Correlation between South China and India and development of double rift systems in the South China-India Duo during late Neoproterozoic time

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Abstract

South China, India and their derivative terranes/blocks preserve a larger amount of similar magmatic and sedimentary records related to the tectonic transition from Rodinia to Gondwana. They provide crucial insights into not only the paleogeographic correlation between them but also the geodynamic mechanism for such a transition. Our new results together with published big data from these terranes/blocks point out that South China kept a linkage with India at least from the late Tonian (ca. 830 Ma) to Early Cambrian and formed the South China-India Duo located at the western margin of Rodinia. The identical magmatism and sedimentation reflect that double late Neoproterozoic rift systems in the South China-India Duo could have developed owing to the rollback of subducting oceanic slab beneath them, including an intracontinental rift (the Nanhua-Aravalli-Delhi rift) separating the Yangtze-Marwar from Cathaysia-Bundelkhand terranes and a contemporaneous intra-arc rift along the northern and western margins of the Yangtze Terrane, through the Marwar Terrane of western India, and then into the Seychelles and Madagascar terranes. Such an intra-arc rift is also the most feasible explanation for the common development of coeval arc-like and extension-related magmatic rocks and extensional sedimentary sequences on the western margin of the South China-India Duo and in Seychelles and Madagascar, and even other subduction zones.

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Abstract

South China, India and their derivative terranes/blocks preserve a larger amount of similar magmatic and sedimentary records related to the tectonic transition from Rodinia to Gondwana. They provide crucial insights into not only the paleogeographic correlation between them but also the geodynamic mechanism for such a transition. Our new results together with published big data from these terranes/blocks point out that South China kept a linkage with India at least from the late Tonian (ca. 830 Ma) to Early Cambrian and formed the South China-India Duo located at the western margin of Rodinia. The identical magmatism and sedimentation reflect that double late Neoproterozoic rift systems in the South China-India Duo could have developed owing to the rollback of subducting oceanic slab beneath them, including an intracontinental rift (the Nanhua-Aravalli-Delhi rift) separating the Yangtze-Marwar from Cathaysia-Bundelkhand terranes and a contemporaneous intra-arc rift along the northern and western margins of the Yangtze Terrane, through the Marwar Terrane of western India, and then into the Seychelles and Madagascar terranes. Such an intra-arc rift is also the most feasible explanation for the common development of coeval arc-like and extension-related magmatic rocks and extensional sedimentary sequences on the western margin of the South China-India Duo and in Seychelles and Madagascar, and even other subduction zones.

Key words: Detrital zircon U-Pb-Hf isotope, Neoproterozoic-Early Paleozoic sedimentary sequences, South China-India Duo, late Neoproterozoic rift systems, Proto-Tethys Ocean

1. Introduction

Supercontinent forms when nearly all continental blocks on earth collide with each other and assemble into a solely large landmass (Zhao et al., 2018a). Rodinia and Gondwana are the most important ones of supercontinents in Earth's history (Zhao et al., 2018a). Increasing lines of evidence including reliable geological, paleomagnetic and paleontological data have established that they formed ca. 1.00 Ga and ca. 0.55 Ga ago, respectively (e.g., Cawood et al., 2013, 2018, and references therein). Although the paleogeographic position of major continental blocks in Rodinia and Gondwana have been widely accepted (Cawood et al., 2018; Zhao et al., 2018a), the reconstructions of some microcontinents in Rodinia and Gondwana and their tectonic evolution during the transition from Rodinia to Gondwana remain unknown. In particular, South China and India, as two important continental blocks in Asia, have been documented to be involved in the tectonic evolution of both Rodinia and Gondwana based on magmatic, sedimentary and paleontological evidence (e.g., Cawood et al., 2013, 2018; Jiang et al., 2003; Metcalfe, 2013; Yang et al., 2004; Zhao et al., 2018b). Their paleogeographic position and correlation in Rodinia and Gondwana and their tectonic affinity are still the subject of debate (Cawood et al., 2013, 2018; Chen et al., 2021; Jiang et al., 2003; Metcalfe, 2013; Wang et al., 2017a, 2021; Yang et al., 2004; Yao et al., 2014; Zhao et al., 2018b). Additionally, the tectonic framework and geodynamic mechanism for the tectonic evolution of supercontinents particularly during the transition from Rodinia to Gondwana remain unresolved (Cawood et al., 2018; Li et al., 2002; Wang et al., 2017a; Zhao et al., 2018b). Fortunately, in recent years, a large number of data about Neoproterozoic-Early Paleozoic magmatic rocks and sedimentary sequences related to the tectonic evolution of these two landmasses in South China and India and even their derivative terranes/blocks have been published (Chen et al., 2021; Wang et al., 2017a, 2021; Yao et al., 2014; Zhao et al., 2018b). A combination and further analysis of these big data are crucial to decode the aforementioned issues.

