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Prototethyan orogenesis in southwest Yunnan and Southeast Asia

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Abstract The Prototethyan Ocean has been suggested as an Early Paleozoic Ocean developed at the Gondwana northern margin. However, its spatial pattern, subduction style and closure time in SW Yunnan and SE Asia still remain unknown. The Prototethyan evolution in SW Yunnan and SE Asia and its internal connection with the South China Kwangsian (Ordo-Silurian) intracontinental orogenesis are also poorly constrained. By summarizing and analyzing the Early Paleozoic geological records in the Sibumasu and Indochina blocks, the eastern South China and SW Japan, this paper proposes the existence of a giant Ordo-Silurian igneous belt along the Gondwana northern margin. A preliminary limitation has been obtained regarding the source nature and migration pattern of the igneous belt. Our data allow us to propose a model of the Early Paleozoic Andean-type active continental margin along the East Gondwana northern margin. This is the foundation to determine the southward subduction of the southern branch of the eastern Prototethyan Ocean underneath the Sibumasu and Indochina blocks along the Yunxian-Menghai (SW Yunnan)-Thailand Peninsula and the Tam Ky-Phouc Son suture in Central Vietnam, respectively, and the eastward linkage with the Early Paleozoic Osaka subduction zone in SW Japan across the peripheral Sanya area. These data synthetically indicate an *easterly-diachronous and* propagating Andean-type Cambrian (Furongian)-Silurian (Llandovery) orogenesis along the Gondwana northern margin from Nepal, NW India, South Tibet, Qiangtang to Central Vietnam across South Indochina and Sibumasu. This paper reconstructs the Early Paleozoic locations of the Sibumasu and Indochina fragments, as well as SW Japan and South China continent in the Gondwana northern margin, and proposes the far-field effect on the South China Kwangsian intra-continental orogenesis from the subduction of the Early Paleozoic Prototethyan southern branch.

Keywords Igneous rocks, Sedimentary sequence, Early Paleozoic, Prototethyan southern branch ocean, Andean-type orogenesis, SW Yunnan and SE Asia

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1. Introduction

A series of continental fragments (i.e., South China, Indochina, Sibumasu and Qiangtang) had been accreted to the Eurasian continent through the Proto-, Paleo- and Neotethyan evolution, thus forming the unique global geological domain (Figure 1; e.g., Sengör et al., 1988; Zhong, 1998; Wang Y et al., 2018, 2020a; Dong et al., 2018; Li et al., 2018; Liu et al., 2021). Among them the Prototethyan Ocean, as the most important element of the Tethyan evolution, has attracted more and more attention. It is considered as an east-west-direction Early Paleozoic Ocean growing between the Gondwana and Laurasia continents in response to the Rodinia breakup. It might have westerly joined the Iapetus Ocean closed in the latest Early Paleozoic period (e.g., Cawood et al., 2001; Stampfli et al., 2002, 2013; Scotese, 2004;

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Cocks and Torsvik, 2013). Available data show that the geological records related to the Prototethyan evolution are mainly preserved in East Asia. In China, this ocean has been considered as a Sinian-Early Paleozoic Ocean located between the southern North China and northern Sibumasu blocks (e.g., Li et al., 1995; Pan et al., 1997; Zhong, 1998). Since the rock unites related to the Neoproterozoic-Early Paleozoic oceanic subduction were identified in the Kunlun regions during the 1980s, numerous researches have been conducted in the Kunlun, Qilian and Qinling belts along the southern North China block. These studies have determined the northern branch of the Prototethyan Ocean and illustrated when and how the Prototethyan Ocean went through the subduction process (e.g., Scotese, 2001, 2004; Xiao et al., 2009; Li et al., 2018; Dong et al., 2018; Zhao et al., 2018; Liu et al., 2021 and references therein). However, the Prototethyan Ocean in SE Asia, herein defined as the Prototethyan southern branch ocean in northern Sibumasu and Indochina, is poorly known as to its spatial distribution and, hotly debated regarding the details of its formation and evolution (e.g., Metcalfe, 1999, 2013; Wang Y et al., 2013b, 2020a, 2020b, 2021a, 2021b; Li et al., 2018; Liu et al., 2021).

Some scholars believe that the Prototethyan southern branch ocean might have tectonically been a passive continental margin (e.g., Brookfield, 1993; Gao et al., 2005; Zhang et al., 2012). However, after Gansser (1964) proposed that the Himalayan orogenic belt was formed in the Early Paleozoic period, more and more scholars have identified Early Paleozoic (529–457 Ma) igneous rocks, angular unconformity and contemporaneous metamorphism in NW India, Nepal, Himalaya and South Tibet, which are most likely indicatives of the Andean-type active continental margin related to the Prototethyan subduction (e.g., DeCelles et al., 2000, 2004; Hughes, 2002; Liu et al., 2004, 2007; Zhou et al., 2004; Xu et al., 2005; Zhang et al., 2008; Qi et al., 2010; Zhang et al., 2012). However, it remains a mystery as to whether this event had extended in SW Yunnan, Thailand Peninsula and Malay Peninsula, or even Sumatra, and how it had extended southerly. It is still not quite decided whether the Prototethyan southern branch ocean had gone eastward from South Tibet to SW Yunnan and SE Asia through Namcha Barwa. The manifestation of the ocean basin and its closure time are yet unknown (e.g., Zhong, 1998; Mao et al., 2012; Lehmann et al., 2013; Metcalfe, 2013; Stampfli et al., 2013; Wang B D et al., 2018; Liu et al., 2020, 2021). In addition, little is known about the influence exerted by the Prototethyan evolution in the eastern South China Early Paleozoic orogenesis (named as South China Kwangsian intra-continental Orogen; e.g., Wang Y et al., 2010, 2013a, 2013b).

Available data show that the Sibumasu block was characterized by Gondwana fauna during the Cambrian-early Permian period, and had maintained the same paleo-latitude location as that of NW Australia until the Devonian-early Permian period (e.g., Burrett and Stait, 1985; Fang et al., 1989; Burrett et al.,1990; Huang and Opdyke, 1991; Metcalfe, 1994, 2021; Archbold and Shi, 1995). The Early Paleozoic animal fossil assemblage of the Indochina block resembled that of East Gondwana, and hadn't turned into the Cathaysian warm-water animal-plant assemblage until early-middle Devonian (e.g., Fang et al., 1989; Metcalfe, 1994, 2013). Both the Sibumasu and Indochina blocks belonged to the Prototethyan tectonic domain during the Early Paleozoic period, suggestive of the potential passing domains for the Prototethyan southern branch (e.g., Metcalfe, 2013; Wang et al., 2021a, 2021b).

In combination with available data and the authors' latest advantages, this paper presents a comprehensive analysis of the Early Paleozoic geological records of the Sibumasu and Indochina blocks in SW Yunnan and SE Asia, as well as the easternmost South China and SW Japan, so as to determine the potential location of the eastern Prototethyan southern branch and further explore the source nature and tectonic implication of the Ordo-Silurian giant igneous belt along the Gondwana northern margin. Our work allows us to put forward an orogenesis model to illustrate the Early Paleozoic Andean-type active continental margin in response to the easterly diachronous and northerly propagating development of the Prototethyan southern branch ocean. In addition, the Early Paleozoic locations of the Sibumasu, Indochina and the eastern South China blocks have been herein reconstructed and a proposal has been put forward that the consumption of the East Prototethyan southern branch ocean had been the driving force for the Kwangsian intracontinental orogenesis in the eastern South China block.

2. Prototethyan geological records in the Sibumasu block

The Early Paleozoic fauna with Australian affinities, the Cimmerian-type Carboniferous-Permian cold-water fauna and associated sedimentary sequences have been recorded in the Sibumasu block, showing it as a part of eastern Gondwana (e.g., Bunopas, 1982; Sevastjanova et al., 2011; Metcalfe, 2013, 2021). The Sibumasu block geographically covers Sumatra, Thailand Peninsula, western Malay Peninsula, NW Thailand and the Shan Plateau of Myanmar, and SW Yunnan in China (Figure 1). Its western part is the Mogok metamorphic belt, Andaman Sea and middle Sumatra tectonic belt. Its eastern part is confined by the Paleotethyan suture zone, mainly including the Tengchong, Baoshan and Shan fragments, along with the western Malay fragment extending southward (Figures 1 and 2; e.g., Hutchison, 1989; Zhong, 1998; Wang et al., 2021b; Feng, 2002). However, due to strong tectonic overprinting, the Early Paleozoic geolo-

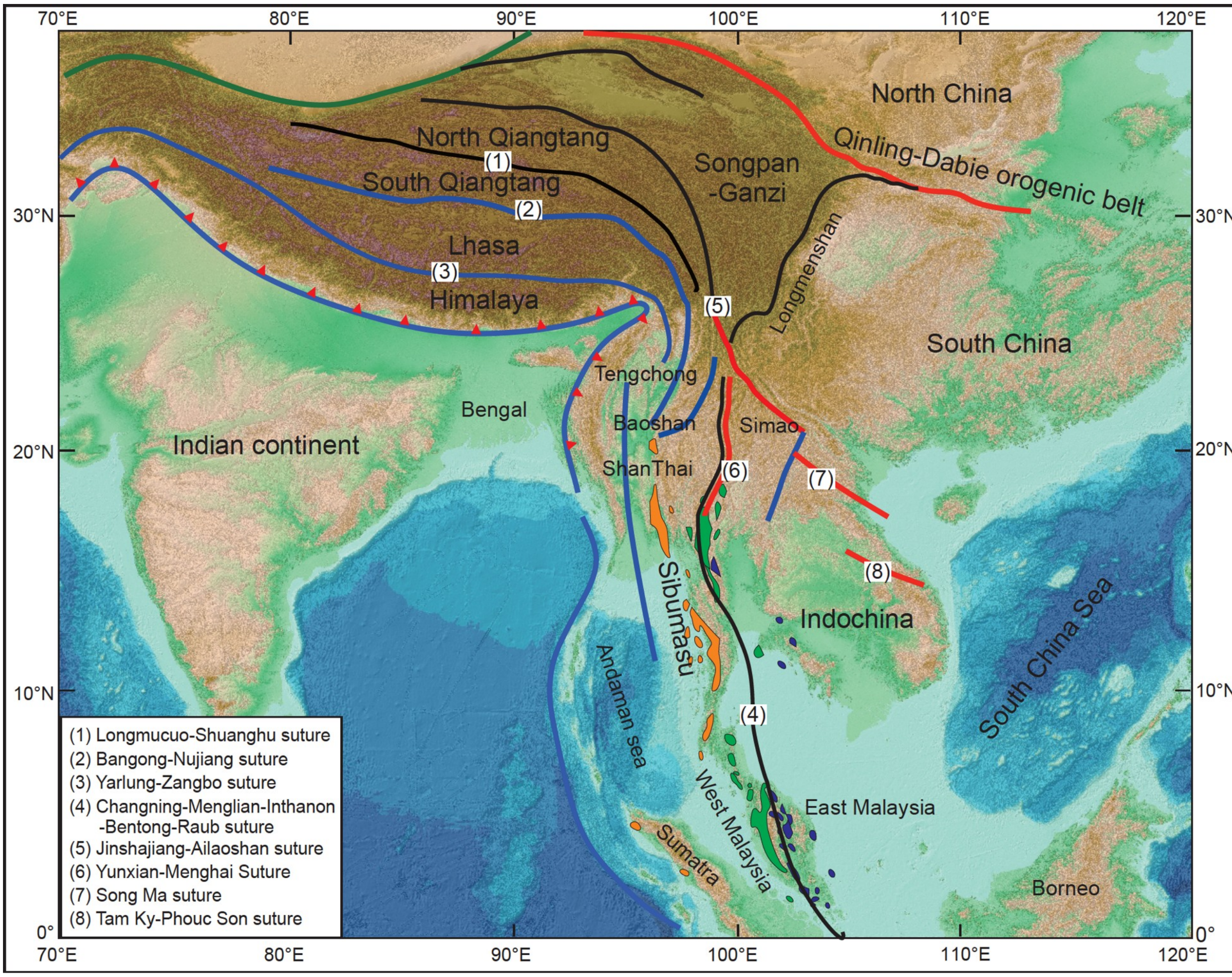

Figure 1 Simplified map of the main blocks and tectonic boundaries of the Tethyan domain, with the Proto-, Paleo-, and Neo-Tethyan tectonic sutures marked by the red, black and blue lines, respectively.

gical signatures were mostly "covered-up". Recent researches on the ancient metamorphic sequences, e.g., the Lancang and Ximeng groups in SW Yunnan, Tarutao Group in Thailand Peninsula, the Machinchang and Jerai formations in western Malay Peninsula, and related igneous rocks in the fragment have provided important data for determining the Prototethyan evolution in the Sibumasu block (e.g., Metcalfe, 2013, 2021; Wang et al., 2021b).

2.1 Redefinition of the lower Paleozoic strata in the Sibumasu block

The Cambrian sequences in Sibumasu, i.e., Gongyanghe Group and Hetaoping Formation, are considered as the flysch silt-slate unit intercalated with volcanic rocks, chert and marlstone, and show the sedimentary signatures of the transition to normal shallow shelf-facies. In this region, the Ordovician strata are characterized by littoral- neritic facies shale, sandstone, argillaceous siltstone and marlstone. In the Wanyaoshu area (Mangshi), the Ordovician sequence is angular-unconformably underlain by Gongyanghe Group across the purplish-red basal conglomerate.

The medium-high-graded metamorphic rocks are extensively outcropped in SW Yunnan and Thailand Peninsula in the Sibumasu, e.g., Lancang and Ximeng groups and their equivalents in SW Yunnan, the Inthanon metamorphic rocks in NW Thailand and the Tarutao Group in Thailand Peninsula. The metamorphic rocks have been previously mapped as the Sibumasu basement and unconformably overlain by the Upper Paleozoic silicoclastic and carbonate rocks (e.g., Jia, 1994; Feng et al., 1996; Zhong, 1998). Recent data show that the Lancang, Ximeng and Tarutao groups and their equivalents, originally defined as Precambrian basement on the Sibumasu block, were mainly formed in the late Cambrian-Ordovician period, part of which might have lasted until Llandovery of Silurian. Thus, they most likely belong to the Lower Paleozoic volcanic-sedimentary sequence, resembling the A Vuong and Nam Houay groups and their equivalents in the Indochina block (Figure 3; e.g., Wang et al., 2020a, 2020b, 2021a).

