et al., 2022; Wang et al., 2021a, 2021b, 2022a, 2022b), Indochina (Shellnutt et al., 2013; Tran et al., 2014; Hieu et al., 2015; Shi et al., 2015; Wang et al., 2016; Hou et al., 2019; Nguyen et al., 2019; Minh et al., 2020), Malay Peninsula (Liew & Page et al., 1985; Searle et al., 2012; Ghani et al., 2013; Oliver et al., 2014; Ng et al., 2015; Jamil et al., 2016; Gillespie et al., 2019; Hazad et al., 2019; Cao et al., 2020; Liu et al., 2020; Quek et al., 2021a; Wang et al., 2021a; Yu et al., 2022; Qian et al., 2023), Bangka and Belitung Island (Ng et al., 2017; Wang et al., 2021a) were also compiled.

To ensure data reliability and comprehensiveness, all data were compiled directly from original studies, retaining the authors' own processing approaches—including outlier removal and concordance threshold selection. Compiled data from the

Mesozoic magmatic rocks and the Neogene detrital samples comprising 7,486 zircon U-Pb ages and 4,224 Hf isotopic measurements. The locations of the new study samples and complied samples are shown in Figure 1B. Compiled zircon age data and Hf isotopic data are shown in Supplementary Table S3 and Table S4, respectively.

4. Results

All new zircon grains from the Cretaceous turbidite slice and Upper Oligocene-Neogene sandstones in Sabah display lengths of 60-200 μm, and axial ratios spanning 1:1 to 3:1 (Fig. 2). Most of these detrital zircon data yield ages younger than 500 Ma (Table S1), comprising a total of 114 Paleozoic, 232 Mesozoic and 11 Cenozoic age. Grains exhibit oscillatory zoning (Fig. 2), and have Th/U ratios > 0.1, consistent with a magmatic origin (Corfu et al., 2003). The Triassic and Cretaceous zircons display subrounded to euhedral morphologies, suggesting first cycle to moderately recycled input (Fig. 2).

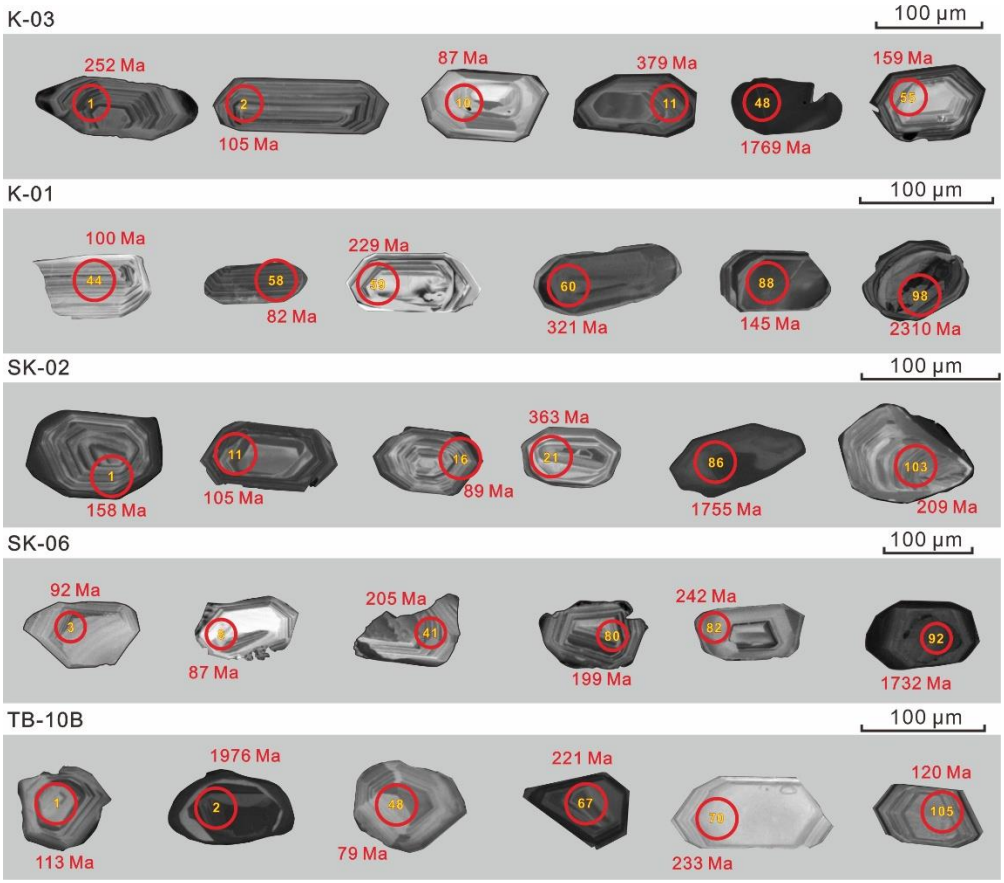


Figure 2. Cathodoluminescent (CL) images of zircons from the Cretaceous turbidite slice and Upper Oligocene-Neogene sandstones sampled in this study.

The five samples exhibit comparable zircon age distributions, while the Cretaceous turbidite slice within the ophiolitic basement (TB-10B) contains a higher abundance of Permo-Triassic and Devonian-Carboniferous zircons (Fig. 3). A limited population of Oligocene to Early Miocene zircons exists in K-03A of Tanjong Formation, documenting potential magmatism associated with Proto-South China Sea subduction during this interval (e.g., Breitfeld et al., 2023a). When integrated with detrital zircons from published Neogene sedimentary rock samples in Sabah (e.g., Breitfeld et al., 2023a; Zhang et al., 2023), these zircons maintained a distribution

pattern dominated by Late Cretaceous (~100 Ma) ages, while the Kernel Density Estimate (KDE) plots show minor age peaks in the Permo-Triassic (~210–260 Ma) and Devonian-Carboniferous (~330–380 Ma; **Fig. 4**). The εHf(*t*) values of these detrital zircons from five samples began to increase in the Latest Triassic, and became overwhelmingly positive during the Jurassic and Cretaceous (εHf(t) = −5.2~ +14.9; **Fig. 5**)

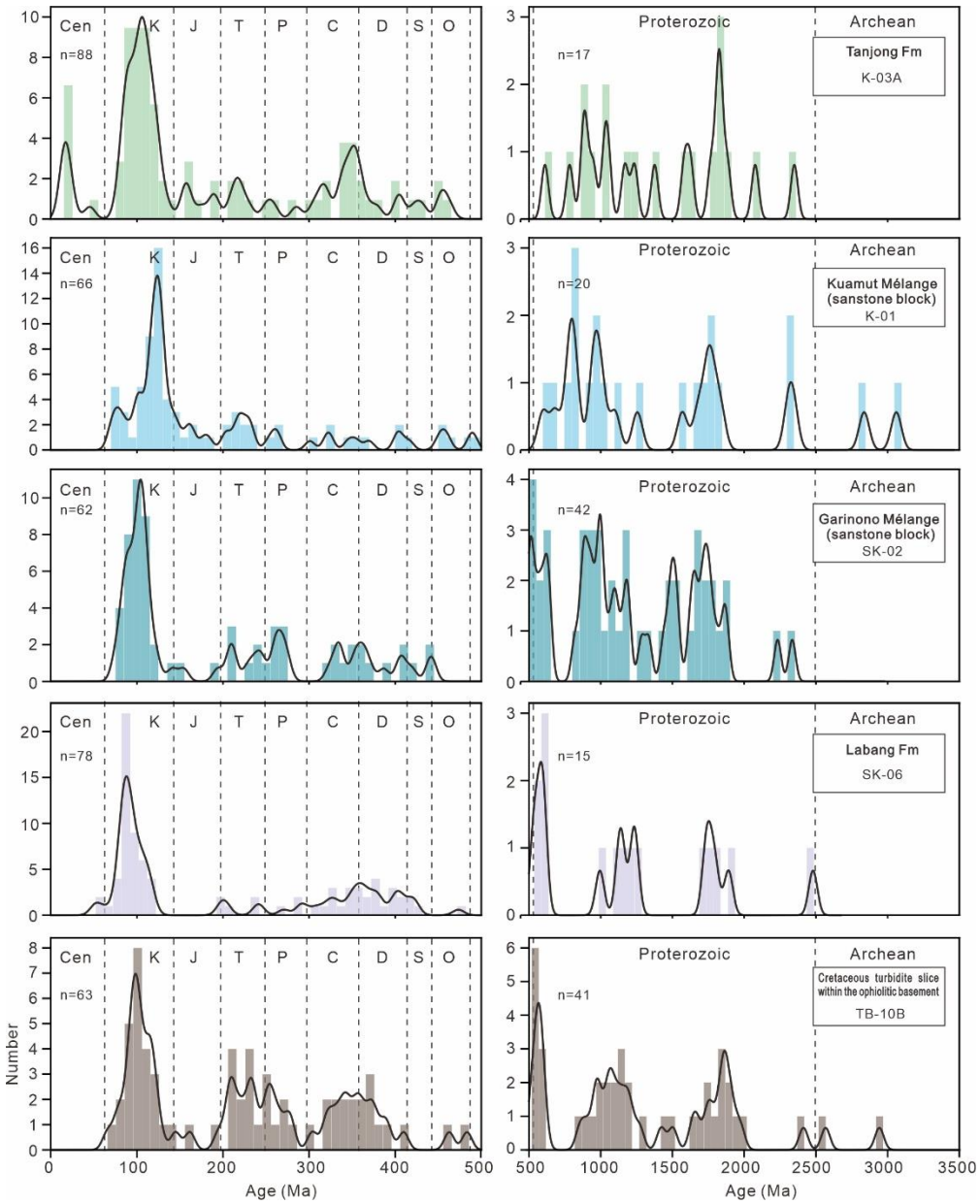


Figure 3. Kernel density estimation (KDE) spectra of detrital zircons from the Cretaceous turbidite slice and Upper Oligocene-Neogene sandstones sampled in this study.