In this contribution, we present new U-Pb and Lu-Hf isotopic analyses of detrital zircons of late Tonian to Ordovician sedimentary sequences from the Eastern Yidun subterrane of South China, and combined with other published big data from South China and other Gondwana- and Rodinia-derived continents, in order to re-evaluate the correlation between South China and India and decode their tectonic evolution during the transition from Rodinia to Gondwana. A new reconstruction model that South China was connected with India and formed the South China-India Duo during late Tonian-early Cambrian time is suggested. The breakup time of South China from Indian Gondwana after the Early Cambrian due to the opening of the Proto-Tethys Ocean is further constrained. Also, we propose the development of double late Neoproterozoic rift systems in the South China-India Duo, including an intra-arc rift along its western margin, and another intracontinental one (the Nanhua-Aravalli-Delhi rift) separating the Yangtze-Marwar from Cathaysia-Bundelkhand terranes in the interior of the South China-India Duo.

2. Geological background and samples

South China was formed by the amalgamation between the Yangtze Terrane to the northwest and the Cathaysia Terrane to the southeast along the Neoproterozoic Jiangnan fold belt (Cawood et al., 2018; Zhao et al., 2011). To its north is the North China Craton and to the southwest is the Indochina Block. It is bounded by the Yidun and Songpan-Ganzê terranes of the Tibetan Plateau to the northwest. The geological characteristics of the Yangtze and Cathaysia terranes have been summarized in detail by some authors (e.g., Cawood et al., 2013, 2018; Chen et al., 2021; Zhao et al., 2018b).

The Yidun Terrane is a microcontinent located between the Qiangtang and Songpan-Ganzê terranes, which is considered to be part of the Yangtze Terrane before the Mesozoic (BGMRSP, 1980, 1984). It is surrounded by two Paleo-Tethys suture zones, the Jinshajiang suture to the west and the Ganzê-Litang suture to the east (Fig. 1a, b; BGMRSP, 1984; Peng et al., 2014). To its southeast is the Yangtze Terrane, which is separated by the Longmenshan-Jinhe Fault (BGMRSP, 1984; Peng et al., 2014). Based on the tectono-stratigraphical distinction on the two flanks of the north-south-trending Xiangcheng-Geza Fault, the Yidun Terrane can be divided into the Western Yidun subterrane (also known as the Zhongza massif; Peng et al., 2014) and the Eastern Yidun subterrane (Fig. 1a, b; Peng et al., 2014).

The western subterrane consists mainly of greenschist to lower amphibolite facies Paleozoic meta-sedimentary rocks intercalated with minor meta-volcanics (BGMRSP, 1984). The eastern subterrane is dominated by Triassic volcano-clastic rocks with minor Neoproterozoic-Paleozoic sedimentary successions in the southeast (BGMRSP, 1984). The oldest strata are greenschist-amphibolite facies Neoproterozoic Qiasi Group exposed in the southeast region of the Eastern Yidun subterrane, comprising a suite of metamorphosed Neoproterozoic volcano-sedimentary succession that consists of meta-volcanic, schist, leptynite and marble (Fig. 1; BGMRSP, 1984). It can be divided into four segments from bottom to top based on its lithologic association characteristics (Fig. 1c, d; BGMRSP, 1984). Unconformably overlying the Qiasi Group is late Neoproterozoic (Ediacaran) sequences, comprised of sandstone, carbonate and dolostone (BGMRSP, 1984). These strata are in turn unconformably overlain by Early Cambrian carbonate intercalated with some siliciclastics (BGMRSP, 1984). Ordovician succession, including sandstone, siltstone and slate (Fig. 1 c, d; BGMRSP, 1984), unconformably overlies Lower Cambrian strata, and is in turn unconformably overlain by Early Silurian slate and silicalite. Above these strata are the Upper Paleozoic sedimentary rocks comprised of Devonian schist, marble and sandstone, Carboniferous-Upper Permian limestone, Upper Permian basalt and slate (BGMRSP, 1984). These Upper Paleozoic strata are unconformably overlain by the Mesozoic and Paleogene sedimentary rocks in some places (Fig. 1c; BGMRSP, 1984). In addition, voluminous Middle-Late Triassic (230-206 Ma), and minor amount of Permian, Cretaceous and Cenozoic igneous rocks are exposed in the Eastern Yidun subterrane (e.g., BGMRSP, 1984; Peng et al., 2014).