(i) **Lancang Group and its equivalents.** The Lancang Group is characterized by schist, quartzite, quartz-sandstone,

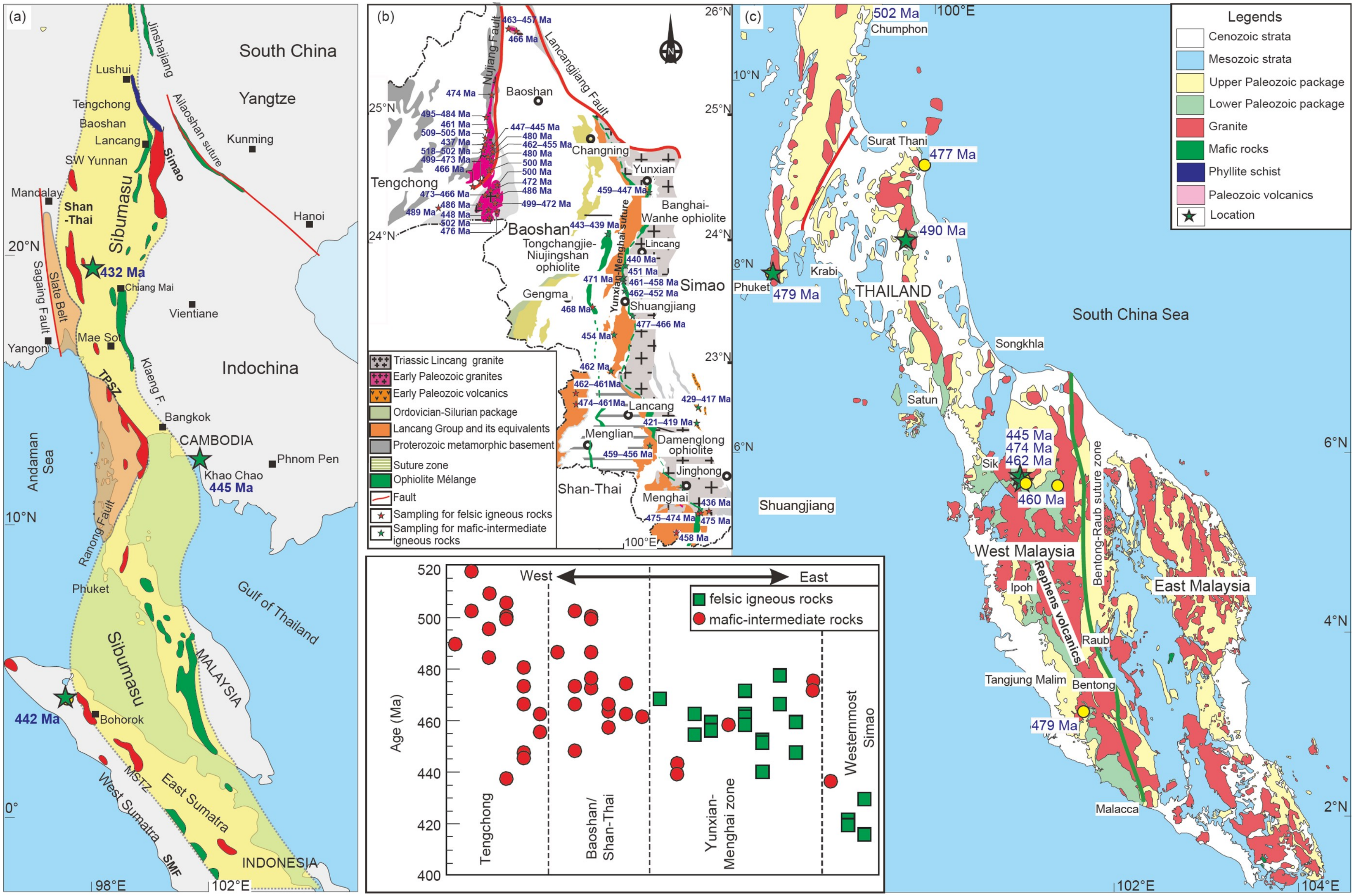

Figure 2 (a) Spatial location for the Sibumasu block, (b)–(c) simplified map for showing the spatial distribution of the Early Paleozoic igneous rocks in SW Yunnan, and Southern Thailand and Malay Peninsula, and (d) the spatial trend of the formation age of the Early Paleozoic igneous rocks in SW Yunnan of the Sibumasu block, respectively (after Wang et al., 2021b).

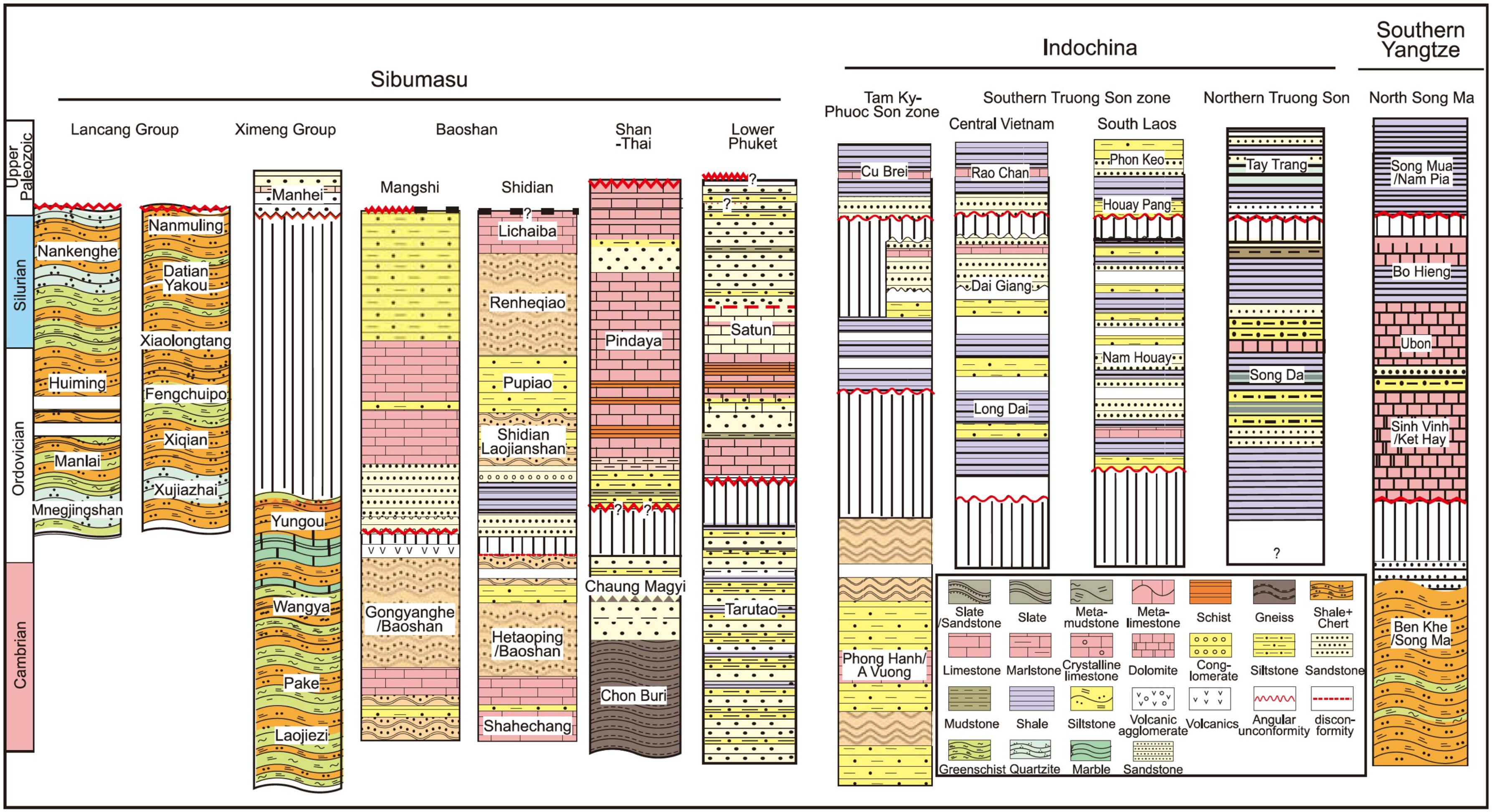

Figure 3 Comparison of the lower Paleozoic strata of the different locations on the Sibumasu, Indochina and the related blocks. Also illustrating the Lancang, Ximeng and Tarutao groups and their contact relationships (modified after Wang et al., 2020a, 2020b, 2021a, 2021b references therein).

slate, phyllite, marble, metabasite, meta-andesite and meta-rhyolite, originally reflecting the rock-association of flysch clastic and carbonate rocks with the mafic volcanic interlayers (e.g., Zhong, 1998). Within the group, there are numerous lenticular mafic-ultrabasic rocks and related felsic rocks interpreted as ophiolite assemblage. In the previous geological maps, the Lancang Group was subdivided into the Mengjingshan, Manlai, Huimin and Nankenghe formations, or Xujiazhai, Xiqian, Fengchuipo, Xiaolongtang, Datianyakou and Songshan formations (Figures 2b and 3; e.g., Zhong, 1998; Shen et al., 2008; Nie et al., 2015). Detrital zircons U-Pb geochronological analyses recently gave the age range of 2664–549 and 3490–489 Ma with $\varepsilon_{Hf}(t)$=−12.3–+6.8 for the Manlai and Huimin formations in the Lancang Group and its equivalents (Figure 4a; Wang et al., 2021b). Detrital zircons U-Pb ages range from 3306 to 428 Ma, with the youngest peak of ~442 Ma for the Nankenghe meta-sedimentary rocks in the Lancang Group. For the Cambrian Huamucun sandstone, the detrital zircons U-Pb apparent ages of 2772–439 Ma have been presented, with $\varepsilon_{Hf}(t)$=

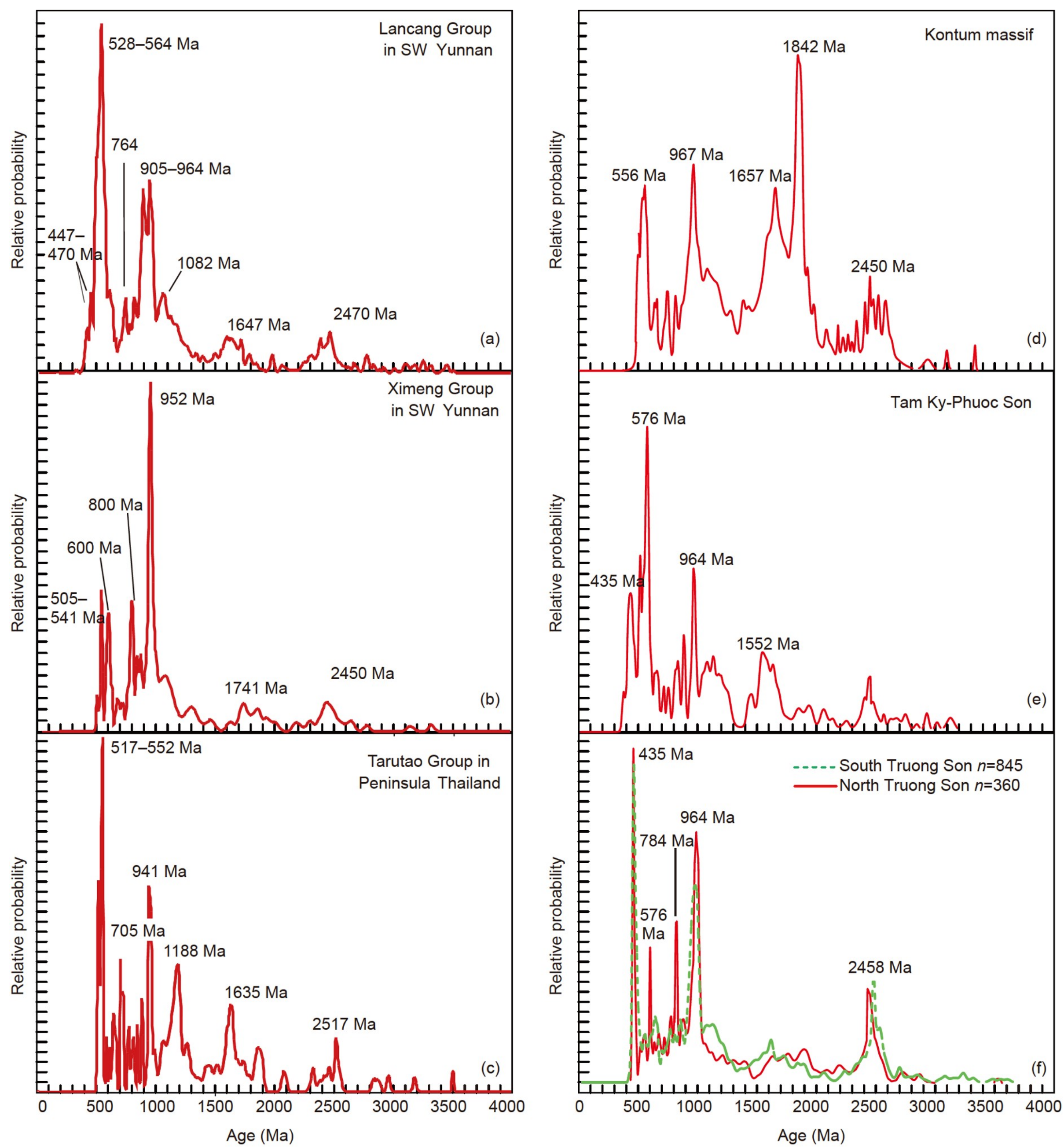

Figure 4 Detrital zircons ages-spectra for the lower Paleozoic meta-sedimentary rocks in the Lancang Group (a), Ximeng Group (b) and Tarutao Group (c) of the Sibumasu block, and in the Kontum massif (d), the Tam Ky-Phouc Son (e) and Truong Son zones (f) of the Indochina block (after Wang et al., 2021a, 2021b).

−19.1–+8.53 and the youngest peak at 488–439 Ma (Wang et al., 2021b). Wang et al. (2017) also reported the detrital zircons U-Pb apparent ages of 3453–443 Ma, with the age-peaks at 566–515 and 1096–916 Ma, and $\varepsilon_{Hf}(t)$ value ranging from −19.1 to +9.0 for the meta-sedimentary rocks in the Lancang Group. In addition, the meta-volcanic rocks and related gabbro-diabase in the Huimin Formation of the Lancang Group yielded the formation ages of 462–454 and 473–439 Ma, respectively (Wang Y et al., 2013b; Xing et al., 2015; Nie et al., 2015; Liu Y et al., 2017; Xing et al., 2017). All these data synthetically indicate that the Lancang Group and its equivalents might have formed during the Ordo-Silurian (Llandovery) rather than the previously-defined Precambrian basement, and their lithology and formation ages might be compatible with the Nam Houay volcano-sedimentary sequence in the Truong Son zone of the Indochina block (e.g., Thassanapak et al., 2018; Loydell et al., 2019; Wang et al., 2020a, 2020b, 2021a).

(ii) **Ximeng Complex and its equivalents**. Based on regional geological maps, the Ximeng Group and its equivalents are subdivided, from base to top, into the Laojiezi, Pake, Wangya and Yungou formations (Figure 3). The rock-types are characterized by marble, quartz-schist, sericite schist, meta-sandstone, phyllite, gneiss and migmatite, all of which are traditionally regarded as the pre-Devonian package. Available detrital zircons U-Pb apparent ages of the meta-sedimentary rocks in the Laojiezi and Pake formations range from 3316 to 504 Ma, with $\varepsilon_{Hf}(t)$ from −18.9 to +13.7, and the youngest age-peak at 541–515 Ma (Figure 4b). Detrital zircons from the meta-sandstones of the Wangya Formation gave the U-Pb apparent ages of 3139–593 Ma, with $\varepsilon_{Hf}(t)$ ranging from −19.0 to +15.2 (Wang et al., 2021b). In addition, the orthogneiss and migmatite in the Ximeng Group yielded the formation ages of 474–452 Ma (e.g., Xing et al., 2015; Wang et al., 2021b). Such data collectively indicate that Ximeng Group and its equivalents, previously defined as the Precambrian basement, were formed during the late Cambrian to early-middle Ordovician period, and thus might be defined as the Ximeng Complex composed of orthogneiss, migmatite and volcanoclastics. It might be equivalent with the A Vuong meta-volcanic-sedimentary rocks and the Kontum migmatite-granite-gneiss in the Indochina block.