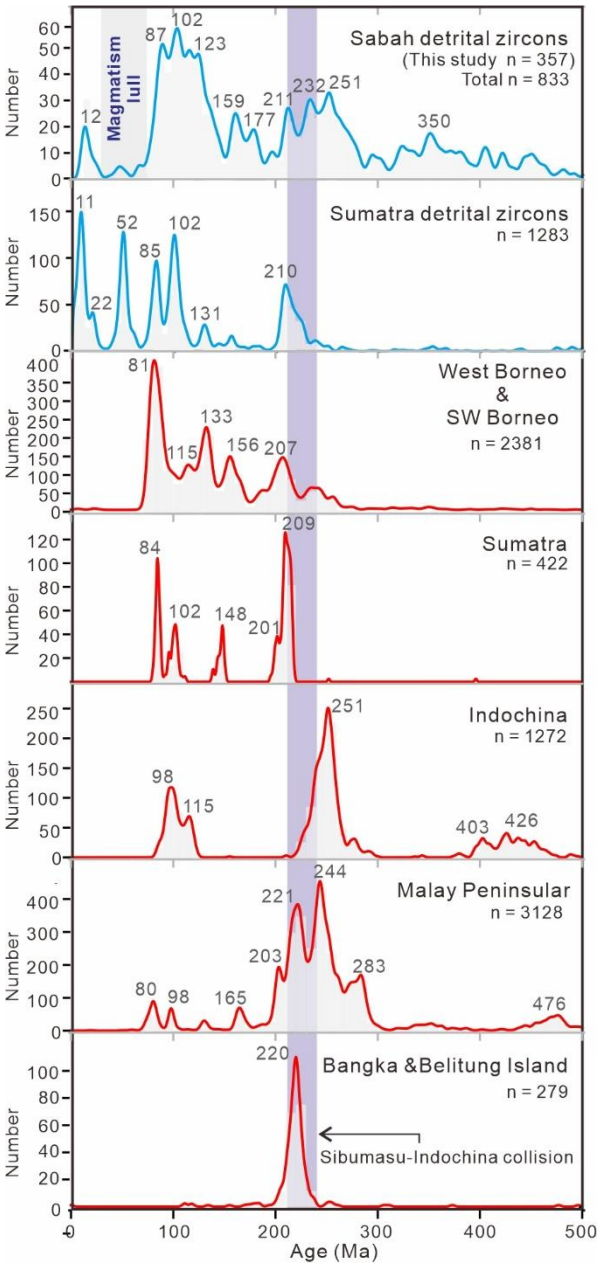


Figure 4. (**A**) Kernel density estimation (KDE) spectra of published zircon U-Pb ages of Mesozoic magmatic rocks around Sundaland. New and compiled detrital zircons U-Pb ages from the Upper Oligocene-Neogene sedimentary rocks in Sabah and

Sumatra are also shown for comparison. For the references pertaining to the compiled dataset, please refer to the Methods section. Supplementary Table S1 and Table S3 present the new and compiled zircon age data, respectively.

Figure 5 shows magmatic activity across West Sumatra and West and Southwest Borneo from the Permian, through the Triassic when Sibumasu collided with Indochina, to Early Miocene. Prior to the latest Triassic, magmatic zircons are scarce in both Borneo and West Sumatra. However, their detrital zircons exhibit scattered εHf(t) values, with detrital zircons from West Sumatra showing more positive εHf(t) values relative to those from West and Southwest Borneo. After the latest Triassic, on the western side (West Sumatra), magmatic zircons exhibit a narrow range in positive εHf values whereas detrital zircons show a progressive trend towards increasingly positive εHf values. This is not seen in the West and Southwest Borneo data, which instead shows a wider scattering of positive εHf values since the latest Triassic. Subduction-related magmatism in the West and Southwest Borneo appears to have ceased for a considerable period following 80 Ma. By contrast detrital zircon data from West Sumatra imply ongoing magmatism and a continuation of the trend of increasing positive εHf values.

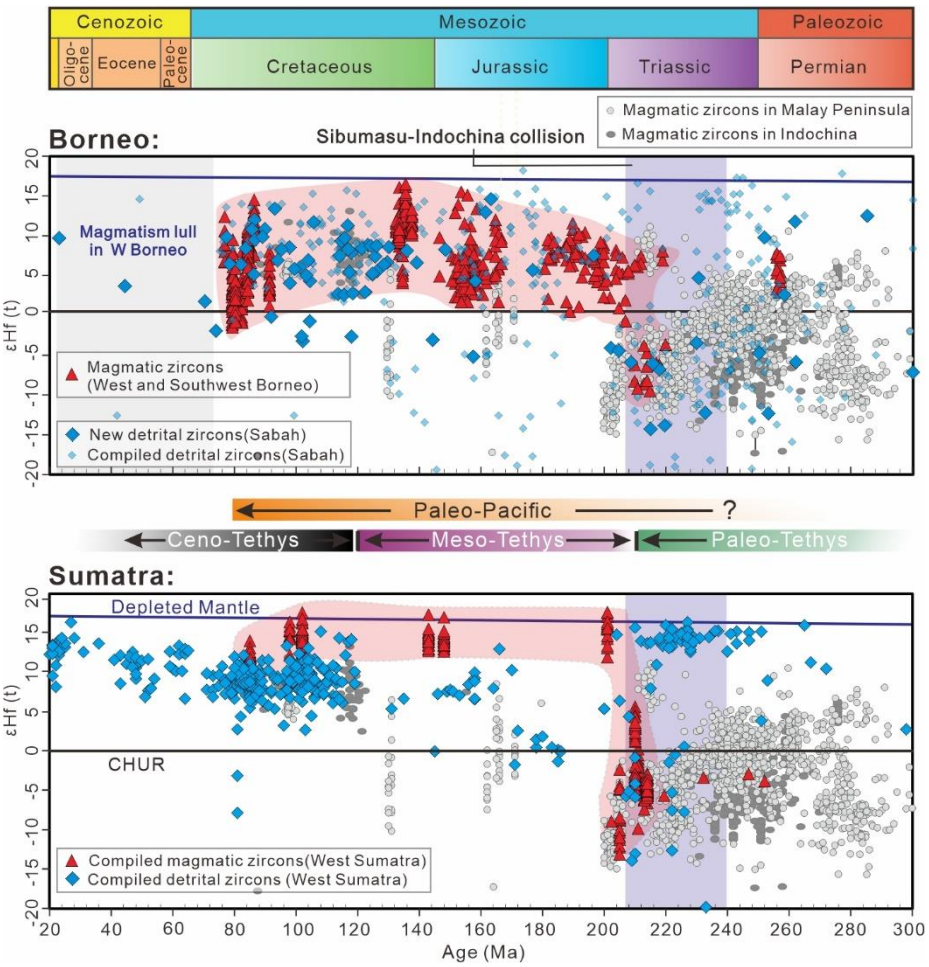


Figure 5. Zircon ages vs. zircon $\varepsilon_{Hf(}t)$ values of the Mesozoic magmatic rocks and Neogene sedimentary rocks in West Sumatra and Borneo. Magmatic zircons compiled from Mesozoic igneous rocks in the Malay Peninsula are also shown for comparison. For the references pertaining to the compiled dataset, please refer to the Methods section. Supplementary Table S2 and Table S4 present the new and compiled zircon Hf isotope data, respectively.

4. Discussion

4.1. Upper Oligocene-Neogene Sediments in Sabah: A Record of Magmatism in the Southern Pacific-Pacific Domain

Previous provenance analyses indicates that sources of Cenozoic sedimentary rocks preserved in Sarawak and Sabah are mainly from West Borneo, Southwest Borneo and the Malay Peninsula with some grains may have been recycled from older sedimentary rocks (e.g., van Hattum et al., 2013; Galin et al., 2017; Hennig-Breitfeld et al., 2019, Breitfeld et al., 2020b, 2023a, b). The Malay Peninsula mainly provided Permian-Triassic zircons, while West Borneo yielded Triassic and Cretaceous zircons, and Southwest Borneo dominantly supplied Cretaceous age grains (**Fig. 4**). New detrital zircon data from Upper Oligocene-Neogene sandstones are also dominated by Cretaceous ages (**Fig. 3**), suggesting that sediment was mainly sourced from West Borneo and Southwest Borneo via the proto-Rajang River drainage system by recycling or directly from the arc, rather than from the Malay Peninsula (e.g., Breitfeld et al., 2020b). The subrounded to euhedral morphological signatures of Triassic zircons indicate that they may directly originate from the Triassic magmatic rocks of West Borneo (Fig. 2), while sedimentary recycling of the Kuching-Sibu zone incorporating Malay-Thai and West Borneo provenance components remains a plausible mechanism (e.g., Breitfeld et al., 2020b; 2023a, b). Similar to the KDE age spectra, an MDS plot (**Fig. 6**; Vermeesch et al., 2016) also shows zircon age distributions from Sabah samples plotting closest to zircon ages from magmatic rocks of West Borneo and Southwest Borneo, suggesting that this was the primary source area.

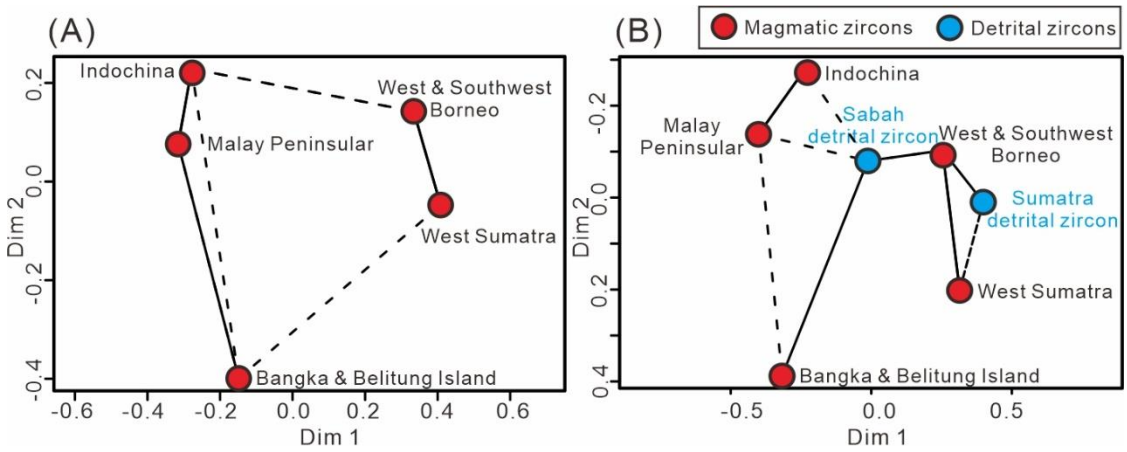


Figure 6. A Multi-Dimensional Scalar (MDS; Vermeesch et al., 2016) plot for compiled zircon U-Pb ages from Mesozoic magmatic rocks around Sundaland, (A) with or (B) without the new and compiled Neogene detrital zircon data in Borneo and Sumatra. For the references pertaining to the compiled dataset, please refer to the Methods section.