(iii) **Tarutao Group and its equivalents**. The medium-high graded metamorphic rocks in the Inthanon and Chon Buri areas (NW Thailand) in the Sibumasu have been previously defined as Precambrian origin (Hansen and Wemmer, 2011). However, recent geochronological data indicate that this is far from the truth. The metamorphic rocks in the Inthanon zone were mainly formed at the late Triassic-late Cretaceous period (e.g., Macdonald et al., 2010; Lin et al., 2013; Wang Y et al., 2018), and those of Chon Buri might range from Cambrian to Cenozoic era in age. The Tarutao Group and its equivalent Trat Group in Thailand Peninsula and the Pengkalan Hulu Formation in western Malay Peninsula are mainly composed of meta-sandstone, shale, quartzite, phyllite, schist, marble, gneiss, with a small amount of volcanic rocks and conglomerate. They are overlain by the Ordovician or Upper Paleozoic strata across the unconformity and have been suggested as the ancient rocks of the Sibumasu block in SE Asia (Figure 3; e.g., Ridd et al., 2011). Wang et al. (2021b) recently reported the detrital zircons U-Pb ages of 3177–510 Ma with the main age-peaks at ~550 and ~964 Ma, with $\varepsilon_{Hf}(t)$=−19.4–+10.7, for the Tarutao Group and its equivalents (Figure 4c). Kawakami et al. (2014) and Wang et al. (2021b) also observed that the Tarutao Group had been intruded by the 490–477 Ma granites in the Phuket and Kalen areas. Thus, the Tarutao Group and its equivalents were most likely formed between Cambrian-early Ordovician periods (~510–480 Ma), slightly earlier than the Lancang Group and its equivalents in SW Yunnan.

Based on the above-mentioned data, it is shown that the Tarutao and Ximeng groups and their equivalents had been formed between late-Cambrian and early-middle Ordovician, equivalent to the A Vuong Group of the Kontum Indochina (Figure 3). The Lancang Group and its equivalents were formed in the Ordo-Silurian, comparable to the Nam Houay volcanoclastic formation in the Truong Son zone. At the Wanyaoshu area in Mangshi, an angular unconformity between the Ordovician basal conglomerate and the underlying Gongyanghe Group (Cambrian system) were observed. In combination with its contact relationship with the lower Paleozoic strata (e.g., A Vuong and Nam Houay Groups) in the Indochina block, it is inferred that the angular inconformity most likely occurred in a regional successive order between the Tarutao/Ximeng and Lancang groups and their equivalents and the Upper Paleozoic package (Figure 3). Detrital zircons U-Pb age-spectra of the Tarutao/Ximeng Groups and their equivalents manifest the main peaks at ~554–528 and 964–905 Ma, and the secondary peaks at ~780 and ~2450 Ma (Figure 4a–4c), similar to those in the meta-sedimentary rocks in eastern Myanmar and in the river sands of southern Thailand and western Malay Peninsula. Detrital zircons U-Pb age spectra of the Ordo- Silurian sedimentary rocks in the Shan State have also recorded the pan-African and Grenvillian magmatic events (Cai et al., 2017).

Available data have revealed the extensive existence of three age-peaks at 1.85–1.65 Ga, 1.2–1.0 Ga and ~520 Ma for the sedimentary rocks in NW Sumatra and NW Australia (e.g., Veevers et al., 2005; Squire et al., 2006; Myrow et al., 2009; Usuki et al., 2013; Burrett et al., 2014). The above-mentioned data indicate that the Lower Paleozoic detrital zircons age-spectra in the Sibumasu block are, on the whole, similar to those in Qiangtang and Himalaya, and have affinities to the Indian and Australian continents of the Eastern Gondwana (Figure 5; e.g., Veevers et al., 2005; Sevastjanova et al., 2011; Metcalfe, 2013; Burrett et al., 2014; Wang et al., 2021b). In addition, the detrital zircon $\varepsilon_{Hf}(t)$ values with the U-Pb apparent ages of ~550 and ~950 Ma for the lower Paleozoic meta-sandstones in SW Yunnan are in the range of −11.8–+9.2 (Wang et al., 2020a, 2020b, 2021a, 2021b), similar to those in Himalaya, Qiangtang and Indochina (Figure 6a–6c; e.g., Veevers et al., 2005; Zhu et al., 2011; Burrett et al., 2014). A line of evidence shows that, during the Early Paleozoic period, the Gondwana-type biota marked the Sibumasu block (e.g., Ali et al., 2013; Meinhold et al., 2013), and it mainly contains Phanerozoic igneous and sedimentary rocks, with minor Precambrian rocks. Besides, the detrital zircons in the lower Paleozoic strata are dominated by circular or subcircular forms with the indication of a relatively long-distance transportation. As a result, the lower Paleozoic sedimentary rocks in the Sibumasu block in SW Yunnan and SE Asia have similar debris provenance, mainly from the Indo-Antarctica continent (e.g., Myrow et al., 2009; Zhu et al., 2012; Burrett et al., 2014; Wang et al., 2021b).

2.2 Early Paleozoic igneous rocks in the Sibumasu block

In SW Yunnan of the Sibumasu block, Yang et al. (2012) got the zircon U-Pb formation age of ~499 Ma for the metabasite in the Gongyanghe Group overlain by the lower-Ordovician basal conglomerate. In the Yunxian-Menghai area of SW Yunnan, lentoid harzburgite, dunite, cumulate gabbro-pyroxenite, gabbro and related granitoid were observed, which have been intercalated in the Lancang Group and its equivalents (Figure 2b; Liu G C et al., 2017; Liu et al., 2018a, 2020, 2021). The late Ordo-Silurian (454–439 Ma) ophiolite mélanges exposed in the Nanting River and Niujingshan areas are characterized by the mafic-ultramafic ophiolite remnants preserved as stratiform- stratoid, vesicular and blocky occurrences, with main rock-types of amphibolite, schist, peridotite-pyroxenite, harzburgite, cumulate gabbro, meta-gabbro and metabasite (Wang B D et al., 2013). The mafic rocks have both MORB- and SSZ-type geochemical

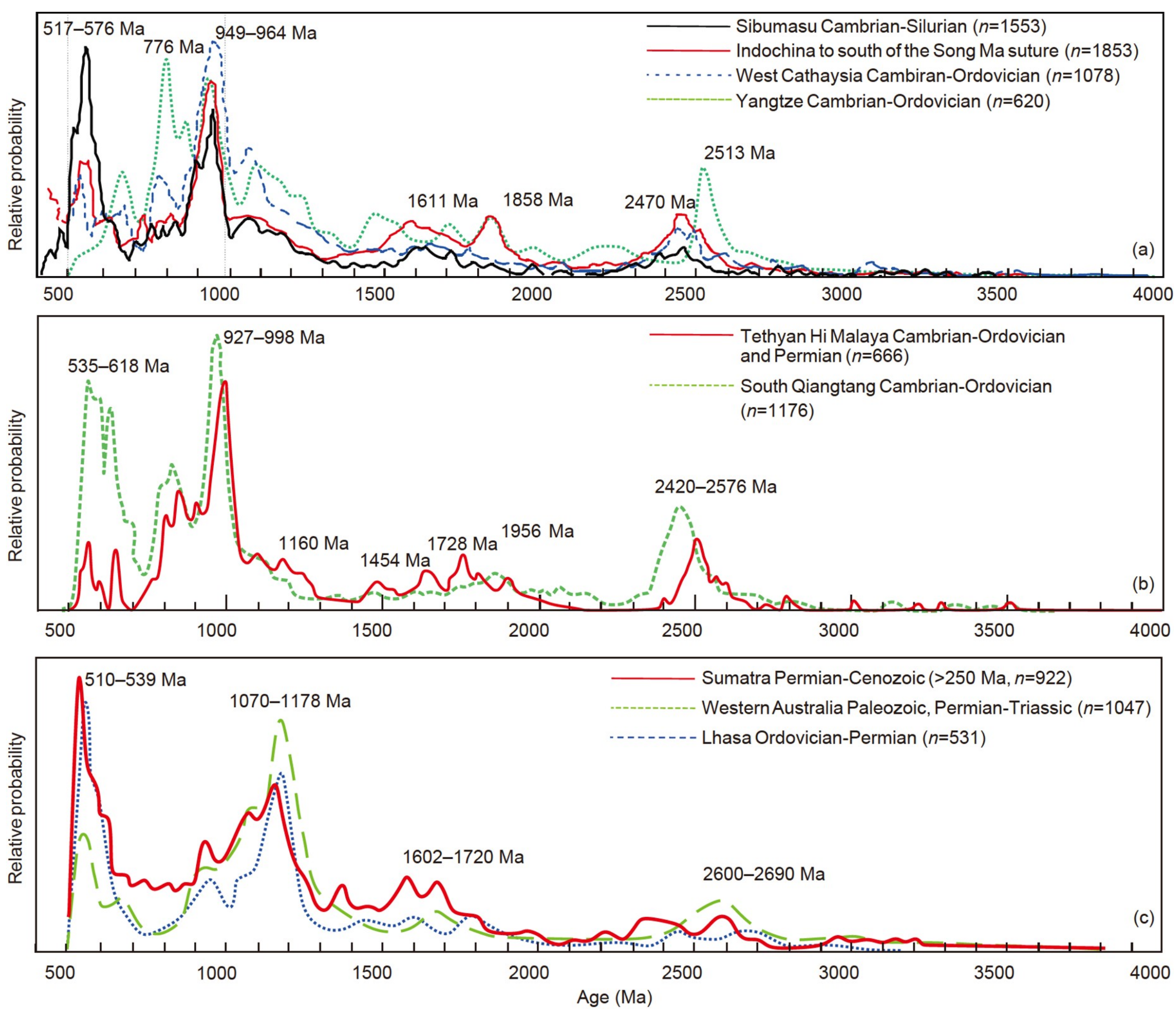

Figure 5 Detrital zircons U-Pb age-spectra for the sedimentary rocks of the Sibumasu and Indochina blocks and the comparison with the associated blocks (after Wang et al., 2021a, 2021b and references therein).

affinities, suggesting the Prototethyan oceanic relicts (e.g., Wang B D et al., 2013, 2016). Sun et al. (2017) reported the existence of ~450 Ma oceanic island basalts along the Changning-Menglian Paleotethyan suture. The Early Paleozoic Wanhe ophiolite mélanges have been identified in the Wanhe-Mengku-Damenglong area to the east side of the Tongchangjie ophiolite mélange, for which the anorthosite gave zircon U-Pb age of 471 Ma, reflecting the intra-oceanic or back-arc basin setting (e.g., Zhang et al., 2008; Liu G C et al., 2017; Liu et al., 2020, 2021). ~460–440 Ma metabasic volcanic rocks, gabbroic diorite, diorite and granodiorite were also identified in the Shuangjiang, Ximeng and Gengma areas of SW Yunnan (Figure 2b).

In SW Yunnan, the Huimin Formation of the Lancang Group accompanied by the Nanting ophiolite belt has preserved the 467–454 Ma meta-basalt and high-Mg andesite with enrichment in LILEs and depletion in HFSEs, with initial $(^{87}Sr/^{86}Sr)_i$ of 0.7144–0.7536 and $\varepsilon_{Nd}(t)$ of −7.6–−14.6, indicating the products of the Early Paleozoic island-arc setting (Figures 6 and 7; e.g., Xing et al., 2015; Nie et al., 2015). In Dapingzhang and Dazhonghe areas to the east of the Yunxian-Menghai ophiolite belt, there exposed the Silurian (432–471 Ma) intermediate-felsic volcanic rocks in the sedimentary-type copper deposit, which show the arc- or back-arc geochemical affinities with initial $(^{87}Sr/^{86}Sr)_i$=0.70598–0.70588 and $\varepsilon_{Nd}(t)$=+4.8–+5.5 (Mao et al., 2012; Lehmann et al., 2013; Ru et al., 2014; Wang B D et al., 2018). In the Sibumasu block of SE Asia, although reports on the Early Paleozoic intermediate and mafic igneous rocks are rare, and granitoids older than the Permian in age are scarce, important clues have been provided to support the existence of Early Paleozoic igneous rocks in this area on the basis of the following observations: (1) In the Chiang Rai-Mae Chan area of NW Thailand, Silurian (435–432 Ma) gabbro-diorite rocks with both arc- and MORB-like geochemical affinities have been identified (Figure 2a; Wang et al., 2021b). (2) Quek et al. (2018) and Wang et al. (2021b) obtained the zircon U-Pb crystallization ages of 480–460 Ma for the Gerik-Dinding meta-intermediate and acid volcanics to the west of Bentong-Raub suture in Malay Peninsula, which have been mapped as elements of the Cambrian-Ordovician Machinchang Formation with the resembling- Tarutao Group in Thailand Peninsula (Figure 2c).

Available data indicate that the Early Paleozoic granitoids probably passed through the Namcha Barwa area and entered southerly into Tengchong and Baoshan (Figure 2a; e.g., Xu

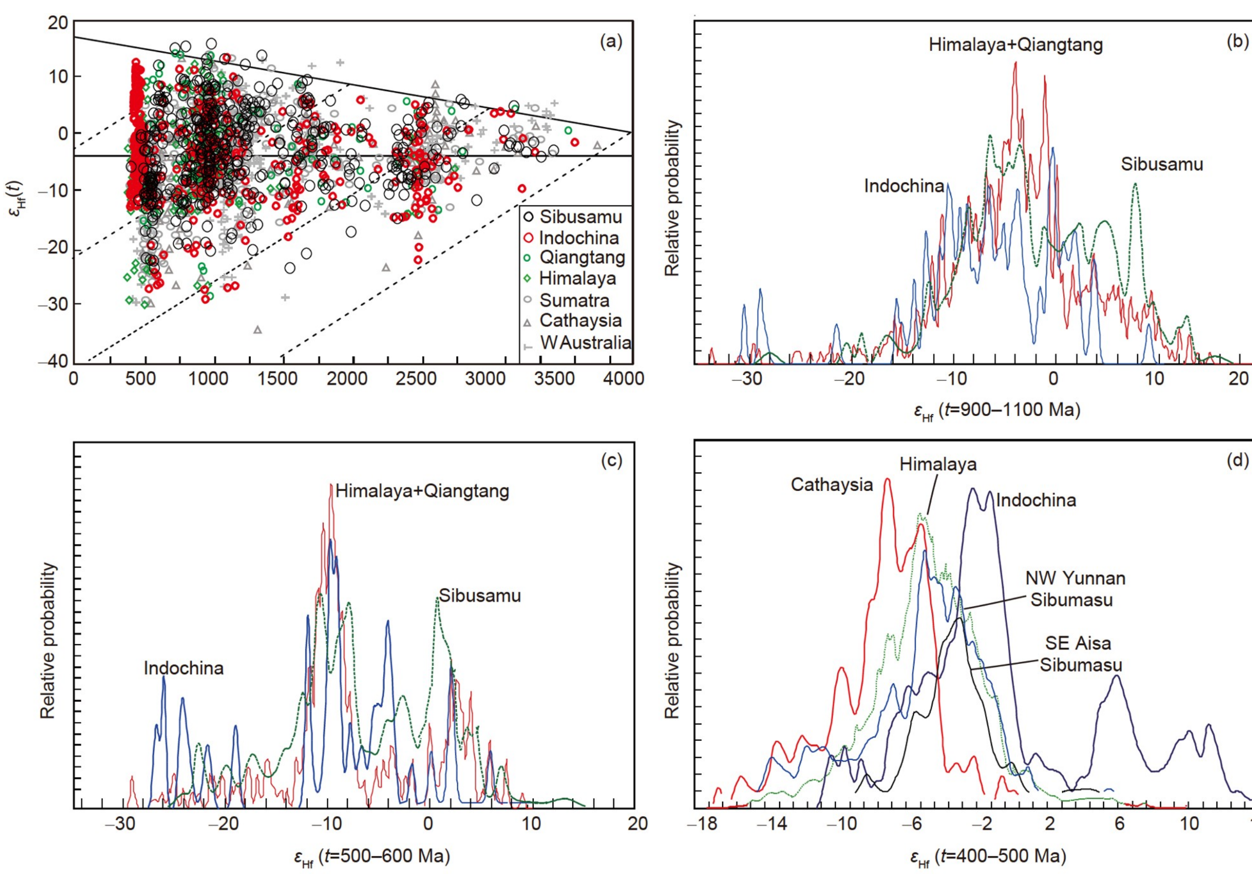

Figure 6 Zircon U-Pb apparent ages and $\varepsilon_{Hf}(t)$ for the lower Paleozoic meta-sedimentary rocks of the Sibumasu, Indochina and associated blocks (a), and frequency $\varepsilon_{Hf}(t)$ values for ~900–1100, 500–600 and 400–500 Ma ((b)–(d)), respectively (modified after Wang Y et al., 2013b, 2020a, 2020b, 2021a, 2021b and references therein).

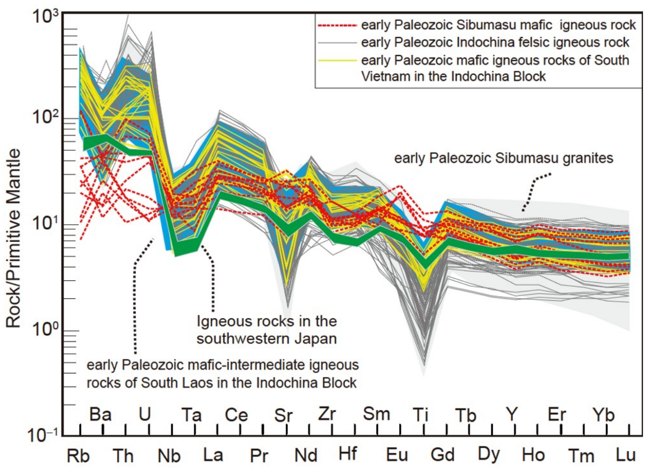

Figure 7 Primitive mantle-normalized incompatible elemental spidergrams for the Early Paleozoic igneous rocks from the Sibumasu and Indochina blocks (modified after Wang Y et al., 2013b, 2020a, 2020b, 2021b and references therein).

et al., 2005; Zhang et al., 2008; Qi et al., 2010; Wang Y et al., 2013b). Numerous orthogneiss, migmatite, granodiorite, two-mica granite, muscovite granite and leucogranite occurred or intruded in the Lancang/Ximeng groups and their equivalents in SW Yunnan of the Sibumasu block (e.g., Song et al., 2007; Dong et al., 2013; Wang Y et al., 2013b; Zhang et al., 2015). The orthogneiss from the Ximeng Group gave zircon U-Pb ages of 474–462 Ma with $\varepsilon_{Hf}(t)$=−6.8 to +3.0, synchronous with the granitoid and leucogranite (472–460 Ma) in this area (Xing et al., 2015). The orthogneiss and granitoid in the Luxi and Pingda areas in the Baoshan fragment, the Mengdui, Songpo and Gaoligong areas of the Tengchong fragment were dated at 502–466 Ma (Figure 2b), and their zircons gave $\varepsilon_{Hf}(t)$ values (−0.84 to −11.4) similar to the Ordovician grains in the Shan State (−1.1 and −6.8; e.g., Song et al., 2007; Shi et al., 2010; Dong et al., 2013; Xing et al., 2015; Wang et al., 2021b). Zhang et al. (2008) and Dong et al. (2009) obtained the metamorphic ages of the Early Paleozoic (503–474 Ma) in the syntaxis area in NE Sibumasu. The granitoids in SE Asian Sibumasu have been previously considered to be formed in the Carboniferous or later (e.g., Lin et al., 2013; Kawakami et al., 2014; Xu et al., 2020). However, Wang et al. (2021b) have recently identified the early Ordovician and Silurian felsic igneous rocks in southern Thailand, Malay Peninsula and NW Sumatra (Figure 2a and 2c). The granitoids from the Thung Song and Sakaeo areas in South Thailand and Phuket Island yielded the zircon U-Pb crystallization ages of 490–445 Ma, with $\varepsilon_{Hf}(t)$ ranging from −1.0 to +0.8. The orthogneiss in western Malay Peninsula was dated at ~462 Ma, of which $\varepsilon_{Hf}(t)$ values were in the range of +0.85 to −4.64. The Takengon orthogneiss in the northwest corner of Sumatra were dated at 443–442 Ma, and gave $\varepsilon_{Hf}(t)$ of −7.8 to −1.3 (Xu et al., 2020; Wang et al., 2021b). Lin et al. (2013) and Kawakami et al. (2014) also reported the zircon U-Pb ages of 502–477 Ma for the Khao Tao orthogneisses and Khao Dat Fa granites. Hansen and Wemmer (2011) obtained the zircon U-Pb ages of 452 Ma for the amphibole-bearing gneisses at Surat Thani in Thailand Peninsula. The 479–460 Ma rhyolitic tuff (Lawin tuff) and contemporaneous orthogneiss were also reported in the Jerai Formation of the Baling Group in western Malay Peninsula (Quek et al., 2018; Wang et al., 2021b).

The Early Paleozoic (502–442 Ma) granitoids in SW Yunnan and South Thailand, Thailand Peninsula, western Malay Peninsula and NW Sumatra have A/CNK=0.84–3.07, A/NK=1.20–3.21 and K_2O/Na_2O>1, showing the evolution trend from normal to high-fractionation granitoids, as shown in Figures 6–8 (Wang Y et al., 2013b, 2021b). Their (La/Yb)cn, (Gd/Yb)cn and Eu/Eu* range from 0.98 to 29.8, 0.46 to 7.91 and 0.05 to 0.56, respectively. They are characterized by enrichment in LILEs and depletion in HFSEs (Figure 7), enriched $(^{87}Sr/^{86}Sr)_i$ ratio (0.7090–0.7344) and negative $\varepsilon_{Nd}(t)$ values (−11.6 to −5.3), similar to the contemporaneous granitoids from the South Tibet and Indochina blocks and the S-type granitoids from the Lachlan fold belt in eastern Australia, and slightly higher than those in the High Himalaya (Figures 7–8a; Parrish and Hodges, 1996; Ahmad et al., 2000; Robinson et al., 2001; Miller et al., 2001; Shi et al., 2010; Zhu et al., 2012). Their $(^{206}Pb/^{204}Pb)_i$, $(^{207}Pb/^{204}Pb)_i$ and $(^{208}Pb/^{204}Pb)_i$ ratios range from 18.63 to 20.31, 15.60 to 15.86, and 38.63 to 40.94 respectively, plotted into the left side of the NHRL (Figure 8b, 8c) and similar to those of the contemporaneous granitoids of the Indochina block (Wang et al., 2020b).

These Early Paleozoic granitoids show CaO/Na_2O=0.08–5.18, Al_2O_3/TiO_2=23–109, Rb/Sr=2.81–11.3 and Rb/Ba=0.13–15.9, suggestive of their derivation from crustal source which is mainly consitiuted by meta-sedimentary with proportional meta- igneous components (e.g., Jung et al., 2000; Wang et al., 2007, 2020a, 2020b, 2021b). With the slightly higher $\varepsilon_{Hf}(t)$ value of the Khao Tao orthogneiss in Thailand Peninsula as an exception, the zircon *in-situ* $\varepsilon_{Hf}(t)$ values of the Ordo-Silurian granitoids in the Sibumasu block range from −0.4 to −14.1 with the peak at −4.0. In comparison with the Early Paleozoic S-type granites in South China and the sedimentary rocks in Himalaya, they have higher $\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$ values but lower $\delta^{18}O$ values, with more remarkable input of mantle-derived components (Figures 6–8; e.g., Wang Y et al., 2013b). In addition, the Early Paleozoic granitoids in SW Yunnan and SE Asia show increasing $\varepsilon_{Nd}(t)$, $\varepsilon_{Hf}(t)$ and $(^{208}Pb/^{204}Pb)_i$ with decreasing formation age, with a sharp transformation in the isotopic compositions at ~475 Ma. Such characteristics suggest the significant input of juvenile crustal materials (Wang et al., 2021b). In the tectonic discrimination diagrams, these granitoids fall in the fields of continental arc and collisional granites, suggestive of an active continental marginal setting.

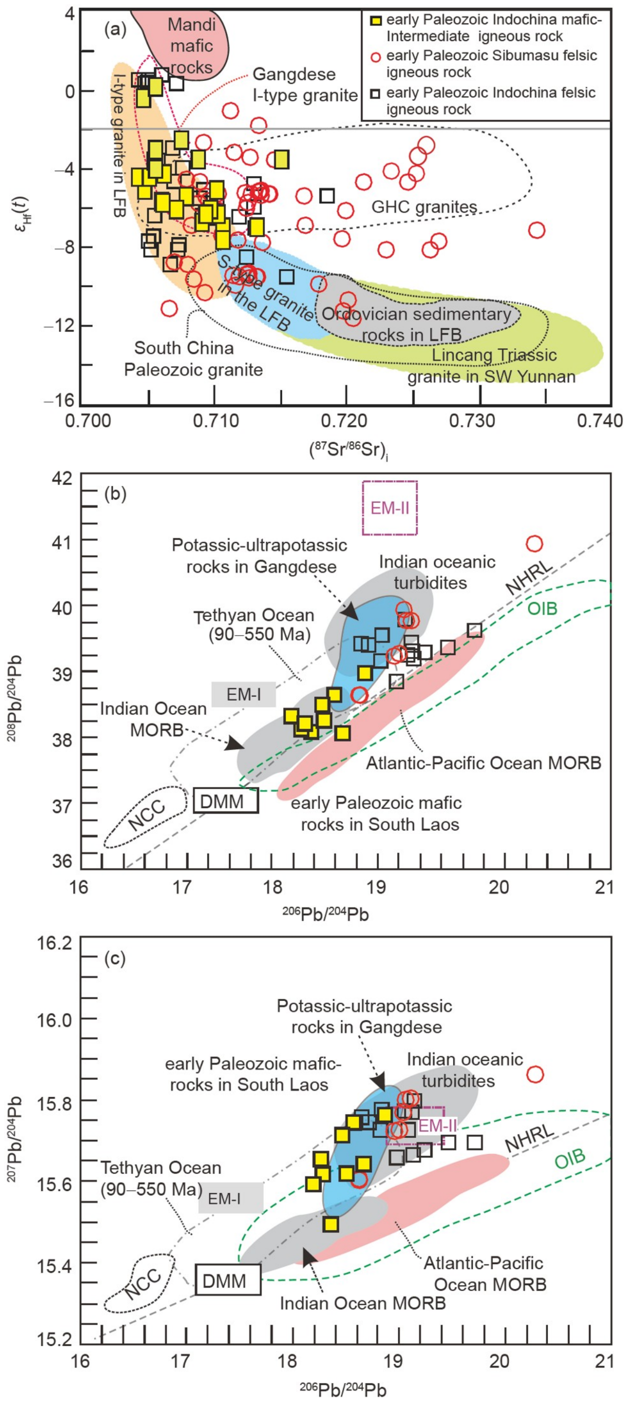

Figure 8 (a)–(c) Sr-Nd-Pb isotopic composition diagrams of the Early Paleozoic igneous rocks from the Sibumasu and Indochina blocks. Also shown the representative tectonic units for comparison (after Wang Y et al., 2013b, 2020a, 2020b, 2021a, 2021b).

3. Prototethyan geological records in the Indochina block

The Indochina block geographically covers eastern Thailand, Cambodia, eastern Malay Peninsula, Laos and most part of Vietnam. As part of a series of continental fragments along the East Gondwana northern margin, it is located between the South China and Sibumasu blocks (Figure 9a). Its southwestern and northern boundaries are defined by the Nan River-Uttaradit or Chiangmai-Chiang Rai (also named as Inthanon) and Ailaoshan-Song Ma suture zones, respectively. Its eastern boundary is hidden beneath the South China Sea (Figure 9a; e.g., Thanh et al., 1996, 2014; Metcalfe, 2013). The granulite-facies metamorphic rocks have been preserved in the Indochina block, thus, it is considered to be a single continental fragment with an ancient crystalline basement (e.g., Hutchison, 1989; Nakano et al., 2007, 2013; Carter and Clift, 2008). Cocks and Torsvik (2013, 2016) also suggested that the Indochina block had experienced, as a whole, the Cathaysia-resembling late Ordo-Silurian (Kwangsian) and Triassic (Indosinian) intracontinental tectonic events (e.g., Lepvrier et al., 2004; Carter and Clift, 2008; Wang Y et al., 2013a; Faure et al., 2018). However, some scholars additionally proposed an Early Paleozoic Andean-type active continental margin setting at the Australian or Indian margin of East Gondwana (e.g., Thanh et al., 2014; Gardner et al., 2017; Nguyen et al., 2019; Loydell et al., 2019; Wang et al., 2020a, 2020b, 2021a; Liu et al., 2021).

3.1 Ordo-Silurian sedimentary records in the Indochina block

The Indochina block was northerly connected with the southern Yangtze of the South China block through the Hoàng Liên Sơn and Po Sen mélanges and Nam Co metavolcanoclastics (e.g., Thanh and Khuc, 2011; Zhou et al., 2020). Fossil assemblages resembling East Gondwana have been noticed in the upper Cambrian-lower Ordovician Ben Khe Formation and its equivalent Songma Formation, which are mainly composed of quartz-sericite schist, meta-basalt, slate, and the coarse-grained sandstone (e.g., Tran and Vu, 2011; Tran et al., 2020). By an angular unconformity, they were in turn underlain by the Precambrian strata and by the upper Ordo-Silurian (Llandovery) Sinh Vinh and Bo Heng shallow sandstone and limestone (e.g., Shergold, 1995; Tran and Vu, 2011; Hau et al., 2018; Tran et al., 2020). In the Late Paleozoic period that began from the early-middle Devonian, fish fossils and Cathaysian biota assemblages were similar to those of the South China block (e.g., Metcalfe, 1999, 2013). The lower Paleozoic package in Central Vietnam, eastern Laos and the Vietnam-Laos-Cambodia border areas is characterized by silicoclastics, carbonate and volcanics (Figure 3), and is overlain by the Devonian Song Mua/Nam Pia Formation across the unconformity (e.g., Tran and Vu, 2011; Tran et al., 2020). According to the distinct tectono-strata and igneous rock-units, the Indochina block might be further subdivided into the Kontum massif, the Tam Ky-Phouc Son tectonic zone, and the Truong Son igneous belt, respectively, from south to north (Figure 9b; e.g., Tran and Vu, 2011; Tran et al., 2014; Ngo and Nguyen, 2016; Faure et al., 2018;