Magmatism in West Borneo and Southwest Borneo has been recognized as divided into Triassic and Jurassic subduction-related magmatic episodes and a Cretaceous magmatic arc associated with the Paleo-Pacific plate subduction (Williams et al., 1988; Breitfeld et al., 2017, 2020a; Hennig et al., 2017; Wang et al., 2021, 2022a, 2024), while some Early Jurassic rift-related within-plate magmatism also developed in Southwest Borneo (Breitfeld et al., 2020a). Zircon εHf(t) values serve as a powerful tracer for sediment provenance (e.g., Zhang et al., 2023), with their capacity to distinguish between mantle-derived material (more positive) and older crustal components (characterized by strongly negative εHf(t) values) providing critical insights into the relative contributions of these endmembers to magmatic

systems (Sundell & Macdonald, 2022). Most detrital zircons younger than 200 Ma have εHf(*t*) values similar to those of West Borneo and Southwest Borneo magmatic rocks (**Fig. 5**), and consistent with the implications of the KDEs and MDS plots that suggest a dominant supply from West Borneo and Southwest Borneo. A scarcity of detrital zircons postdating ~80 Ma aligns with the waning and cessation of subduction-related magmatic activity in West Borneo and Southwest Borneo (Williams et al., 1988; Hennig et al., 2017; Breitfeld et al., 2017, 2020a; Wang et al., 2024). A small number of zircons younger than 200 Ma fall within the εHf(*t*) range of granites in the Malay Peninsula, indicating limited input from that area (e.g., Breitfeld et al., 2020b). The εHf(*t*) values of our detrital zircons from Sabah, that represent an archive of magmatism across West Borneo and Southwest Borneo, began to increase in the Latest Triassic, and became overwhelmingly positive during the Jurassic and Cretaceous (**Fig. 5**). The compiled magmatic zircons from West Borneo and Southwest Borneo also have heterogeneous εHf(*t*) values (varying by up to ~20 ε units) in the Latest Triassic, followed by fully positive εHf(*t*) values with juvenile features (**Fig. 5**). Although the detrital zircons in the Upper Oligocene-Neogene strata was interpreted as multi-recycling products from Rajang Group and/or Crocker Formation (Hennig-Breitfeld et al., 2019; Breitfeld et al., 2020b, 2023a, 2023b), the close similarity of results between Sabah and West and Southwest Borneo supports the view that the Neogene sediments in Sabah effectively document the temporal changes in magmatic activity in West Borneo and Southwest Borneo since the

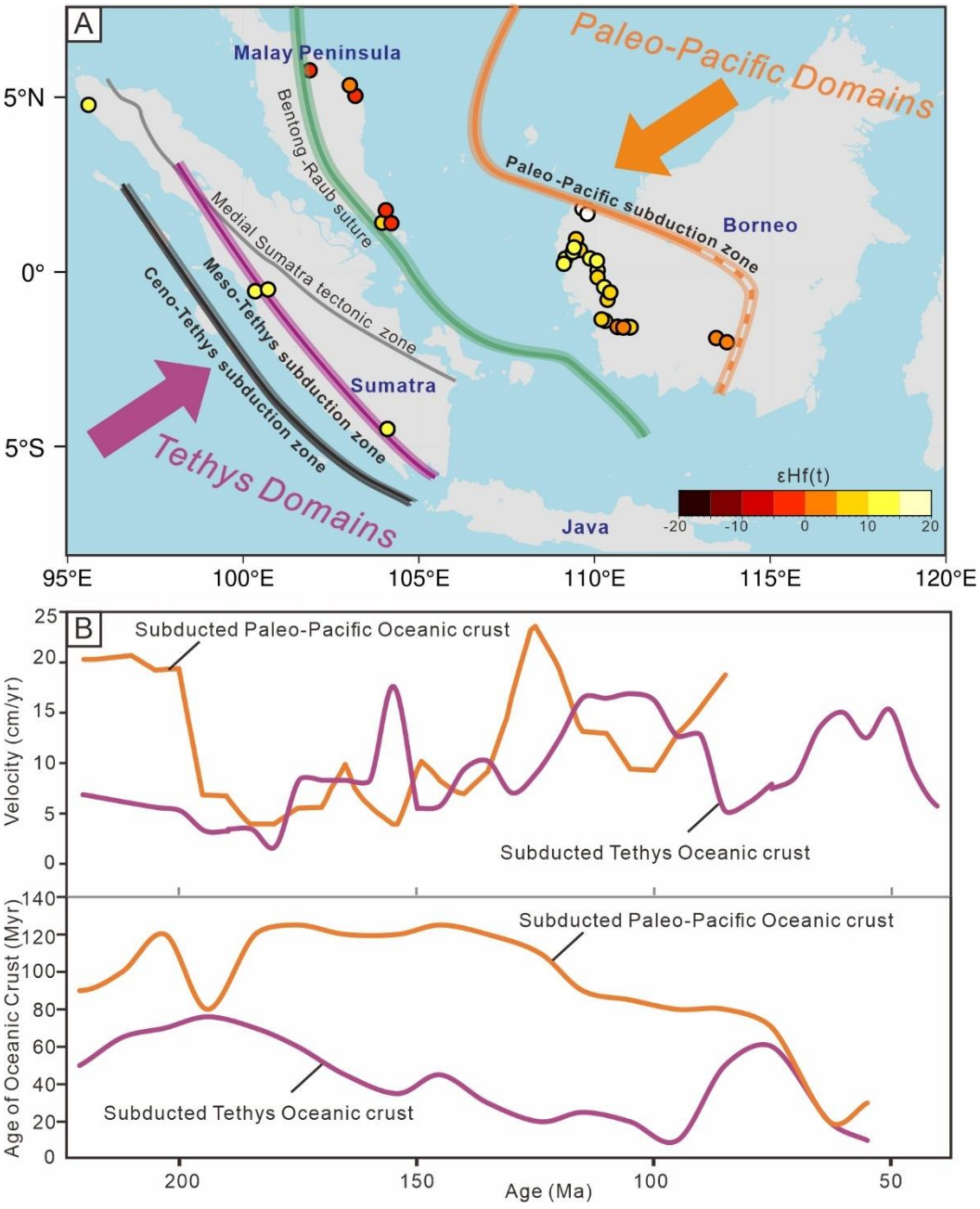
Mesozoic, thus serving as a record of the magmatic evolution of the southern Paleo-Pacific domain.

4.2. Spatiotemporal Evolution of Magmatism in each Subduction System

Published whole-rock elemental and Sr-Nd-Pb-(Hf-O) isotopic results indicate that the Mesozoic magmatic rocks in West Borneo were the products of subduction of the Paleo-Pacific plate under the East Asia active continental margin (Wang et al., 2021; 2022a; 2024), while some Jurassic magmatic rocks in Southwest Borneo are interpreted as rift-related within-plate granites (Breitfeld et al., 2020a). Mesozoic granitoids in Sumatra represent the products of subduction magmatism in the easternmost Tethys (Li et al., 2020). Temporally, Mesozoic magmatism in West Borneo and Southwest Borneo exhibits some similarities in age with Sumatra, as shown by the magmatic zircon U-Pb ages on the KDE and MDS plots (**Fig. 4, 6**). During the Early Permian to Middle Triassic, magmatism associated with Paleo-Tethyan subduction predominantly occurred in East Malaysia, exhibiting distinct negative εHf(t) signatures (**Fig. 5**, e.g., Ng et al., 2015; Gillespie et al., 2019; Liu et al., 2020; Wang et al., 2021a). The positive εHf(t) values of detrital zircons from Sumatra likely preserve information predating its accretion to Sundaland, given that Sumatra may represent the southern extension of the West Burma block (Barber & Crow, 2009; Metcalfe, 2013). In contrast, westward subduction of the Paleo-Pacific plate remained limited or inactive until the Late Triassic (e.g., Zhou et al., 2023).

Therefore, only sporadic magmatism from this period is preserved in West Sumatra and West Borneo (**Fig. 5**). Since latest Triassic, the temporal trends in Hf isotope variations are broadly similar in magmatic and detrital zircons from both Sumatra and Borneo, although εHf(t) values of magmatic and detrital zircons in Sumatra are consistently higher and more uniform than those in Borneo from the same period (**Fig. 5**). This suggests that evolution of the Mesozoic magmatic arc was temporally synchronous across the two active continental margins (Sumatra and Borneo). The notable variation (~20 ε units) in εHf(t) values seen in latest Triassic magmatic and detrital zircons (220–200 Ma) from both Sumatra and Borneo, representing the western and eastern boundaries of Sundaland, suggest a mix of evolved and juvenile crust in each subduction system immediately after Triassic collision between Indochina and Sibumasu. A trend to positive εHf(t) values on Borneo and Sumatra was established during the Jurassic and Cretaceous, indicating that juvenile crustal growth is prevalent on both sides of the interaction zone (**Fig. 5**). In the central part of the overriding plate (Malay Peninsula), magmatic rocks remain isotopically evolved, implying that far from the trench the continental mantle lithosphere is thick (e.g., Chapman et al., 2017). Detrital data show a magmatic lull after ~80 Ma in West and Southwest Borneo, indicating that subduction-related arc magmatism in West and Southwest Borneo had largely ceased by that time (Hennig et al., 2017; Breitfeld et al., 2020a), unlike Sumatra where magmatism continued throughout the Cenozoic (**Fig. 4, 5**).

Spatially, the post-Latest Triassic magmatic rocks of West Sumatra are distributed along a narrow belt near the trench with high and uniformly positive εHf(t) values, while those in West and Southwest Borneo are relatively more widely distributed with lower positive εHf(t) values away from the trench (**Fig. 1B, 7A**), potentially due to differences in the angle, age, and rate of the subducting plates. Although plate kinematics are not well-constrained due to a lack of preserved oceanic lithosphere, reconstructions of global plate motion show that from the Jurassic to the Cretaceous, there is no consistent pattern in reconstructed convergence rates between the two margins of Sundaland (**Fig. 7B**; Műller et al., 2016), this suggests that convergence rate is not the primary factor influencing the spatial distribution patterns of Mesozoic magmatic rocks. However, global plate reconstructions predict the eastern margin of interaction zone was mainly influenced by subduction of older Paleo-Pacific oceanic lithosphere that would be consistent with accreted ocean plate stratigraphy ages in SW Hokkaido, Japan (Ishiga and Ishiyama, 1987). By contrast, West Sumatra initially experienced subduction of relatively younger oceanic lithosphere that separating it from the Woyla Arc (Advokaat et a., 2018). Subduction of more steeply dipping young oceanic lithosphere would tend to form a narrow arc near the trench due to their weaker ability to carry volatiles to the lower crust, compared to more gently dipping subduction of a colder and older serpentinized Paleo-Pacific oceanic lithosphere (e.g., Bastias-Silva et al., 2024).