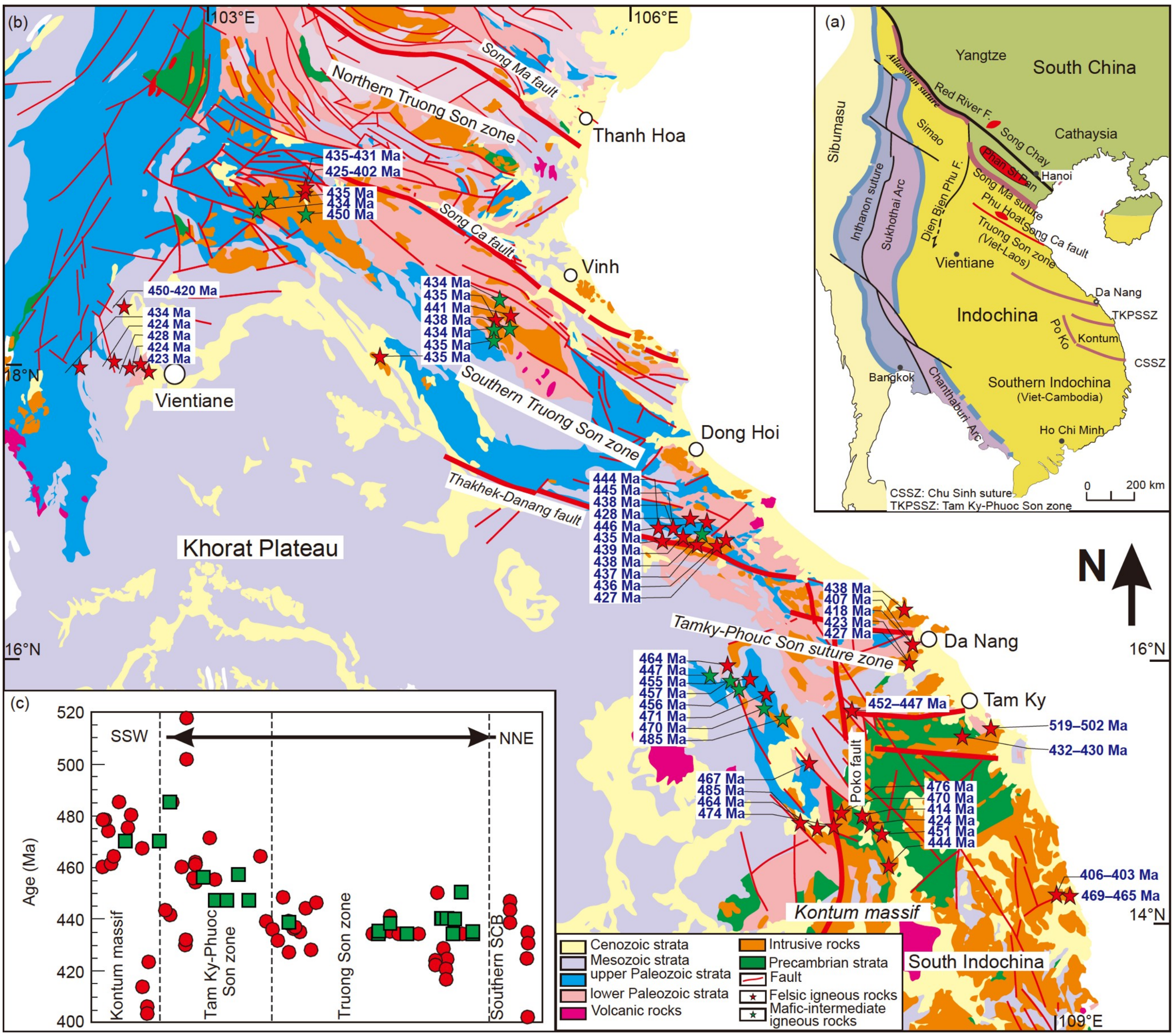

Figure 9 (a)–(b) Tectonic outline of the Indochina and simplified geological map of the eastern Indochina, respectively. (c) Spatial trend for the formation age of the Early Paleozoic igneous rocks for the main tectonic unit of the eastern Indochina (after Wang et al., 2021b).

Nguyen et al., 2019; Wang et al., 2020a, 2020b, 2021a).

The Kontum massif is mainly composed of the granulite-facies Kannak Complex, amphibolite-facies Ngoc Linh Complex, and greenschist-facies Kham Duc Complex, traditionally considered as the ancient crystalline basement of the Indochina block. However, the Archean-Paleoproterozoic rocks are still rarely identified (e.g., Hutchison, 1989; Nguyen et al., 2019). The Phong Hanh Formation, mapped as the lower Paleozoic package, is characterized by schist, quartzite, sandstone, dolomite and meta-volcanic rocks, and is overlain by the upper Paleozoic sandstone, shale and limestone across the angular unconformity (e.g., Tran et al., 2014, 2020). Within the Kontum massif in Central Vietnam and southern Laos, the previously-defined "ancient" gneiss and meta-sandstones have the detrital zircon U-Pb ages of 2944–522 Ma and were intruded by the 474–464 Ma granitoids, suggesting that at least the gneiss in Kontum was partly formed in the Cambrian (Furongian) or later (Wang et al., 2020a, 2020b, 2021a). Detrital zircons U-Pb age-peaks of ~2450, ~1842, ~1657, ~967 and ~556 Ma for the meta-sedimentary rocks, as shown in Figures 4d, 4e and 5, are similar to those of the Paleozoic sedimentary rocks in the Qiangtang, Himalaya and Sibumasu blocks, also consistent with those of the lower Paleozoic sedimentary rocks in the Tam Ky-Phouc Son zone (e.g., Roger et al., 2007; Myrow et al., 2009; Usuki et al., 2009, 2013; Burrett et al., 2014; Hau et al., 2018; Wang et al., 2020a, 2021a).

The Silurian (Llandovery-Wenlocke) sequence in the Tam Ky-Phouc Son zone is characterized by the volcano-sedimentary rocks. It is underlain by the Cambrian (Miaolingian)-lower-middle Ordovician A Vuong meta-volcano-sedimentary rocks through basal conglomerate, and in unconformable contact with the upper Paleozoic quartzite, sandstone, limestone and volcanic rocks (e.g., Tri and Khuc, 2009; Tran and Vu, 2011; Tran et al., 2020). Detrital zircons U-Pb apparent ages range from 3169 to 527 Ma with the peaks at ~1552, ~964, ~576 and ~435 Ma for the lower Paleozoic meta-sandstones within the zone (Figure 4e; Wang et al., 2020a, 2021a, 2021b). The first three age-peaks are consistent with those of the Kontum meta-sedimentary rocks, whose youngest age-peak at ~435 Ma is contemporaneous with the Nam Houay Formation in the Truong Son zone. In addition, Wang et al. (2020a, 2021a) reported that the upper Ordovician-Silurian (Llandovery-Wenlockian) sandstones in the Tam Ky-Phouc Son zone commonly contained volcanic pyroclast and granitic detritus, and showed the northerly-increasing trend, suggesting that the Tam Ky-Phouc Son zone was close to the volcanic arc in the Silurian (Llandovery-Wenlockian) period and received the provenance supply from its south (e.g., Loydell et al., 2019; Nguyen et al., 2019; Wang et al., 2020a, 2021a). In view of the Gondwana-type fauna in the Cambrian-Ordovician sequences of the Kontum massif and the angular unconformity between the pre-Ordovician and Ordovician-Silurian packages, it is concluded that the above-mentioned ancient detrital grains were from the Indian continent of the East Gondwana northern margin outside the Indochina block (e.g., Veevers et al., 2005; Cawood et al., 2007; Myrow et al., 2009; Usuki et al., 2009, 2013; Dong et al., 2010; Zhu et al., 2012; Metcalfe, 2013; Burrett et al., 2014; Wang et al., 2021a, 2021b).

The Truong Son igneous belt has been considered to be welded between the Sông Mã and Tam Ky-Phouc Son zone, which was subdivided by the Song Ca fault as the boundary, into southern and northern Truong Son zone, respectively (e.g., Kamvong et al., 2014; Tran et al., 2014; Shi et al., 2019; Qian et al., 2019; Wang et al., 2020a, 2020b, 2021a). In the northern Truong Son zone, the main exposures are characterized by the Neoproterozoic metamorphic rocks and S-type granitoids (e.g., Po Sen and Nam Giai) and the lower Palaeozoic package (e.g., Thanh et al., 1996; Thanh and Khuc, 2011; Nguyen et al., 2019; Tran et al., 2020). The lower Paleozoic packages are mainly characterized by the upper Ordovician-Silurian (Llandovery-Wenlockian) deep-water turbidites of the Sinh Vinh/Ket Hay Formation, whose sedimentary supplies are from the Yangtze southern margin (Wang et al., 2021a, 2021b). The lower Paleozoic package in the southern Truong Son zone is marked by the Ordo-Silurian Nam Houay and Song Ca/Long Dai formations, characterized by flyschoid deep-water sedimentary sandstone, graptolite, radiolarian shale, limestone, tuff and meta-volcanic rocks, and Silurian (Pridoli) neritic sedimentary rocks, and overlain by the Devonian-Permian silicoclastics and limestone with an angular unconformity (e.g., Tran and Vu, 2011; Kamvong et al., 2014; Udchachon et al., 2017; Thassanapak et al., 2018; Loydell et al., 2019; Tran et al., 2020; Wang et al., 2020a, 2021a). The shale and silicolite in the Nam Houay/Koduk Formation in the southern Truong Son zone contain Silurian (Llandovery) graptolites and radiolarian (Loydell et al., 2019). Wang et al. (2020a, 2021a) reported the zircon U-Pb ages of 445–434 Ma for the rhyolite-dacite-tuff interlayer and related diabase/gabbro from the Nam Houay/Koduk Formation, and 434–423 Ma for the rhyolite to the west of Vientiane (e.g. Long et al., 2019). In addition, the Ordo-Silurian sandstones in the southern Truong Son zone in lithology resemble to those in the Tam Ky-Phouc Son zone, and are characterized by greywacke with pyroclast and crushed granitic debris. Their zircon U-Pb apparent ages range from 3559 to 414 Ma, with peaks at ~2458, ~1600, ~953, ~591 and ~440 Ma, respectively. Each sample defines the detrital zircons U-Pb age-peak at ~440 Ma (Figure 4f). The corresponding $\varepsilon_{Hf}(t$=440 Ma) values for detrital zircons range from −2 to +6, distinctive from those for the Silurian grains in the Cathaysia of the South China block, as shown in Figure 6 (e.g., Usuki et al., 2009; Thanh and Khuc, 2011; Tran et al., 2014, 2020; Thassanapak et al., 2018; Loydell et al., 2019; Shi et al., 2019; Nguyen et al., 2019; Wang et al., 2021a, 2021b). Thus, the Nam Houay Formation and its equivalents, extensively exposed in the southern Truong Son zone, are of the late Ordovician-Silurian (~448–420 Ma) origin. Their provenance is likely the Tam Ky-Phouc Son zone and Kontum massif or their south, rather than South China block to the north (Wang et al., 2021a).

3.2 Ordo-Silurian igneous rocks in the Indochina block

The Ordo-Silurian mafic-acid volcanic and related intrusive rocks have been exposed in the Kontum massif in Central Vietnam and the Cambodia-Laos-Vietnam border, northward through the Tam Ky-Phouc Son zone into the Truong Son igneous belt (Figure 9b; e.g., Lan et al., 2003; Roger et al., 2007; Thanh et al., 2014; Ngo et al., 2015; Nulay et al., 2016; Gardner et al., 2017; Nguyen et al., 2019; Wang et al., 2020a, 2020b, 2021a, 2021b). In the Truong Son zone, a large amount of Permian-Triassic mafic-felsic igneous rocks and a small amount of the 448–420 Ma orthogneiss and granitoid were developed (Figure 9b; e.g., Roger et al., 2007; Zhang et al., 2013; Shi et al., 2015, 2019; Wang et al., 2020b, 2021a). However, the Neoproterozoic S-type granitoids (Nam Giai) and Precambrian basement rocks (Phu Hoat) were only exposed in the northern Truong Son zone (e.g., Thanh et al., 1996; Thanh and Khuc, 2011; Nguyen et al., 2019; Tran et al., 2020). The 445–423 Ma rhyolite-dacite-tuff in the Nam Houay/Koduk Formation and associated diabase/gabbro dikes have been identified successively in the southern Truong Son zone (e.g., Zhao et al., 2016; Long et al., 2019; Wang et al., 2020a, 2021a, 2021b).

In the Tam Ky-Phouc Son zone, a large amount of lentoid harzburgite, dunite, cumulate gabbro, pyroxenite, gabbro, and plagiogranite of unknown age and uneven size have been preserved, and were intercalated with marble, shale, mudstone and greywacke. They are considered as representatives of the Early Paleozoic ophiolite mélange or the Triassic intracontinental orogenesis (e.g., Izokh et al., 2006; Huynh et al., 2009; Tri and Khuc, 2009; Tran and Vu, 2011; Tran et al., 2014, 2020; Nguyen et al., 2019; Wang et al., 2021a). Recently, in the zone, the 519–502 Ma plagiogranite, 485–456 Ma gabbro-diorite-granite and 447–434 Ma andesite-rhyolite were also identified (e.g., Lan et al., 2003; Usuki et al., 2009; Gardner et al., 2017; Nguyen et al., 2019; Wang et al., 2020a, 2020b, 2021a, 2021b).

In the Kontum massif, there developed abundant Early Paleozoic orthogneiss, migmatite, granitoid and rhyolite/dacite, whose zircon U-Pb ages range from ~485 Ma to ~418 Ma (Figure 9b, 9c; e.g., Roger et al., 2007; Nakano et al., 2013; Tran et al., 2014; Shi et al., 2015, 2019; Hieu et al., 2016; Gardner et al., 2017). Wang et al. (2021a) and Gardner et al. (2017) additionally identified the 485–470 Ma high-Si adakitic rhyolite and dacite at the Laos-Vietnam border of the Kontum masssif. It is worth noting that the Early Paleozoic (477–460 Ma) MORB-type pyroxenite, gabbro, amphibolite and arc-like diorite-rhyolite were also observed in the Po Ko and Chu Sinh "suture" of the Kontum massif (e.g., Gardner et al., 2017; Tran et al., 2020).

Available data show that the Early Paleozoic igneous rocks in Central Vietnam and South Laos have SiO_2=44.48–78.17 wt.%, Al_2O_3=12.27–19.65 wt.%, FeO_t=1.93–17.17 wt.%, MgO=0.25–9.48 wt.% and TiO_2=0.21–2.77 wt.%, classified as calc- alkalic gabbro/basalt and rhyolite/dacite (e.g., Wang et al., 2020a, 2020b, 2021a). In the Tam Ky-Phouc Son zone and the Kontum massif, there preserved not only the Early Paleozoic (485–447 Ma) MORB-like mafic-ultramafic rocks, but also the Cambrian-Ordovician arc-like gabbro-diorite and intermediate-mafic volcanic rocks (e.g., Phong Hanh). The arc-like igneous rocks are enriched in LILEs and depleted in HFSEs, and show Nb-Ta negative anomalies (Figure 7), with Th/Nd=0.20–0.60, Nb/Y=0.18–0.55, La/Nb=2.44–4.64, Ce/Pb=1.72–6.60 and Th/Nb=0.63–2.58. $(^{87}Sr/^{86}Sr)_i$=0.7044–0.7109, $\varepsilon_{Nd}(t)$=−6.2–−2.6, $(^{206}Pb/^{204}Pb)_i$ =18.08–18.68, $(^{207}Pb/^{204}Pb)_i$=15.50–15.77, $(^{208}Pb/^{204}Pb)_i$ =38.04–38.97 (Figure 8). Their zircon *in-situ* ε_{Hf} (t) and $\delta^{18}O$ values range from +1.6 to −6.5 and 6.1‰ to 8.6‰, respectively (Wang et al., 2020a, 2021a). In petrogenesis, they are originated from the wedge source modified by recycled sediments (Wang et al., 2020a, 2021a).