422

423 **Figure 7**. (A) Spatial distribution of zircon εHf(t) values Mesozoic magmatic rocks

424 (200–66 Ma) in West Sumatra, Malay Peninsula, and West and Southwest Borneo.

425 Filled circles represent the mean εHf(t) values of magmatic zircons. (B) Convergence

426 rate and oceanic plate age along the two subduction zones of Sundaland (orange

427 line=Paleo-Pacific; blue=Tethyan) based on global plate reconstructions of Műller et

428 al. (2016, 2019).

4.3. Inward Dipping Double Subduction Initiated in Latest Triassic

Spatiotemporal variations in radiogenic isotope compositions can shed light on the evolution of subduction zone dynamics. In Sumatra, a fundamental restructuring of the arc system in the Latest Triassic is identified based on the marked increase in εHf(t) values observed in zircons from Mesozoic granitoids, as well as detrital zircons from Cenozoic strata and modern river sediments (**Fig 5;** Zhang et al., 2019; Li et al., 2020). An extensional fringing arc related to NW-SE trending extensional basins in Sumatra (Barber and Crow, 2009) or slab retreat or rollback that occurred shortly after the Middle-Late Triassic collision of Sibumasu with Indochina and East Malaya, have been considered as indicative of the initial input of juvenile material in Sumatra (Li et al., 2020).

For Borneo, the presence of Mesozoic supra-subduction zone ophiolites and Mesozoic-Cenozoic basin indicates that Borneo has been subjected to a protracted extensional setting since the Late Triassic (Burton-Johnson et al., 2023). The development of the Triassic Sadong and Kuching Formations and Cretaceous Pedawan Formation—characterized by forearc basin successions in West Borneo—provides critical evidence for syn-depositional extensional tectonics (Pieters et al., 1993; Breitfeld et al., 2017, 2023c; Mazumder et al., 2021), likely associated with episodic slab rollback during subduction of the Paleo-Pacific plate (Zhou et al., 2023). Significant extensional collapse around 215 Ma also characterizes the

Sibumasu terrane, particularly in northern Thailand and potentially other regions (Morley, 2018). Therefore, the notable variation (220–200 Ma, ~20 ε units) in magmatic and detrital zircon εHf(t) values from both Sumatra and Borneo suggest the addition of juvenile material in an extensional setting in each subduction system.

The initiation of double subduction is usually associated with collision, such as the Solomon subduction zone (Sun et al., 2021). Numerical modelling indicates that during the early stages of a double subduction system, the stress on the overriding plate either remained in an extensional state (Lyu et al., 2019) or transitioned from compression to extension, typically within the first few million years (Zhang et al., 2024). Therefore, we consider that an inward-dipping double subduction system underneath Sundaland (the interaction zone) began to be established immediately after latest Triassic collision between Indochina and Sibumasu (**Fig. 8**).

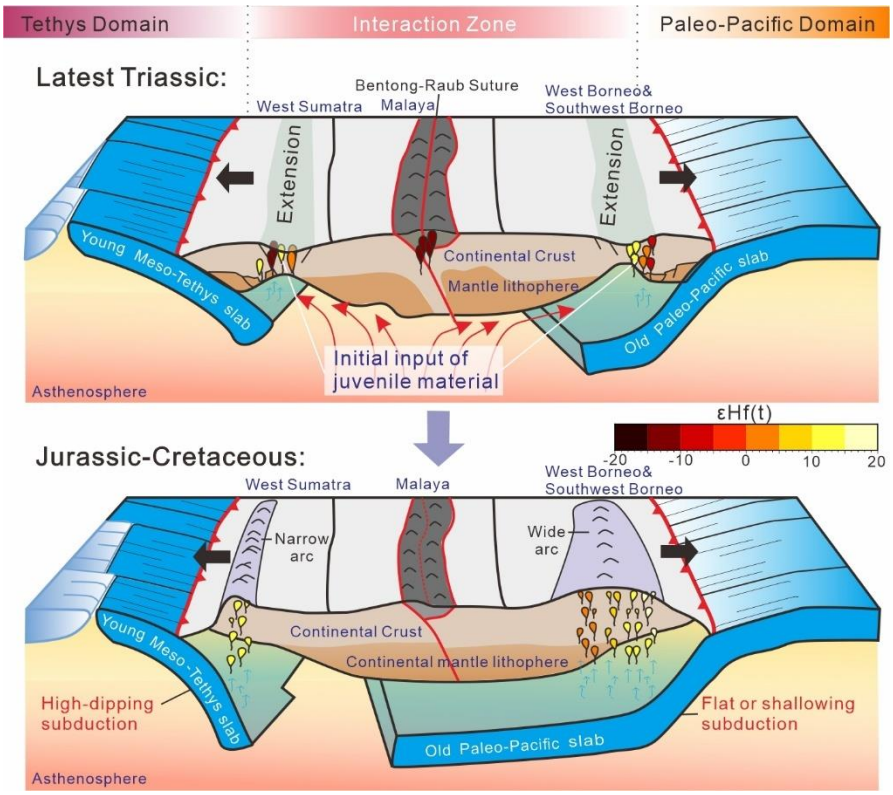


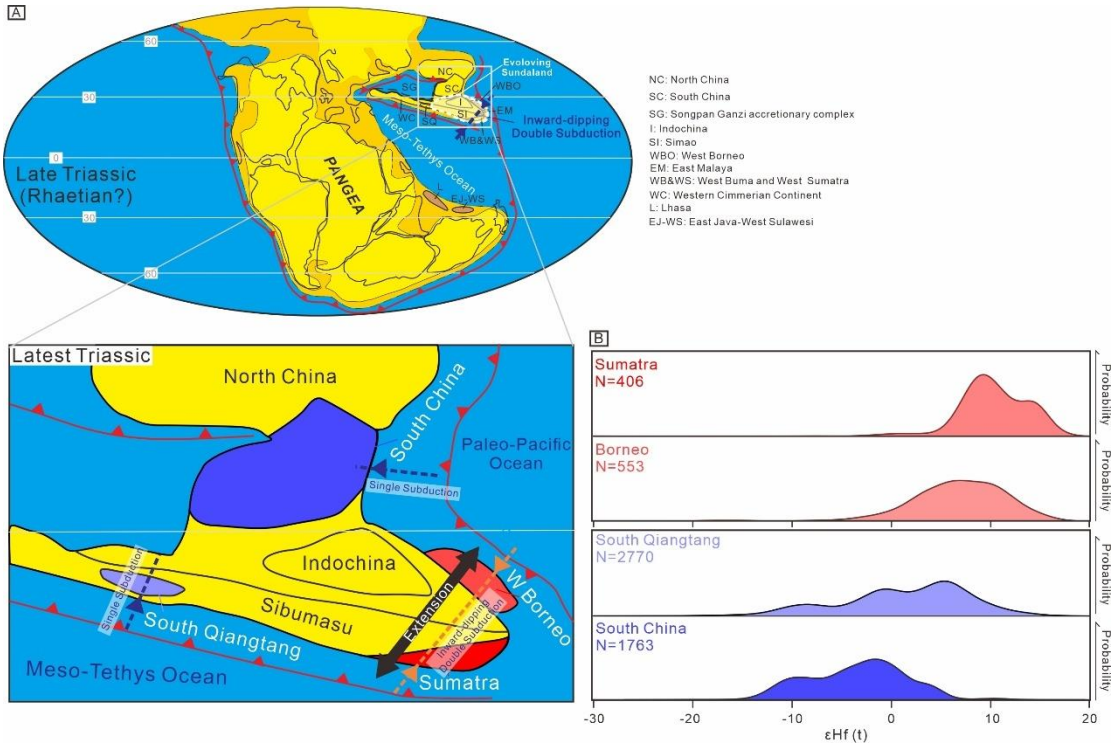
Figure 8. Input of juvenile material into Sumatra and Borneo, initiated in the Latest Triassic and continued to develop from the Jurassic to the Cretaceous due to the extension of the inward-dipping double subduction.

During the Jurassic and Cretaceous, the positive εHf(t) values on Borneo and Sumatra indicate that the melt source region of the two subduction zones is predominantly depleted asthenospheric mantle but, mixed with varying proportions of isotopically evolved continental lithospheric mantle. The contrasting ranges of positive εHf(t) values imply the double subduction system evolved asymmetrically. The narrow spatial distribution observed in the arc magmatism of Sumatra and their uniformly positive εHf(t) isotopic values is thus attributed to the absence of continental lithospheric mantle near the trench during the high-angle subduction of the Meso-Tethys slab (e.g., Chapman et al., 2017). In contrast, the wide arc magma belt and broader Hf isotopic values in Borneo represent varying degrees of involvement of continental mantle lithosphere during more shallow dipping subduction of the Paleo-Pacific oceanic crust in that time (Zhou et al., 2023; **Fig. 8**). Around 80 Ma, this stable asymmetric double subduction system was disrupted, marked by the complete cessation of subduction-related arc magmatism in Borneo while magmatism continued in West Sumatra. In SE Vietnam (north of West Borneo) subduction-related magmatism had also ceased by c. 80 Ma (Hennig-Breitfeld et al., 2021), implying the waning of the Paleo-Pacific subduction zone at that time. The

magmatic arc in West Sumatra has maintained isotopically juvenile signals even after 80 Ma (**Fig. 5**). This aligns with numerical models suggesting that large-scale extension, along with extensive and vigorous mantle upwellings, persists even after one of the two subductions ceases (Li et al., 2024).