The intermediate-basic rocks in the southern Truong Son zone are dominated by the 445–434 Ma andesite and synchronous gabbro-diabase in the Nam Houay Formation. Zircon *in-situ* $\varepsilon_{Hf}(t)$ and $\delta^{18}O$ values range from +5.0 to +12.3 and 5.53‰ to 7.43%, respectively. They have SiO_2, Al_2O_3, TiO_2, K_2O+Na_2O, MgO and Mg-values in the range of 44.48–54.50 wt.%, 14.13–19.65 wt.%, 1.13–2.77 wt.%, 3.19–5.11 wt.%, 4.78–9.48 wt.% and 46–56 respectively, and show enrichment in LILEs and LREEs, and depletion in HFSEs, with Nb/La=0.41–0.89. Their $(^{87}Sr/^{86}Sr)_i$ and $\varepsilon_{Nd}(t)$ range from 0.70446 to 0.71521 and +5.9 to −2.3 respectively (Figures 7 and 8). Such geochemical signatures reveal their origin from the mantle wedge source modified by low-proportional (<5%) recycled sediment-derived components (Wang et al., 2020a, 2021a). In addition, the 434–423 Ma rhyolite with $\varepsilon_{Nd}(t)$=+0.3–+0.7 was identified to the west of Vientiane in the southern Truong Son zone, which is characterized by enrichment in LILEs and depletion in HFSEs with (Nb/La=0.18–0.46), $(^{87}Sr/^{86}Sr)_i$=0.70442–0.70723, zircon $\varepsilon_{Hf}(t)$=+2.4–+6.9 and $\delta^{18}O$=5.6–6.6‰, reflective as melting products of the juvenile crust (Long et al., 2019; Wang et al., 2021a). Such data collectively indicate the coeval formation of the juvenile crust and recycled crustal materials-modified wedge source at the ~445–420 Ma, suggesting the development of the Ordo-Silurian subduction in the southern Truong Son zone.

As shown in Figure 9b–c, in the Kontum massif, the Tam Ky-Phouc Son and southern Truong Son zones of the Indochina block, the Early Paleozoic (485–407 Ma) intermediate-basic igneous rocks and granitoids are extensively exposed. From the Kontum to the Tam Ky-Phouc Son and then to the Truong Son zone, the formation ages of the igneous rocks decrease progressively from south to north, showing a northwardly-accretionary orogenesis. The granitoids in the three tectonic units are dominated by orthogneiss, granodiorite and granitoids, and have K_2O>Na_2O, enrichment in LILEs and depletion in HFSEs with Nb-Ta, Sr-P and Ti negative anomalies. Their Nb/La ratios range from 0.13 to 0.41, $(^{87}Sr/^{86}Sr)_i$ from 0.70510 to 0.71559, $\varepsilon_{Nd}(t)$ from −9.5 to −3.0, and zircon *in-situ* $\varepsilon_{Hf}(t)$ from −10.6 to +1.0, distinctive from those of the ancient crust-derived South China S-type granites, but similar to those of the contemporaneous granitoids in the Kailash and Sibumasu (Figures 6–8). Such Sr-Nd-Hf isotopic compositions are generally similar to or slightly lower than those of the synchronous intermediate-mafic igneous rocks in the region (Figure 8; e.g., Roger et al., 2007; Tran and Vu, 2011; Wang Y et al., 2013b, 2018, 2020a, 2021a, 2021b; Tran et al., 2014, 2020; Hieu et al., 2016; Shi et al., 2019; Minh et al., 2020).

4. Prototethyan southern branch and its closure

As to the Prototethyan closure along the East Gondwana northern margin, two distinct models of the pan-African and Andean-type orogenesis have been proposed (e.g., Cawood et al., 2007; Zhang et al., 2008; Dong et al., 2010; Wang Y et al., 2013b; Wang X X et al., 2011, 2012b; Zhu et al., 2012).

Available data show that high-latitude "Cimmerian- type" sedimentary strata and the Early Paleozoic fauna are characteristics of the Sibumasu block, similar to those in Australia with tectonic affinity of the East Gondwana northern margin (e.g., Metcalfe, 2013). As mentioned above, the Early Paleozoic (473–432 Ma) mafic-ultramafic rocks (characterized by peridotite, cumulate gabbro-pyroxenite, gabbro, anorthosite) and intermediate-mafic intrusive rocks (e.g., gabbro diorite, diorite and granodiorite) were developed along the Yunian-Menghai (SW Yunnan) and its western side. Contemporaneous (432–439 Ma) mafic-ultramafic rocks were also observed in the Chiang Rai-Mae Chan area in NW Thailand (Figure 2). The ophiolite assemblages (~450 Ma) in SW Yunnan (e.g., Wanhe ophiolite) were mainly developed along the Yunxian-Menghai area or to the east of the Changning-Menlian paleotethyan suture (Figure 2b). These rocks were intercalated or enclosed in the Lancang Group and its equivalents with lenticular, stratiform-stratoid or lumpy forms, and show MORB-, OIB- or arc-like geochemical affinities (Figures 2, 7, and 8), representing products in the Prototethyan-related supra-subduction process (e.g., Wang B D et al., 2013; Liu et al., 2021). In addition, the middle Ordovician-late Silurian meta-basic volcanic rocks and high-mg andesites were preserved with arc-like geochemical affinities along the Tinghe, Shuangjiang and Huimin areas in SW Yunnan, and the Golden-Triangle-Chiang Rai area in NW Laos and NW Thailand. The 432–417 Ma intermediate-felsic volcanic rocks were observed in the Dapingzhang and Dazhonghe areas, the sedimentary exhalative copper deposits to the east of the Yunxian-Menghai ophiolite zone. In SW Yunnan and SE Asia within the Sibumasu block, there occurred a giant Early Paleozoic (502–418 Ma) granitoid zone extending southward from Gaoligong-Ximeng in SW Yunnan into western Malay Peninsula and NW Sumatra via southern Thailand (Figure 2; e.g., Lin et al., 2013; Kawakami et al., 2014; Wang et al., 2021b), which were derived from the meta-volcano-sedimentary source in the arc or synorogenic setting (e.g., Cawood et al., 2007; Zhu et al., 2012; Wang Y et al., 2013b). Such data consistently suggest an Early Paleozoic arc-trench system related to the Prototethyan Ocean and its westward subduction style beneath the Sibumasu block. In addition, the Tarutao, Ximeng and Lancang groups and their equivalents are overlain by the carboniferous-Permian tillite and/or middle-upper Permian carbonate rocks with an angular unconformity (Figure 3; e.g., Metcalfe, 2013; Burrett et al., 2014). These data, in combination with the 503–474 Ma metamorphic records in the Namche Barwa and Tengchong areas (Zhang et al., 2008), consistently suggest an Early Paleozoic (~505–420 Ma) orogenesis in SW Yunnan-South Thailand, and even western Malay Peninsula, on the Sibumasu eastern margin. The ophiolite mélanges along the Yunxian-Menghai area might be the Prototethyan remnants, named herein as the Yunxian-Menghai Prototethyan Ocean, with its southwestward subduction beneath the Sibumasu block till the Silurian (Figures 2 and 10a, 10b; e.g., Liu G C et al., 2017; Wang et al., 2017, 2020a; Liu et al., 2020, 2021).

As shown in Figure 2d, from Gaoligong (Tengchong), Mangshi (Baoshan) to Yunxian-Menghai and Dazhonghe, the formation ages of the Early Paleozoic igneous rocks in SW Yunnan decrease gradually. In addition, the igneous rocks coexisted spatially with the Ximeng and Lancang groups and their equivalents, and they share similar formation ages (Figure 2b). Among them, the Precambrian-middle Ordovician "Tarutao and Ximeng groups and their equivalents" are an assemblage composed of migmatite, gneiss, granite and volcanoclastic rocks. The "Lancang Group and its equivalents" contain numerous detrital zircons with similar age to the Indian continent of East Gondwana. These sequences consist of the middle Ordo-Silurian volcano-sedimentary sequences or olistostrome intercalated with the mafic-ultramafic rocks, suggestive their formation in a continental arc or an active continental margin (Figure 5). Prior to ~490 Ma, the Sibumasu block was located on the East Gondwana northern margin and received the debris supply from India and Antarctic (Figure 10c). Such a trend appears to suggest a southerly diachronous and easterly accretionary orogenesis of the Prototethyan southern branch ocean along eastern Sibumasu. Further southeasterly to the westernmost Simao, the Dapingzhang and Dazhonghe metavolcanic-sedimentary rocks were formed at 432–417 Ma and showed the arc- or back-arc-like geochemical signatures, reflecting the Prototethyan subduction continuing to the late Silurian.

The Indochina block is suggested to have experienced either the Early Paleozoic South China intracontinental orogenic event, or the Early Paleozoic oceanic subduction (e.g., Thassanapak et al., 2012, 2018; Thanh et al., 2014; Loydell et al., 2019; Nguyen et al., 2019; Wang et al., 2020a, 2020b, 2021a, 2021b). According to the geochronological and geochemical data in Figures 6–9, the subduction-related Early Paleozoic igneous rocks is evidenced to be preserved within the Indochina block. It is manifested in the fact that from the Kontum massif to the Truong Son zone, the intermediate-mafic igneous rocks all show arc-like geochemical signatures, marked by low Nb/La, Nd/Pb, $\varepsilon_{Nd}(t)$, $\varepsilon_{Hf}(t)$, and high $\delta^{18}O$, Th/Nd, Th/Nb, Ce/Nb, as well as high Δ8/4 and Δ7/4. They coexisted with turbidites, and radiolarian siliceous, clastic and carbonate rocks, and are compatible with 485–418 Ma I- and S-type granites in the arc or collisional setting (Wang et al., 2020b, 2021a). In the Tam Ky-Phouc Son tectonic zone, the ~519–502 Ma plagiogranite in Early Paleozoic "ophiolite mélanges" (e.g., Thanh and Khuc, 2011; Nguyen et al., 2019; Wang et al., 2020a, 2021a) has the intra-oceanic arc-like geochemical affinity (e.g., Nguyen et al., 2019). In the Nam Houay/Long Dai deep-water sequence of

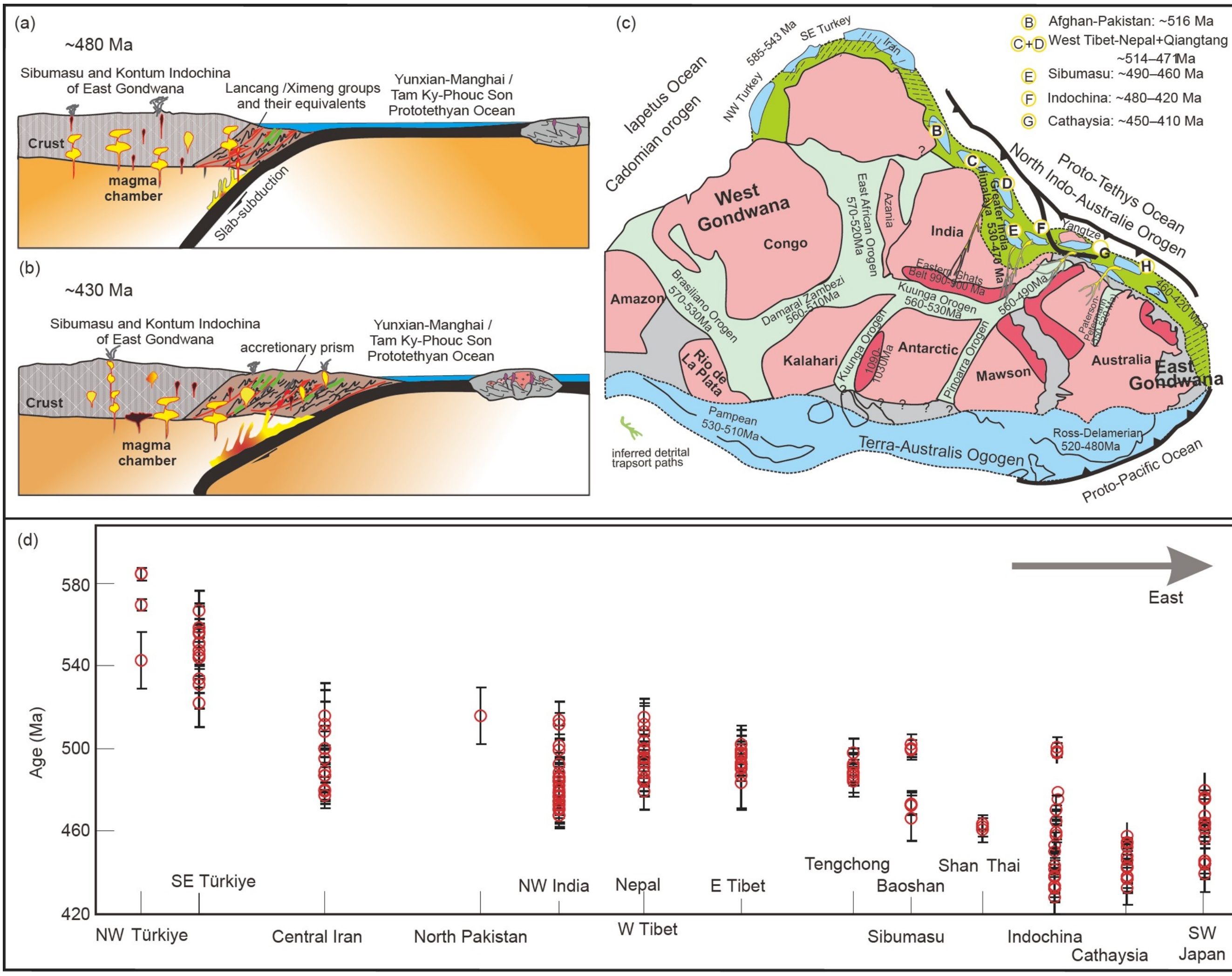

Figure 10 (a), (b) Andean-type orogenic model of the Eastern Prototethyan southern branch ocean along the Yunxian-Menghai and Tam Ky-Phouc Son sutures at ~480 and ~430 Ma, respectively (a), (b). (c) Early Paleozoic paleo-location reconstruction of the main blocks on the Gondwana northern margins and (d) age-migration trend of the Early Paleozoic giant igneous belt along the Eastern Gondwana northern margin (after Wang Y et al., 2010, 2013b, 2020a, 2020b, 2021a, 2021b and references therein).

the southern Truong Son zone, Loydell et al. (2019) identified both the Silurian (Llandovery) radiolarian and graptolite fauna, distinctive from those in South China but similar to those in Europe and Arab (e.g., Thanh and Khuc, 2011; Thassanapak et al., 2018). This indicates that the Indochina block might be separated by the Early Paleozoic ocean along the Tam Ky-Phouc Son zone, and that the Kontum massif had not yet bordered the northern Truong Son zone or the South China block until the Silurian (Llandovery) period (e.g., Tran et al., 2014; Ngo et al., 2015; Thassanapak et al., 2018; Loydell et al., 2019; Nguyen et al., 2019). The Early Paleozoic Indochina might be far smaller than its present scope and might only be represented by the Kontum massif and/or its south. The MORB-like pyroxenite, amphibolite, gabbro, adakitic diorite and rhyolite in Chu Sinh in the southern Kontum massif and the "Po Ko ophiolite mélange" in the western Kontum massif might have been the earlier accretionary boundary or the suture equivalent to the Tam Ky-Phouc Son zone. The current geographical pattern might be the result of the large-scale tectonic displacement since the Early Paleozoic (e.g., Burrett et al., 2014; Tran et al., 2014, 2020; Wang et al., 2021a).

As shown in Figure 9c, the Early Paleozoic (~485–418 Ma) magmatism in the Indochina block tended to be younger northerly (Wang et al., 2020a, 2021b). From Kontum to the southern Truong Son zone, the $\varepsilon_{Nd}(t)$-$\varepsilon_{Hf}(t)$ values gradually decrease but the $\delta^{18}O$ values increase (Wang et al., 2021b). In addition, (1) the granitoids in the southern Truong Son zone contain abundant inherited zircons, indicating the northerly-increasing input of the "ancient crustal materials" into the magma source region (Wang et al., 2020b, 2021a). (2) The large-scale thrust nappe occurred from top-to-the north, and the Early Paleozoic (455–424 Ma) metamorphism was characterized by the *P-T-t* clockwise path in the Kontum massif and the Tam Ky-Phouc Son zone (e.g., Nakano et al., 2007, 2013; Tran et al., 2014, 2020; Faure et al., 2018; Wang et al., 2020b, 2021a). (3) Two angular-unconformities have been observed between the Cambrian (Miaoling) and lower Ordovician sequences (equivalent to Tarutao Group), and between the middle-upper Ordovician/Silurian (Llandovery) (equivalent to Lancang Group in SW Yunnan) and the middle-lower Devonian sequences in the Kontum massif and the southern Truong Son zone (Figure 3; Vuong et al., 2006, 2013; Tri and Khuc, 2009; Thanh and Khuc, 2011; Tran et al., 2014). However, in the Truong Son zone, only an angular unconformity has been observed between the middle-upper Ordovician-Silurian (Llandovery) and the middle-lower Devonian package (e.g., Vuong et al., 2006, 2013; Tri and Khuc, 2009; Thanh and Khuc, 2011; Tran et al., 2014). (4) In the Kontum massif and the Tam Ky-Phouc Son zone, the 446–424 Ma granulite and the 476–430 Ma I- and S-type orthogneiss are enclosed or across-cut by the ~427–407 Ma porphyritic granites (e.g., Nam et al., 2001; Roger et al., 2007; Nakano et al., 2007, 2013; Usuki et al., 2009; Tran et al., 2014; Gardner et al., 2017). (5) The Devonian fish and tentaculitoid fossils in the southern Truong Son zone are similar to those of the South China block, indicating that the biota could migrate freely between the Indochina and South China blocks at that time (e.g., Thanh et al., 1996; Nam et al., 2001; Thassanapak et al., 2012, 2018; Udchachon et al., 2017; Loydell et al., 2019). All these data synthetically indicate that the Tam Ky-Phouc Son Ocean might be an Ordo-Silurian Prototethyan Ocean in the Indochina block, and its southward subduction beneath the Kontum massif started at ~485–470 Ma (Figure 10a), marked by the first angular unconformity. Such an orogenesis developed northerly and reached the southern Truong Son zone by ~430 Ma. It also induced the formation of the mantle wedge and juvenile crustal source within the Indochina block (Figure 10b). The ending of this accretionary orogenesis, marked by the regional angular unconformity between the Ordo-Silurian and Devonian packages, has been limited at ~410 Ma of the earliest Devonian (Figure 2; e.g., Wang et al., 2020a, 2020b, 2021a).

As shown in Figure 10d, all the data reveal that a giant Early Paleozoic igneous belt was developed on the Gondwana northern margin. The formation ages of its granitoids decrease progressively from NW Turkey (~585–543 Ma), Central Iran (~557–522 Ma), NW Pakistan (~516 Ma), to NW India and Nepal (~514–471 Ma), and then to Tibet and Namcha Barwa (~495 Ma) from west to east (e.g., Garzanti et al., 1987; Brookfield, 1993; Miller et al., 2001; Zhu et al., 2011). Similar trend is also shown for its metamorphic ages ranging from 529 Ma in NW Turkey, to 505–480 Ma in Nepal and India, and then to 503–474 Ma in Namcha Barwa (Cawood et al., 2007, 2021; Myrow et al., 2009; Wang Y et al., 2013b). Such a trend goes further southward to eastern Sibumasu (~490–460 Ma) and Thailand Peninsula, western Malay Peninsula and NW Sumatra (~490–430 Ma). All the data, along with the spatial and temporal pattern of the sedimentation and metamorphism in the Sibumasu and Indochina blocks, consistently suggest the northward or eastward (present location) accretionary orogenesis (Figure 10). The Yunxian-Menghai (-South Thailand) suture along the eastern Sibumasu block might link easterly with the Tam Ky-Phouc Son zone in the present Indochina, which represent two segments of the Prototethyan southern branch ocean along the East Gondwana northern margin (Figures 2 and 9–10). The Early Palaeozoic igneous rocks of the Indochina block most likely represent the eastward extension of the giant Prototethyan igneous belt. Thus, a Cambrian (Furongian)-Silurian (Llandovery) Andean-type orogenesis is herein proposed, which went from Nepal, northwest India, southern Tibet, Qiangtang, across eastern Sibumasu to Central Indochina on the East Gondwana northern margin. The orogenesis developed easterly and diachronously and was accompanied by the outward accretionary expansion, as shown in Figure 10a–10d. This model suggests that, during ~530–500 Ma or earlier, the Sibumasu and Indochina blocks received abundant debris from the India-Antarctica or Australian continent (Figure 10c). During ~480–440 Ma, the Yunxian-Menghai and Tam Ky-Phouc Son Prototethyan southern branch ocean experienced, respectively, the southwestward and southward (present location) subduction beneath the Sibumasu and Indochina blocks, as well as the outward migration of debris sediment and suture boundaries (e.g., Vuong et al., 2020). In response to the outward accretionary orogenesis, the continuous retreat of slab and the collapse of thickened crustal roots might have successively induced the synchronous magmatism. And inside the region, the angular unconformity between Silurian and Devonian sequences and the unified Cathaysian late Paleozoic biota indicated that the converging process ended in the earliest Devonian (~410 Ma).

5. Coupling the Prototethyan evolution with the South China Kwangsian orogeny

As mentioned above, the Early Paleozoic tectonic setting is characterized by the closure of the Prototethyan southern branch ocean and the easterly diachronous Andean-type orogenesis in the Sibumasu and Indochina blocks of the East Gondwana northern margin. At this time, the South China block was also located on the East Gondwana northern margin, therefore, the Early Paleozoic structural deformation, magmatism and metamorphism of the South China were closely related to the northern branch evolution of the Prototethyan Ocean (e.g., Dong et al., 2018; Li et al., 2018; Zhao et al., 2018). However, the eastern South China continent to east side of the Xuefeng Mountains once experienced an intense Ordo-Silurian orogenesis, traditionally named "Kwangsian movement or Caledonian Orogeny" (e.g., Ting, 1929; Huang, 1945; Chen et al., 2010, 2012; Wang Y et al., 2010, 2012, 2013a). Thus, a key scientific question arises regarding the internal relationship between the eastern South China Kwangsian orogenesis and the Prototethyan southern branch evolution. In this case, two distinct viewpoints of the "oceanic subduction" and "intracontinental orogeny" have been proposed. For the oceanic subduction model, the Early Paleozoic South China continent has been regarded as the typical "arc-trench" system, and the "Early Paleozoic South China Ocean" was developed along NE Jiangxi and SW Anhui in South China, and the "Kwangsian Movement" resulted in the final closure (e.g., Guo et al., 1980; Xu et al., 1996; Chen et al., 2006). However, the "intracontinental orogeny model" suggested the development of sialic crust within the South China hinterland since the Neoproterozoic period (e.g., Ren, 1991; Wang Y et al., 2010, 2013b; Shu et al., 2020, 2021). Available data show that, from the Cathaysia to Central Yangtze in the eastern South China, the Cambrian-Ordovician strata were characterized by neritic and slope-facies sediments, instead of the deep-sea rock-association, and the sedimentary rocks changed gradually from clastic- to carbonate platform-facies through interlaced sedimentary facies (e.g., Shu et al., 2008; Li et al., 2010; Xiang and Shu, 2010; Wang et al., 2010). Rong et al. (2007) and Chen et al. (2010) also gave evidence to the continuous and unified intracontinental basin from Xuefeng in the Central Yangtze to Cathaysia based on the palaeontological, stratigraphic and palaeoecological data. In view of the similar detrital zircons U-Pb age-spectra for the lower Paleozoic sequences across the Jiangshan-Shaoxing fault (Wang et al., 2010), the eastern Yangtze and Cathaysian shared a similar or almost the same debris provenance during the Early Paleozoic period, and at that time the Jiangshan-Shaoxing fault hadn't become a barrier for the westward/northwestward transportation of the debris from the east or southeast (Wang et al., 2010).

The Kwangsian igneous rocks in the eastern South China are dominated by granitoids, with a planar and nonlinear spatial pattern, and have the formation ages of ~454–400 Ma with the peak at 440–428 Ma (Figure 11a, 11b). They are mainly derived from the Precambrian metamorphic crust with poor input of mantle-derived components (e.g., Shu and Charvet, 1996; Shu et al., 2008, 2011; Wang Y et al., 2010, 2013a; Shu et al., 2021). In addition, the Early Paleozoic ophiolite melanges, deep-marine siliceous rocks and arc-like igneous rocks have not yet been observed in the South China hinterland. The small amount of intermediate-mafic igneous rocks, sporadically exposed along the main faults, were mostly formed at 440–420 Ma, contemporaneous with or slightly later than the crust-derived granitoids, which have been interpreted as derivation of the ancient enriched lithospheric rather than depleted mantle source (e.g., Wang Y et al., 2013a). In the eastern South China continent, especially the Wuyi-Yunkai area, the amphibolite- and granulite-facie metamorphism with the clockwise P-T path was developed, whose metamorphic ages range from 450 Ma to 420 Ma with the peak at ~435 Ma, synchronous with those of the granitoids in the region (Figure 11b; e.g., Yu et al., 2005, 2007; Wang Y et al., 2012, 2013a; Wang X et al., 2012a). Thus, more and more scholars tend to believe the absence of "Early Paleozoic South China remnant Ocean", and its tectonic model has been accepted as the intracontinental orogenesis (e.g., Charvet et al., 1996, 2010; Shu et al., 2008; Wang Y et al., 2010, 2013a; Shu et al., 2021). However, different models, i.e., the deep-subduction of the South and North China blocks vs the intracontinental assemblage of the Yangtze with Cathaysia vs the convergence of the South China with Indochina blocks vs the Prototethyan oceanic consumption, have been proposed as the power origin driving the eastern South China Kwangsian intracontinental orogenesis (e.g., Yu et al., 2007; Wang Y et al., 2007, 2010, 2013a; Wan et al., 2010; Charvet et al., 2010).

A line of evidence shows that the detrital zircons U-Pb ages for the lower Paleozoic sandstones in the Cathaysia and eastern Yangtze range from 3335 Ma to 464 Ma with characteristic peaks at ~2550, ~1870–1840, ~1100–1080, ~890–860 and ~790–760 Ma, and with abundant detrital grains of ~900–550 Ma. In the Yunkai region of southern South China, the Luohong conglomerate at the base of the Ordovician sequence contains gravels resembling the Himalaya Precambrian basement (Xu et al., 2014). These data, along with the paleo-current data for the lower Paleozoic strata in eastern South China (e.g., Wang et al., 2010), collectively suggest that, during Neoproterozoic-Early Paleozoic period and prior to the Ordovician, the eastern South China continent had tectonic affinity with the northern margin East Gondwana. The root of the South China Kwangsin orogenesis or the supply region of the debris provenance was in the southeastern South China or its east (Figure 10a; e.g., Yu et al., 2007; Shu et al., 2008; Xiang and Shu, 2010; Shu, 2012; Wang Y et al., 2010, 2013a; Shu et al., 2014, 2021). Moreover, in eastern South China, the Early Paleozoic tectonothermal event and the paleontological response time are limited at ~460–400 Ma (Rong et al., 2010; Chen et al., 2014; Wang Y et al., 2013a), and the angular unconformity shows a diachronous progression from southeast to northwest (Figure 11a), i.e. the Cambrian-Ordovician Yunanian Movement, suggested herein as the Kwangsian-I orogeny, in the southernmost South China (e.g., Yunkai and North Hainan); and then the originally-defined Kwangsian Movement between the Ordo-Silurian and Devonian package, recommended herein as the Kwangsian-II orogeny, in the South China hinterland (e.g., Central Hunan and Jiangxi). The Kwang-

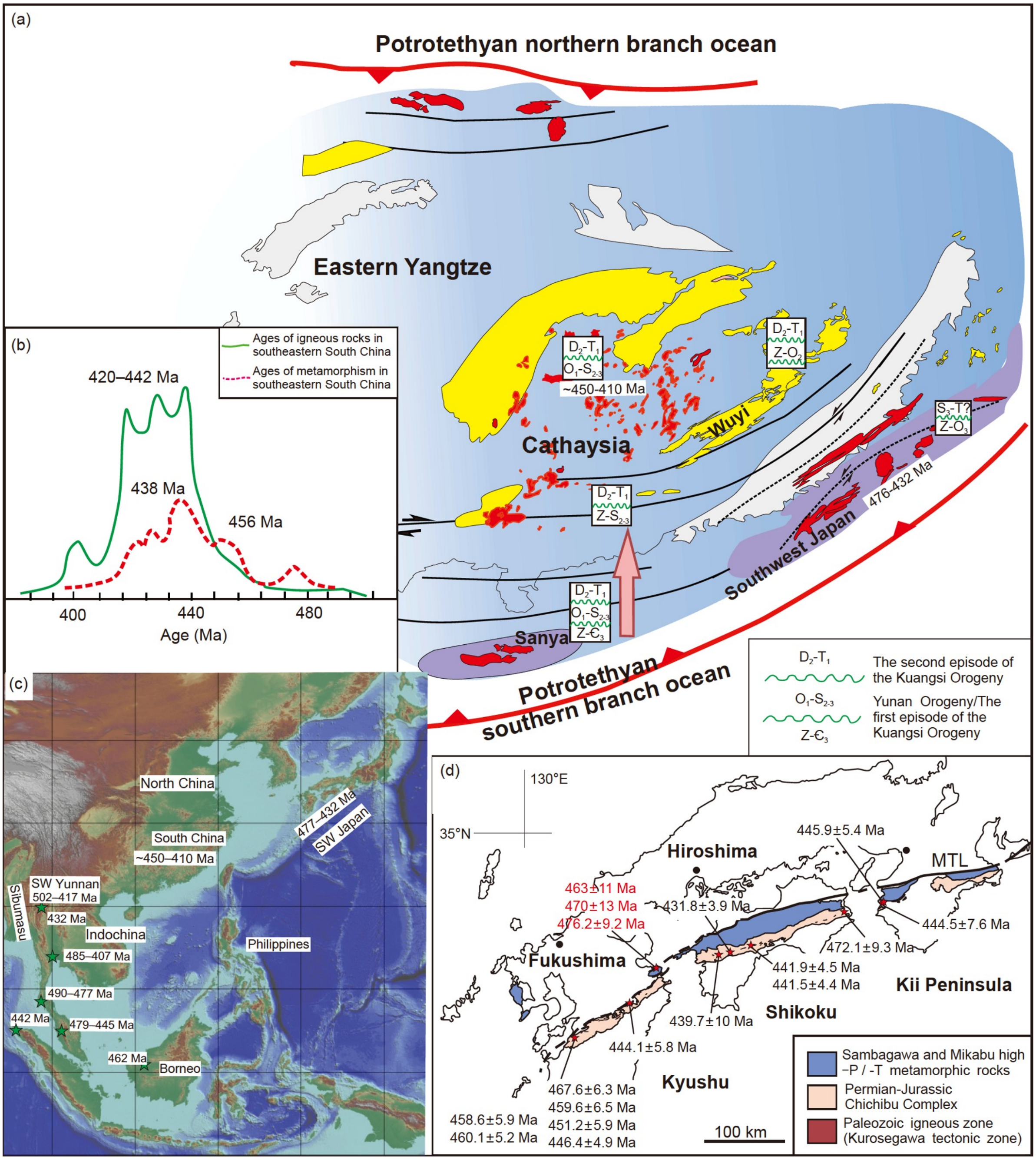

Figure 11 (a) Potential tectonic pattern of the PrototethyanSouth China continent, (b) age spectra of the Early Paleozoic magmatism and metamorphism for the Eastern South China, and (c)–(d) geographical location of SW Japan and its Early Paleozoic geological records, respectively (modified after Wang Y et al., 2013a; Aoki et al., 2015; Kawaguchi et al., 2020 and references therein).

sian-I and -II orogenic events are justly compatible with two angular unconformities in the Sibumasu and Indochina blocks. Thus, it is concluded that the scope of the Early Paleozoic Kwangsian intracontinental orogenesis in southeastern South China most likely originated from the oceanic closure to the south or southeast of eastern South China, i.e. northernmost Indochina or areas along Sanya to southwest Japan (Figure 11).