4.4. Juvenile Crust Production in SE Asia Linked to Double Subduction

Our data show a significant isotopic shift from isotopically evolved to isotopically juvenile in the continental arc of the Sundaland margin around 200 Ma, triggered by collision between Sibumasu and Indochina and the initiation of an inward-dipping double subduction regime (**Fig. 5**). During the latest Triassic to Jurassic, Southeast Asia served as an interaction zone connecting the Qiangtang block of western Meso-Tethys and South China of the northern Paleo-Pacific, where single subduction developed (**Fig. 9A**). However, isotopic data for contemporary batholith from South Qiangtang in the Meso-Tethys domain and South China in the Paleo-Pacific domain exhibit εHf(t) values lower than those measured from West and Southwest Borneo and West Sumatra in the interaction zone (**Fig. 9B**). This raises the possibility that, compared to single subduction in the Meso-Tethys or Paleo-Pacific domains, an inward-dipping double subduction system is more conducive to the formation of juvenile crust.



503

504 **Figure 9**. (A) Palaeogeographic reconstructions for the Paleo-Pacific and Eastern

505 Tethys in late Triassic (after Metcalfe, 2017). Notes the enlarged view of the

506 interaction zone. (B) Density curves of εHf (t) from latest Triassic to early Late

507 Cretaceous (200–80 Ma) for batholith in the Tethys and Paleo-Pacific domains. Data

508 of batholith in the South Qiangtang and South China are from Gong et al. (2024),

509 Zhang et al. (2023) and references therein.

510

511 Numerical simulations indicate that inward-dipping double subduction results in

512 larger-scale upper plate extension and greater volumes of upwelling mantle compared

513 to single subduction (Lyu et al., 2019; Li et al., 2024; Zhang et al., 2024). This fits

514 with evidence of widespread extension across Sumatra and Borneo (Barber and Crow,

515 2009; Pieters et al., 1993; Breitfeld et al., 2017, 2023c; Mazumder et al., 2021;

516 Burton-Johnson et al., 2023; Zhou et al., 2023). Isotopically juvenile signature in

Sumatra persist to the present day (**Fig. 5**) and may be a residual feature inherited from the time of double subduction (e.g., Li et al., 2024). Our study emphasizes that the role of inward-dipping double subduction in Southeast Asia, including its influence on mantle structure and temperature.

5. Conclusions

Records of magmatic and detrital zircons from both Borneo and Sumatra show an inward-dipping double subduction system beneath Sundaland initiated in the latest Triassic, coinciding with the collision of Indochina and Sibumasu. Magmatism persisted on both West and Southwest Borneo and West Sumatra from the latest Triassic to the Cretaceous; however, it evolved asymmetrically due to differences in the subducting oceanic lithospheres—specifically, the younger, steeply dipping Meso-Tethys and the older, more shallowly dipping Paleo-Pacific oceanic lithosphere. After 80 Ma, subduction-related magmatism on the Borneo side ceased following the termination of subduction of Paleo-Pacific oceanic crust, while on the Sumatra side, magmatism with isotopically juvenile compositions continued. Furthermore, our study establishes a possible causal link between the strengthened juvenile crustal signatures in Southeast Asia and the large-scale extension of the overriding lithospheric plate in an inward-dipping double subduction system.

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Open Research

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Figure 1.

A

Muyunk
North China
Qilian
Tarim
Qaidam
Songpan Ganzi
Karakum
N.Qiangtang
S.Qiangtang
South China
Lhasa
Helmand
Tethys Domains
West Burma
Indochina
Pacific Domains
Sibumasu
Sukhothai Arc
Indian Craton
?
Interaction zone
W Borneo
B
West Sumatra
East Java-West Sulawesi

Proto-Tethys sutures
Paleo-Tethys sutures
Meso-Tethys sutures
Ceno-Tethys sutures
Paleo-Pacific subduction zone
Present-day subduction zone

Time-Scale
Tectonic domians
Tethys
Pacific
Cenozoic
Quater-mary
Neo-gene
Paleo-gene
Mesozoic
Creta-ceous
Jura-ssic
Tria-ssic
Paleozoic
Per-mian
Carb.
Devo-nian
S
O
Camb-rian
Precambrian
Neo-proterozoic
Paleo-Tethys
Meso-Tethys
Ceno-Tethys
Paleo-Pacific
Proto-Tethys

90°E
95°E
100°E
105°E
110°E
115°E
120°E

B

Malay Peninsula
Sabah
Paleo-Pacific subduction zone
Sibu
Sarawak
Borneo
West Borneo
Hennig Line
Bangka
Southwest Borneo
Belitung
Medial Sumatra Tectonic Zone
East Sumatra
West Sumatra
Woyla Terrane
Sumatra

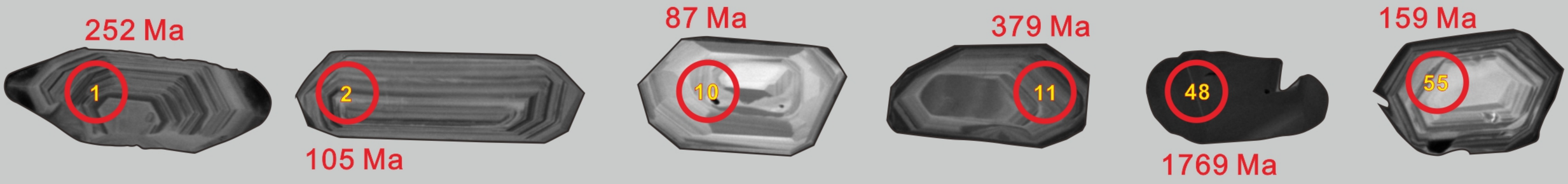
Magmatic zircons (compiled):
Triassic
Jurassic
Cretaceous
Detrital zircons:
This study
Compiled
Mesozoic magmatism

5°N
0°
5°S

Figure 2.

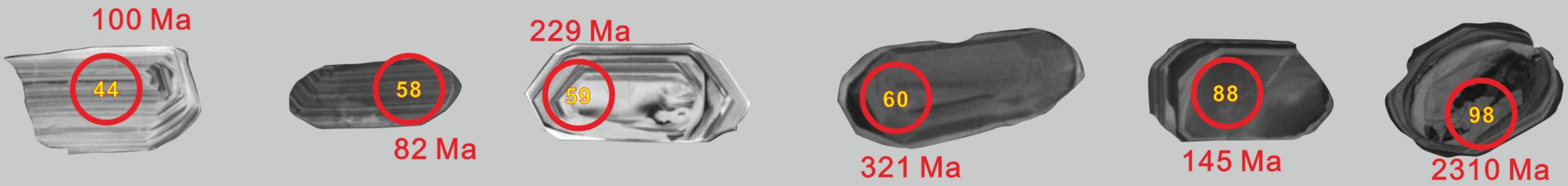
K-03

100 µm



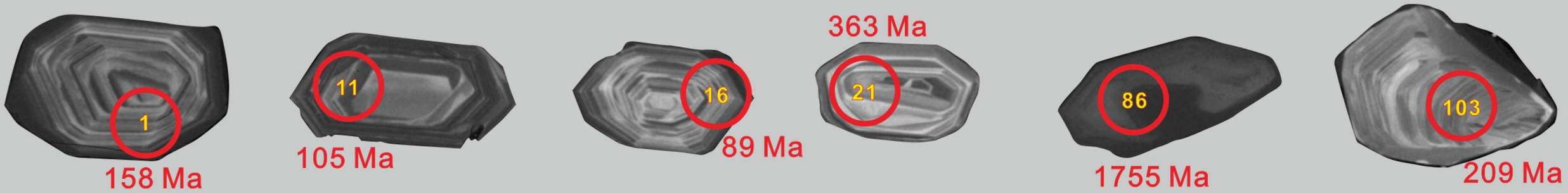
K-01

100 µm



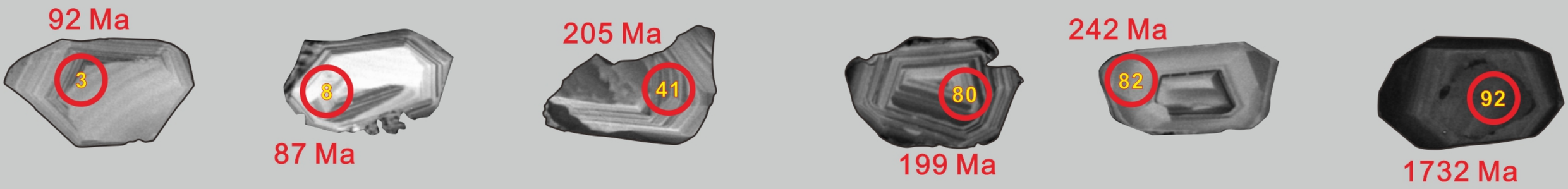
SK-02

100 µm



SK-06

100 µm



TB-10B

100 µm

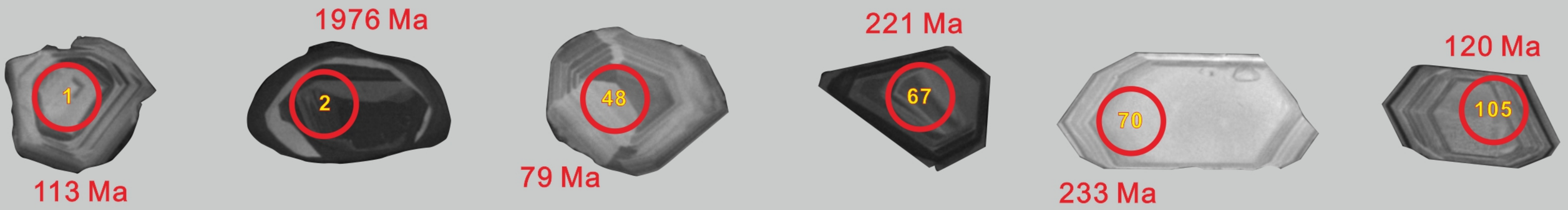


Figure 3.

Cen K J T P C D S O

n=88

n=17

Proterozoic

Archean

Tanjong Fm

K-03A

n=66

n=20

Kuamut Mélange (sanstone block)

K-01

n=62

n=42

Garinono Mélange (sanstone block)

SK-02

n=78

n=15

Labang Fm

SK-06

n=63

n=41

Cretaceous turbidite slice within the ophiolitic basement

TB-10B

Number

Age (Ma)

Figure 4.