As shown in Figure 5d, the Early Paleozoic detrital zircons Hf isotopic compositions for the lower Paleozoic sandstones in the Indochina block are distinct from those in the eastern South China block. The elemental and Sr-Nd isotopic compositions of the Early Paleozoic granitoids are also different from those of the contemporaneous granitoids in the eastern South China block (Figures 7 and 8). A line of evidence indicates that the Ordovician paleo-latitude of the South China block was at 9°–24°S, but the Ordovician trilobites in the Indochina block might be classified as cold-water fauna assemblage (e.g., Li et al., 2004; Duan et al., 2011). This indicates that the Indochina block might not be adjacent to the eastern South China continent during the Ordovician period. In fact, the Sông Mã tectonic zone to the north of the Indochina block preserved not only the geological records related to the Late Paleozoic Paleotethyan branch evolution, but also the Early Paleozoic metabasite, gabbro-diorite, plagiogranite, amphibolite and serpentine with the fore-arc tectonic affinity (e.g., Findlay and Trinh, 1997; Ngo et al., 2015; Ngo and Nguyen, 2016; Hau et al., 2018). The greywacke intercalated into the above-mentioned tectonic lumps contain Cambrian-Ordovician fossils, among which the Thanh Long plagiogranite yielded zircon U-Pb ages of 475–470 Ma (e.g., Ngo et al., 2015; Ngo and Nguyen, 2016). In addition, the Vit Thu Lu calc-alkalic arc-like granitoids and granodiorites, and the Huoi Tong granitoid in western Diên Biên Phu were dated at 446–415 Ma (Nguyen et al., 2004). In the northern Truong Son zone, i,e., Phu Kham, Long Chieng and Laosang, the granitoids and rhyolites have zircon U-Pb ages of 446–420 Ma (e.g., Roger et al., 2007; Shi et al., 2015; Wang et al., 2020b, 2021a). Monazite in garnet-bearing schist gave the Sm-Nd isochronal metamorphic age of 424 ±15 Ma (e.g., Tran et al., 2014). The meta-sedimentary rocks from the Hoang Lien Son and Song Chay Complexes have the zircon U-Pb age-peaks of ~2900, ~2300, ~1800, ~838 and ~760 Ma, similar to those of the Yangtze southern margin (e.g., Yan et al., 2006; Wang et al., 2019; Tran et al., 2020). Within the northern Truong Son zone, the Silurian sandstones are overlain by the middle-lower Devonian with an angular unconformity and are characterized by the poorly-sorted greywacke with the detrital zircons age-peak at ~784 Ma, compatible with the Neoproterozoic (~770 Ma) Po Sen and Nam Giai S-type granitoids (Figure 4f, Thanh et al., 1996; Nguyen et al., 2004; Tran and Vu, 2011; Tran et al., 2014; Wang et al., 2020b, 2021a). Hau et al. (2018) proposed that the upper Ordovician-Silurian (Llandovery) Sinh Vinh/Ket Hay Formation in Sông Mã or northern Truong Son zone is marked by deep-water turbidite, for which the detrital zircons defined the youngest U-Pb age-peak at ~440 Ma. In addition, westward into the Ailaoshan-Diancangshan area along the Song Ma zone, the Silurian (446–404 Ma) andesite, gabbro, basalt, diorite or amphibolite xenoliths have been identified (e.g., Jian et al., 2009; Liu et al., 2018b), showing both intraplate- and arc-like geochemical affinities. Thus, during the late Ordovician-Silurian period, the Sông Mã and the northern Truong Son zone in the present northern Indochina/Simao might have received the debris supply from the southern Yangtze of the South China block, from which the Ordo-Silurian orogenesis might have developed (e.g., Gardner et al., 2017; Tran et al., 2020).

In Tunchang of Central Hainan, Cambrian-Ordovician arc-like volcanic rocks have been identified (e.g., Ding et al., 2002; Xu et al., 2007; Zhou et al., 2021). In the upper Ordovician sequence in Sanya of South Hainan, the debris from the Tunchang volcanic arc have also been observed (Xu et al., 2014). Detrital zircons age-spectra and Lu-Hf isotopic compositions of the Cambrian sandstones in Sanya are distinct from those of the synchronous sequence in eastern South China, but similar to those of the Meso-proterozoic Northampton Complex in NW Australia (Xu et al., 2014). Trilobite fossils preserved in the Cambrian strata in Sanya further suggest the spatial connection of South Hainan with the western Australian continent in the early period of Early Paleozoic. On the contrary, at that time, the eastern South China continent, SE Asian Sibumasu and Indochina blocks might be connected with the India continent or located at the joint area of India and Australia (Figure 10c). Available data show that NW Australia was separated from the Indian continent by the Kuunga Ocean in the early period of Early Paleozoic. The oceanic closure at the Cambrian-Ordovician resulted in the final collage of the East Gondwana continent (Figure 12), which happened in respond to the Terra Australis accretionary orogenesis of eastern Australia on the eastern margin of East Gondwana. Although future work is still required, we herein propose that this ocean most probably extended northerly from NW Australia into the northern South China Sea-South Hainan or northernmost Indochina and then into SW Japan, representing the eastward extension of the Prototethyan southern branch ocean among eastern South China, Indochina and Australia (Figures 10 ang 11; Cocks and Torsvik, 2013).

A line of evidence shows that the Early Paleozoic fossil fauna in SW Japan might be compared with those in the South China block (e.g., Shimojo et al., 2010; Fujisaki et al., 2014; Isozaki and Kase, 2014). A question arises as to whether a power had been developed in SW Japan to drive the South China Kwangsian intracontinental orogenesis (Figure 11c). The Cambrian (Furongian)-Silurian package has been identified in SW Japan so far, i.e., the Hitoegane Formation in Hida, Okanaro Group in west Shikoku, Yokokurayama Formation in Central Shikoku and Gionyama Formation in Central Kyushu (e.g., Nakama et al., 2010; Kido and Sugiyama, 2011). The package was characterized by the volcano-sedimentary rocks in the fore-arc or back-arc setting, the Ordo-Silurian sandstones of which contain the Archean, Mesoproterozoic and Neoproterozoic detrital zircons (e.g., Shimojo et al., 2010; Nakama et al., 2010; Shimojo et al., 2010). The Mitaki granitoids in Kyushu also have abundant inherited zircons with the U-Pb apparent ages of 3090–464 Ma. Isozaki and Kase (2014) and Isozaki et al. (2016) and also pointed out that the debris provenance of the Silurian sedimentary rocks in SW Japan was the Cathaysian of the South China block, and SW Japan might be located in the easternmost Cathaysian during the Early Paleozoic period. The Cambrian (Furongian)-Ordovician igneous rocks were mainly exposed in Chichibu area (Central Kurosegawa)

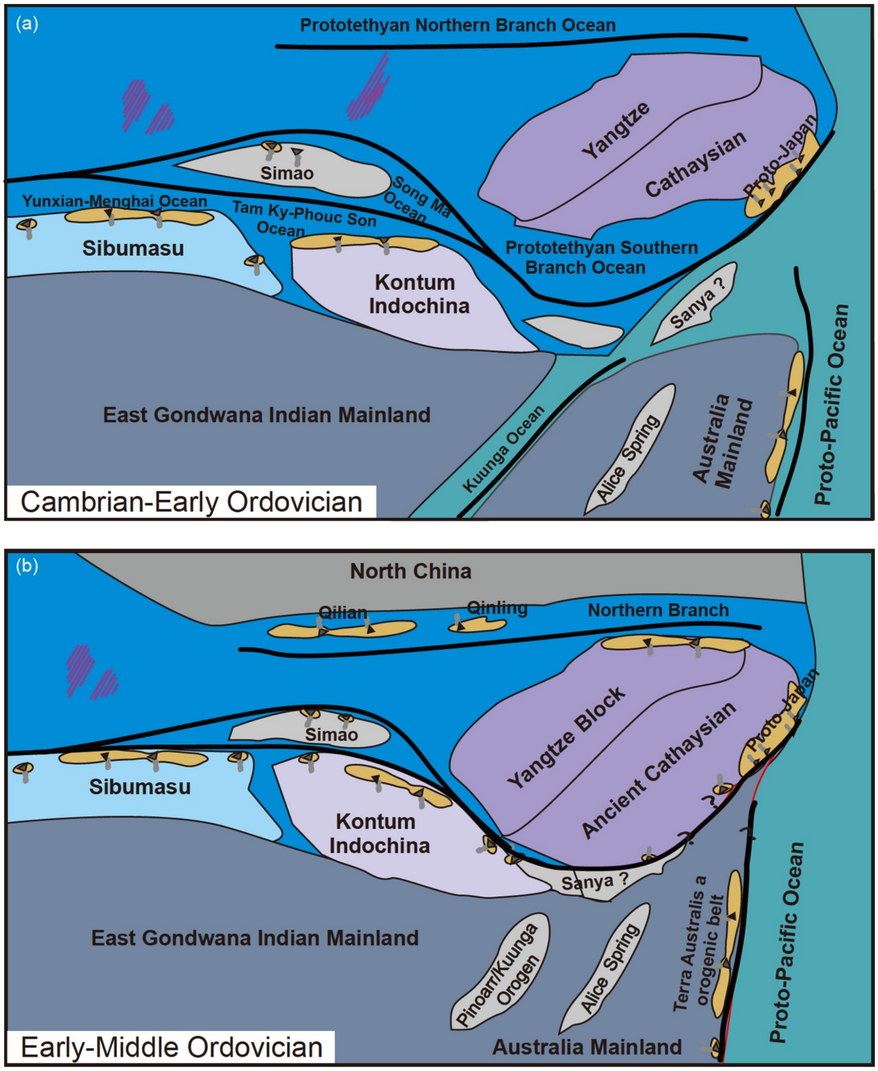

Figure 12 Spatial configuration of the Sibumasu, Simao, Indochina and South China blocks in the Cambrian-early Ordovician (a) and early-middle Silurian (b) period, respectively.

in SW Japan and characterized by the lentoid mafic-ultramafic and neritic sedimentary rocks, including the "Jishino metamorphic Complex", "Santaki and Kurosegawa igneous rocks" and 476–432 Ma granitoids (Figure 11d; e.g., Maruyama, 1981; Hada et al., 2000; Aoki et al., 2015; Kawaguchi et al., 2020). In addition, the meta-gabbro and amphibolite that had experienced the low-temperature and low-pressure metamorphism yielded zircon U-Pb ages of 453–439 Ma in SW Japan (e.g., Kato and Saka, 2003; Osanai et al., 2014). Preliminary geochemical data show that the granodiorites in Santaki, Sankoko and Saganoseki are metaluminous calc-alkalic rocks, characterized by enrichment in LILEs, depletion in HFSEs (Figure 7), and initial Sr isotopic ratios as low as 0.7032–0.7037, which most likely suggests its derivation from juvenile crust in arc setting (e.g., Aoki et al., 2015; Kawaguchi et al., 2020). Thus it is concluded that, in Kyushu-Shikoku and Kii Peninsula, there developed the Ordo-Silurian (476–432 Ma) granitoids, gabbro and their equivalents in the juvenile arc environment (Figure 11d). In addition, the tuff overlying the Santaki igneous rocks were dated 427.2±7.6 Ma via zircon U-Pb dating method (Hada et al., 2000), suggesting that the volcanic activity might have continued until the late Silurian. All the above-mentioned data collectively indicate that SW Japan might be located to the easternmost of the South China continent, at which an Early Paleozoic (~480–420 Ma) subduction setting in SW Japan has been developed in relation to the Prototethyan southern branch ocean (Figures 10–12). It might be connected with the Sông Mã and Sanya zone, and constituted the northern segment of the Indo-Australie Andean-type active continental margin. Such an assemblage to the southeast of the South China continent resulted in the South China Kwangsian -I and II intracontinental orogenesis, signed by the Cambrian-Ordovician and Ordo-Silurian angular unconformities in southern and interior South China, respectively (Figures 11 and 12).

However, due to the junction of the Proto-Pacific and Prototethyan domains in SW Japan (Figures 11 and 12), further research is required to evaluate whether the Early Paleozoic assemblage in SW Japan was a part of the Terra Australis accretionary orogenesis. If so, the eastern South China Kwangsian intracontinental assemblage mechanically resembles the Alice Springs intracontinental convergence in Central Australia in response to the Terra Australis accretionary orogenesis (e.g., Raimondo et al., 2014). Nevertheless, the power mechanism of the eastern South China Kwangsian intracontinental orogenesis might be from the oceanic subduction to its southeast or the far-field impact of the plate-marginal consumption.

All the data conclusively allow us to delineate the Early Paleozoic spatial configuration among the Sibumasu, Simao, Indochina and South China blocks on the northern margin of the East Gondwana and the possible connection among the subduction zones, as shown in Figure 12. These fragments were juxtaposed successively along the East Gondwana northern margin to the east of Qiangtang during the early period of Early Paleozoic (Figures 10d and 12a). They constituted the segments of the *easterly-diachronous Andean-type* accretionary orogenesis from Nepal, NW India, to South Tibet, and then across the Sibumasu into Indochina blocks. To the east of the Qiangtang block, two branches of the Prototethyan Ocean were bifurcated, one of which went northward to the Yangtze northern margin and formed the Early Paleozoic Qinling Ocean that became the northern branch of the Prototethyan Ocean later. The northern branch closure and subsequent Yangtze-North China collision led to the formation of Early Paleozoic Qilian-Qinling orogenic belt and created the Prototethyan northern boundary (e.g., Dong et al., 2018; Li et al., 2018; Zhao et al., 2018). The other branch developed as the Yunxian-Menghai Ocean along the Sibumasu eastern margin, and the Tam Ky-Phouc Son Ocean to the Indochina Kontum massif, and the Ailaoshan-Sông Mã Prototetheyan branch to the northern Simao block, which subducted southerly beneath the Sibumasu, Kontum Indochina and Simao blocks. They jointly constituted the Prototethyan southern branch ocean. This branch might have extended easterly into the present Sanya-Osaka area to the southeast of the Cathaysian block (Figure 12). The southern branch ocean initially closed at ~485 Ma, and the North Indo-Australie Andean-type orogenesis in SW Yunnan and SE Asia ended at ~410 Ma. It is noteworthy that, during the Cambrian-Ordovician period, the Sanya-Osaka segment of the Prototethyan southern branch ocean might be *connected* with the northward extension of the Kuunga Ocean, separating NW Australia from India. The Prototethyan-related North Indo-Australie Andean-type orogenesis might overlap with the Proto-Pacific subduction-related Terra Australis accretionary orogenesis (Figure 12).

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