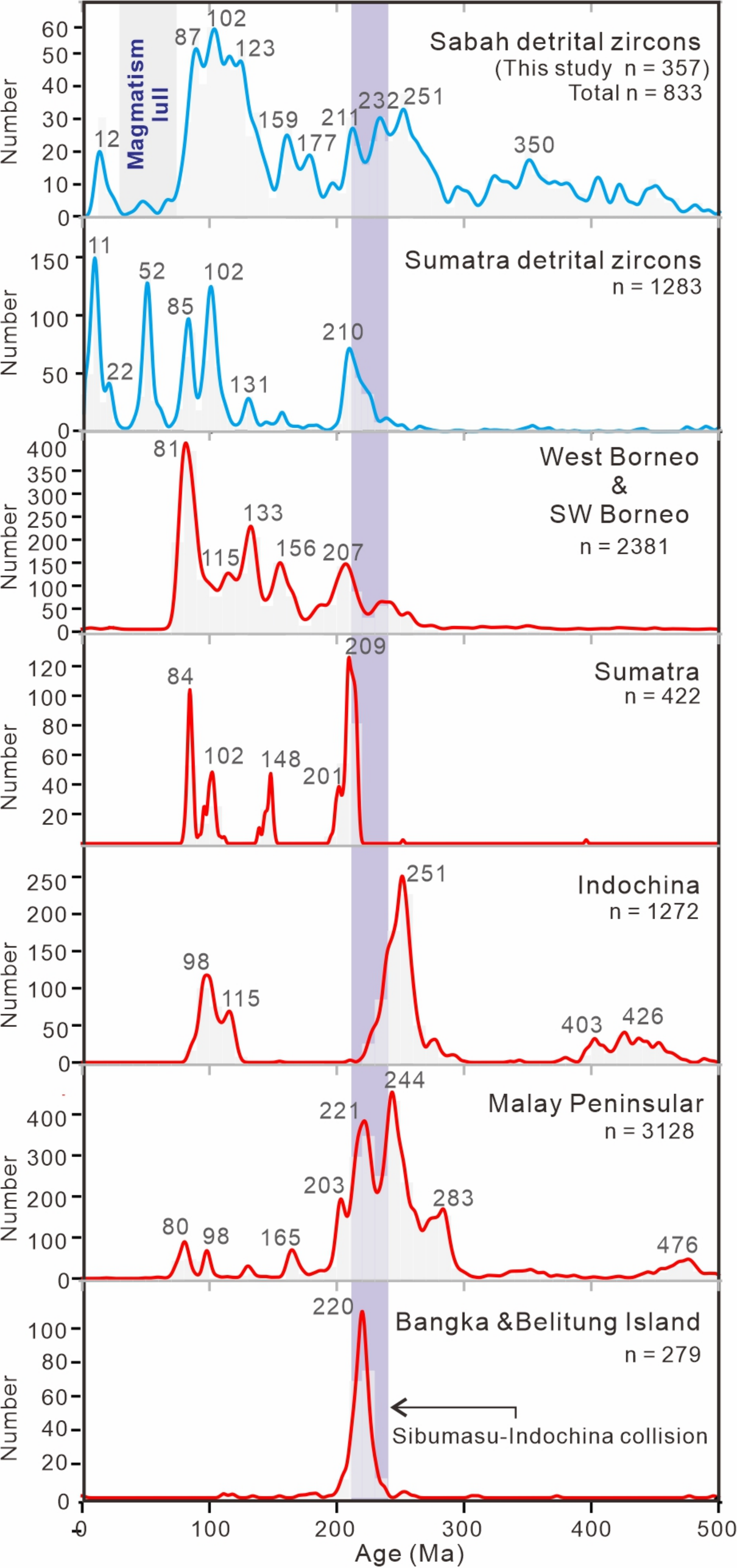

Sabah detrital zircons
(This study n = 357)
Total n = 833
Magmatism lull
12
87
102
123
159
177
211
232
251
350
Sumatra detrital zircons
n = 1283
11
22
52
85
102
131
210
West Borneo
&
SW Borneo
n = 2381
81
115
133
156
207
Sumatra
n = 422
84
102
148
201
209
Indochina
n = 1272
98
115
251
403
426
Malay Peninsular
n = 3128
80
98
165
203
221
244
283
476
Bangka &Belitung Island
n = 279
220
Sibumasu-Indochina collision
Number
Age (Ma)

Figure 5.

Cenozoic | Mesozoic | Paleozoic

Oligo-cene | Eocene | Paleo-cene | Cretaceous | Jurassic | Triassic | Permian

Magmatic zircons in Malay Peninsula

Magmatic zircons in Indochina

Borneo:

Sibumasu-Indochina collision

Magmatism lull in W Borneo

Magmatic zircons (West and Southwest Borneo)

New detrital zircons(Sabah)

Compiled detrital zircons(Sabah)

εHf (t)

Paleo-Pacific ?

Ceno-Tethys | Meso-Tethys | Paleo-Tethys

Sumatra:

Depleted Mantle

CHUR

Compiled magmatic zircons(West Sumatra)

Compiled detrital zircons (West Sumatra)

Age (Ma)

Figure 6.

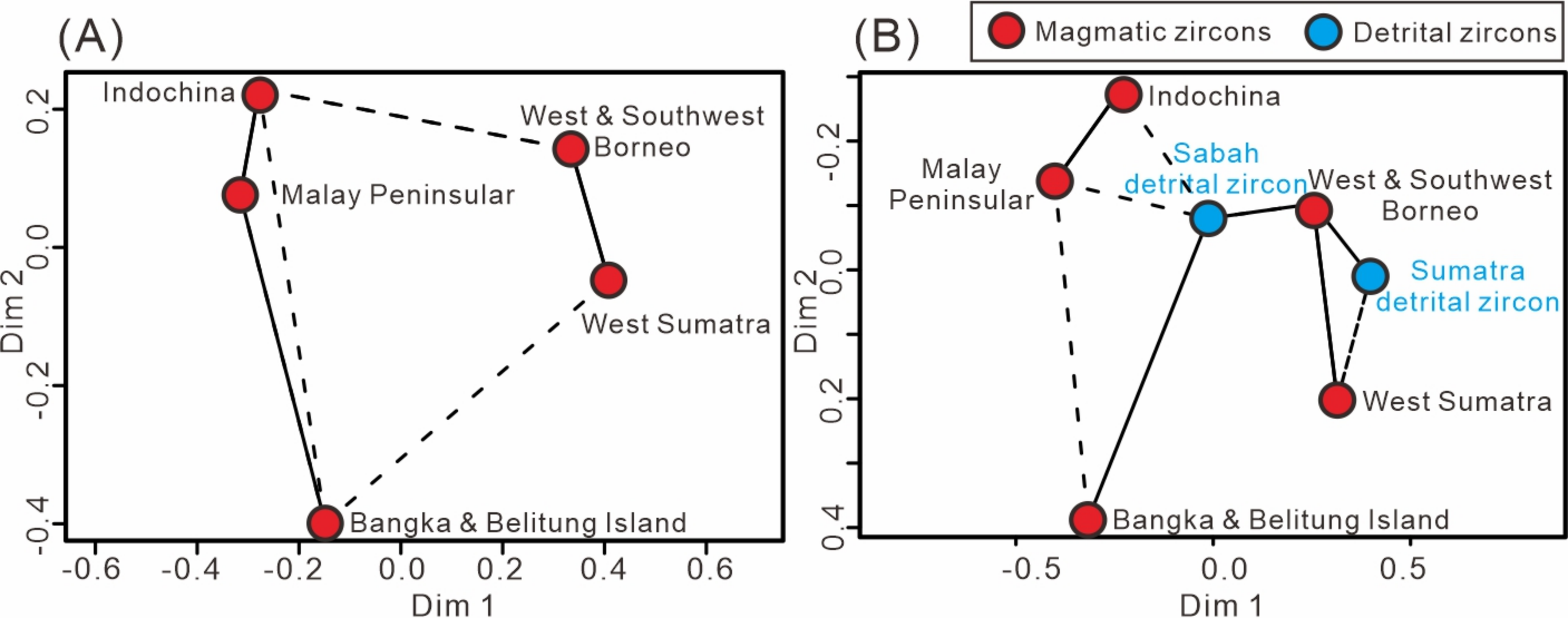
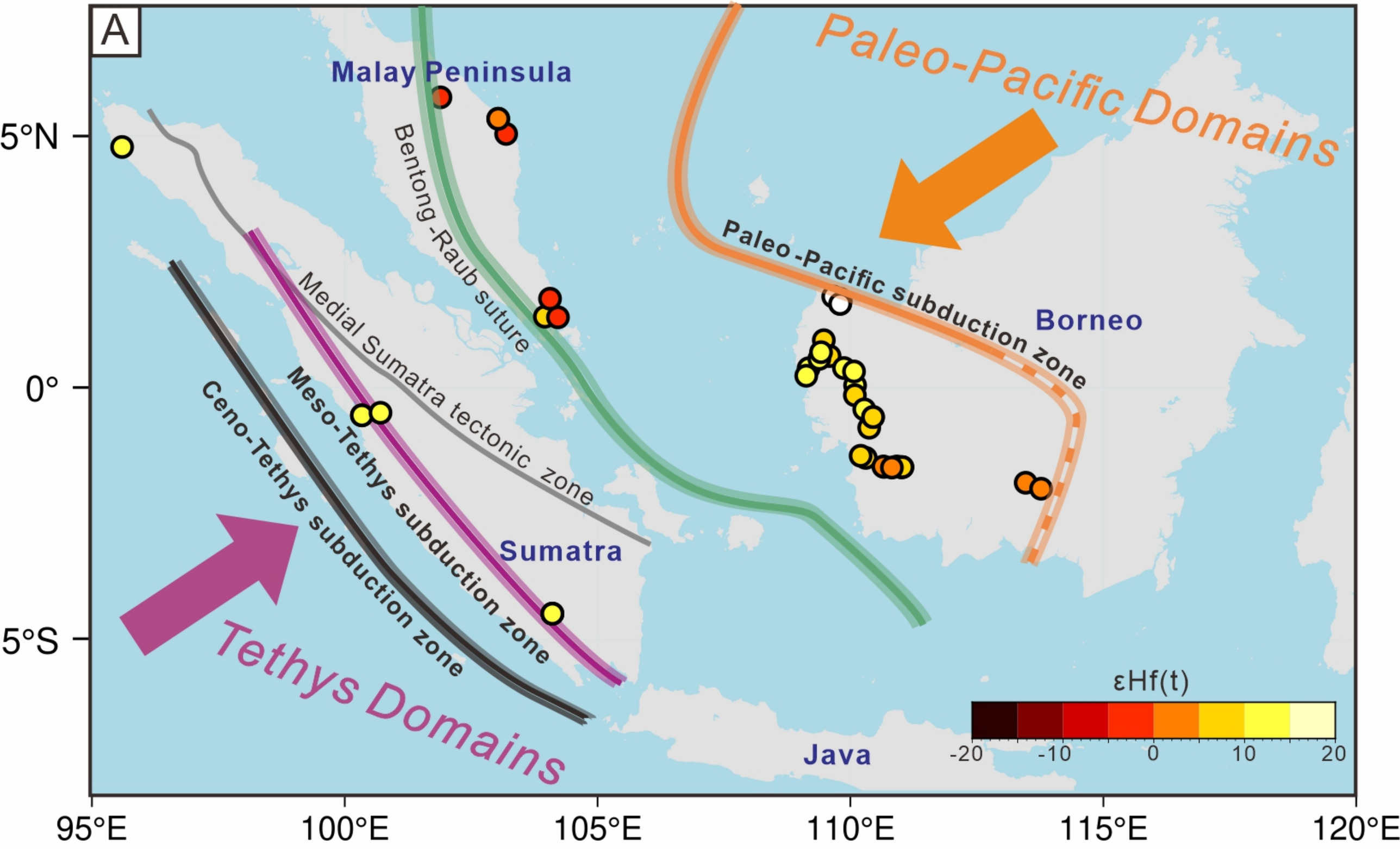

(A)
Indochina
West & Southwest
Borneo
Malay Peninsular
West Sumatra
Bangka & Belitung Island
0.2
0.0
-0.2
-0.4
Dim 2
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
Dim 1
(B)
Magmatic zircons
Detrital zircons
Indochina
Malay
Peninsular
Sabah
detrital zircon
West & Southwest
Borneo
Sumatra
detrital zircon
West Sumatra
Bangka & Belitung Island
-0.2
0.0
0.2
0.4
Dim 2
-0.5
0.0
0.5
Dim 1

Figure 7.


A
Malay Peninsula
Bentong-Raub suture
Medial Sumatra tectonic zone
Meso-Tethys subduction zone
Ceno-Tethys subduction zone
Sumatra
Tethys Domains
Paleo-Pacific Domains
Paleo-Pacific subduction zone
Borneo
Java
εHf(t)
-20
-10
0
10
20
5°N
0°
5°S
95°E
100°E
105°E
110°E
115°E
120°E

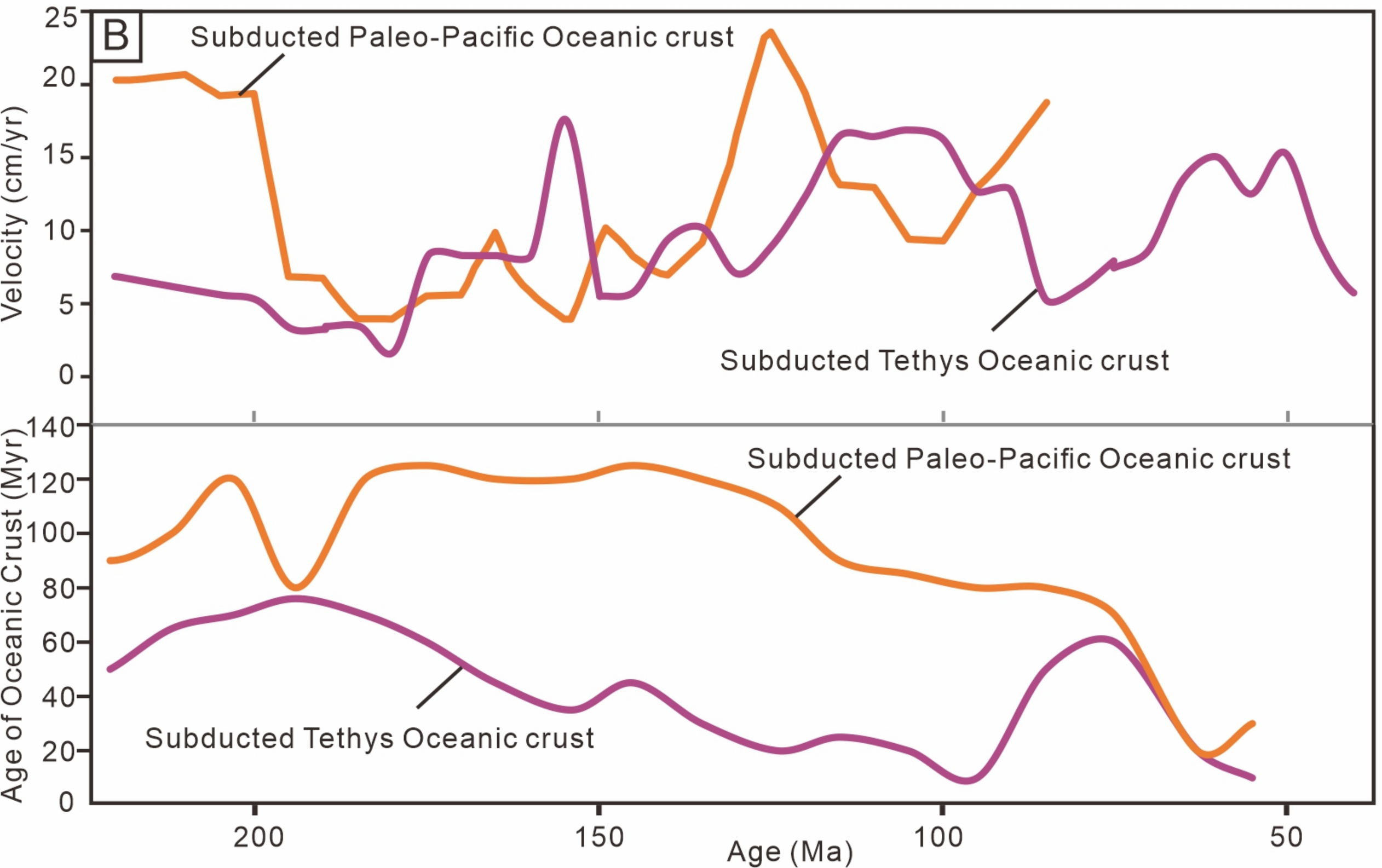
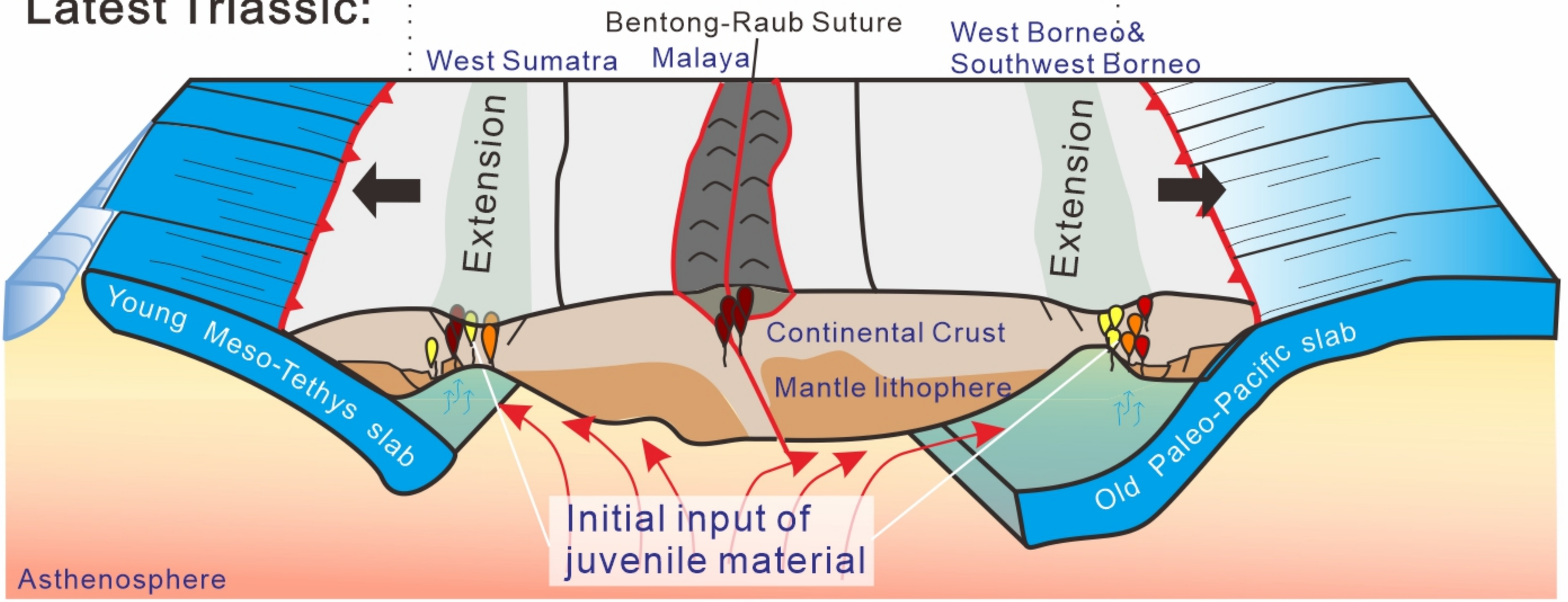

B
Subducted Paleo-Pacific Oceanic crust
Subducted Tethys Oceanic crust
Velocity (cm/yr)
25
20
15
10
5
0
Subducted Paleo-Pacific Oceanic crust
Subducted Tethys Oceanic crust
Age of Oceanic Crust (Myr)
140
120
100
80
60
40
20
0
200
150
100
50
Age (Ma)

Figure 8.

Tethys Domain | Interaction Zone | Paleo-Pacific Domain

Latest Triassic:



Jurassic-Cretaceous:

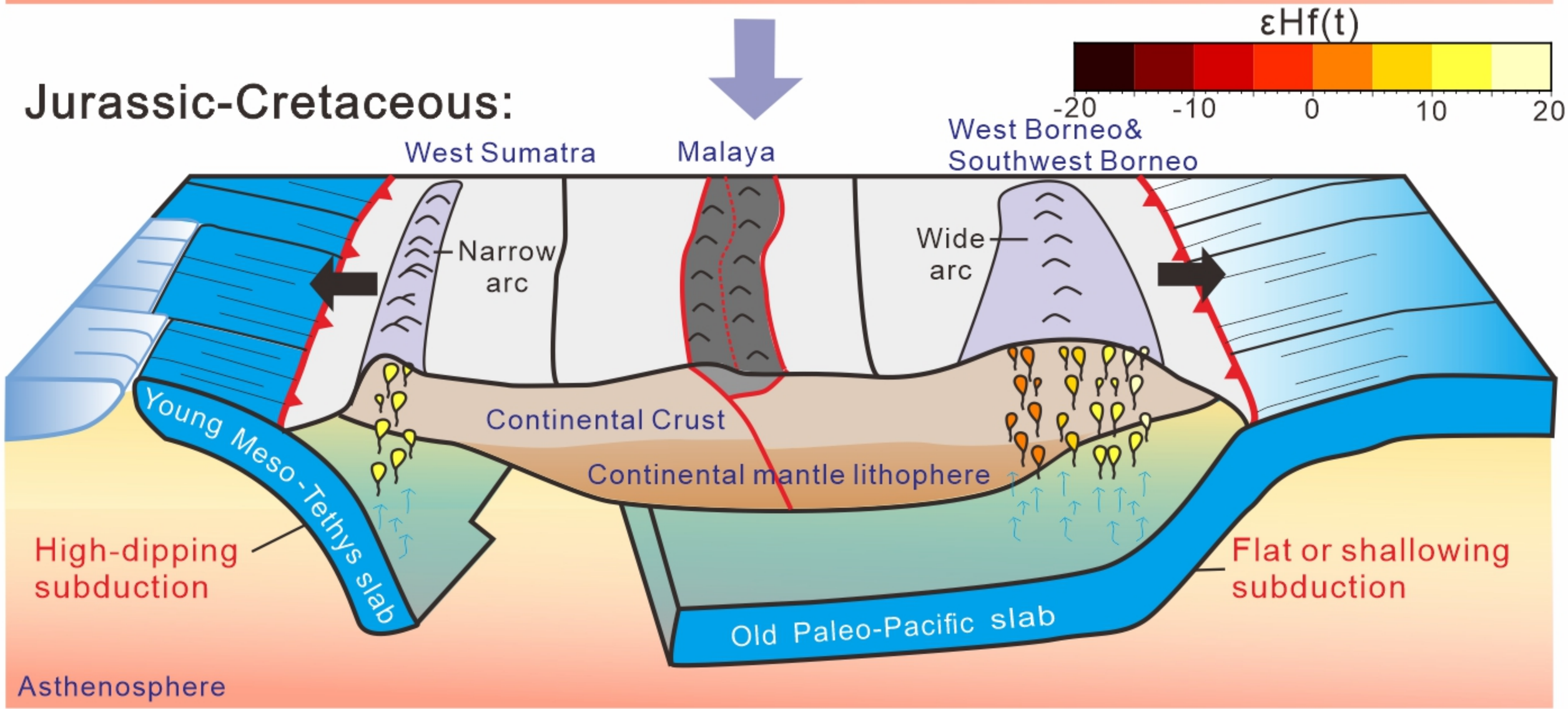
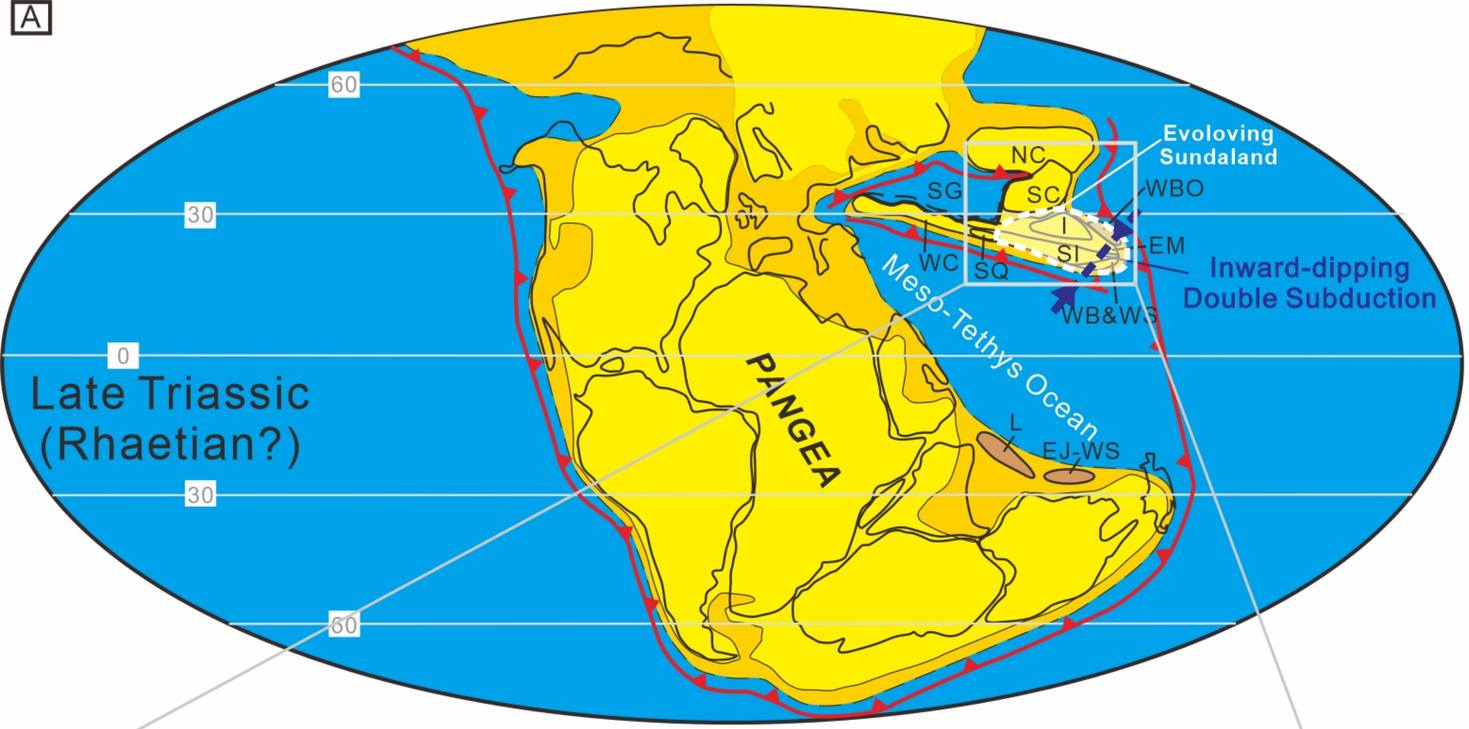
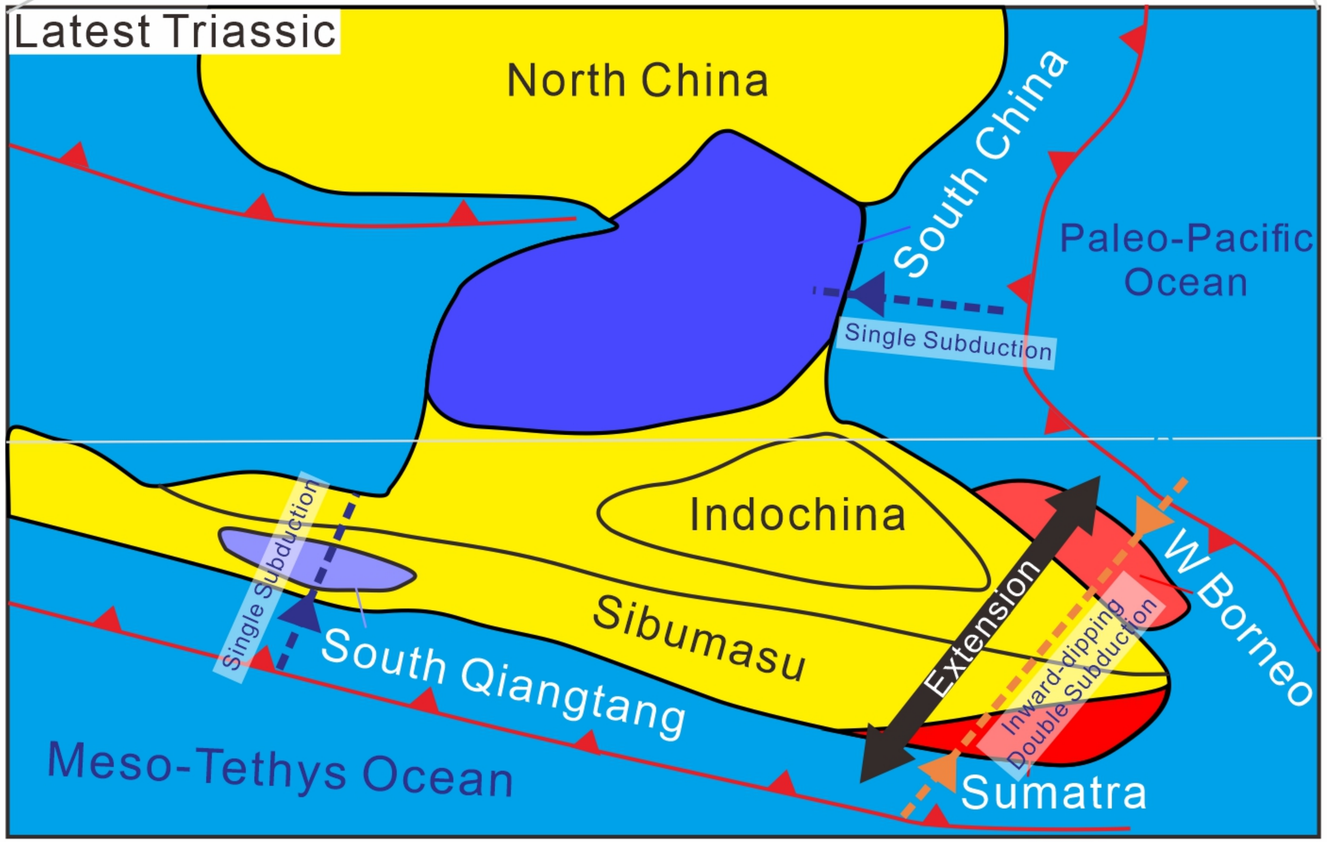


Figure 9.

A



NC: North China
SC: South China
SG: Songpan Ganzi accretionary complex
I: Indochina
SI: Simao
WBO: West Borneo
EM: East Malaya
WB&WS: West Buma and West Sumatra
WC: Western Cimmerian Continent
L: Lhasa
EJ-WS: East Java-West Sulawesi



B