A total of five samples were collected for zircon U-Pb ages and Hf isotope analyses (Table 1 and Figs. 1 & 2). Two schist samples (10YD-93 and 10YD-97) were collected from the fourth and third segments of the Qiasi Group, respectively (Table 1 and Figs. 1 & 2). One sandstone sample (10YD-100) was collected from the Ediacaran Dengying Formation and a slate sample (10YD-102) and a schist sample (10YD-99) were collected from the Ordovician strata (Table 1 and Figs. 1 & 2).

3. Analytical methods

3.1 LA-ICP-MS zircon U-Pb dating

ca. 5 kg of each sample was crushed and milled, and then zircons were separated using heavy-liquid and magnetic methods at the Laboratory of the Geological Team of Hebei Province, China. Cathodoluminescence (CL) images were taken at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIG-CAS) for inspecting internal structures of individual zircons and for selecting positions for U-Pb and Lu-Hf isotope analyses. Detrital zircons of varying size and shape were selected randomly, leaving out grains with obvious cracks or inclusions.

In situ zircon U-Pb dating was carried out using an Agilent 7700x ICPMS coupled to a 193 nm ArF Excimer Laser ablation system (GeoLas 2005, Lambda Physik), housed at the Jupu analysis Lab, Nanjing of China. Analytical procedures were the same as those described by Liu et al. (2010). The frequency of laser system was 10 Hz. Gas flow rate of highly purified He as the carrier gas was 0.7 L/mn; auxiliary gas Ar was 1.13 L/mn. The spot diameter was 40 μm in size. Total acquisition time of one spot was 45 s. Zircon 91500 was used as external standard for

U-Pb dating, and was analyzed twice every 5 analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of 91500 (i.e., 2 zircon 91500 + 5 samples) (Liu et al., 2010). Preferred U-Th-Pb isotopic ratios used for 91500 are from Liu et al. (2010). Uncertainty of preferred values for the external standard 91500 was propagated to the ultimate results of the samples. Correction of common lead followed the method described by Liu et al. (2010). Data were processed with the ICPMSDataCal program (Liu et al., 2010). Uncertainties on individual analyses in data tables were reported at a 1σ level. Results were analyzed and plotted using Isoplot 3.0 (Ludwig, 2012). Zircon ages younger than 1000 Ma were based on $^{206}Pb/^{238}U$ ratios, and ages older than 1000 Ma were based on $^{207}Pb/^{206}Pb$ ratios. In this study, we excluded zircon age analyses with >10% discordance (Dickinson & Gehrels, 2009).

3.2 In-situ zircon Hf isotope analysis

After the LA-ICP-MS zircon U-Pb dating, zircon Lu-Hf isotope compositions were analyzed by a 193 nm Ar-F excimer laser ablation system (RESOlution M-50-LR) attached to a multi-collector ICPMS (Neptune Plus), at GIG-CAS. The Hf isotopes were obtained with a beam diameter of 45 μm, pulse rate of 6 Hz, energy density of 80 J/cm^2 and Ablation time was 29 s. Quality control was made by measuring zircon standard Penglai for the unknown samples during the analyses to evaluate the reliability of the analytical data, yielded weighted mean an average $^{176}Hf/^{177}Hf$ ratio of 0.282892 ± 0.000010 (1 standard deviation), which is consistent within errors with the reported values of 0.282906 ± 0.000010. In situ Hf isotope measurements were subsequently done on the same spots or the same age domains for age determinations of the concordant grains, as guided by CL images. The initial Hf isotopic ratios and crustal model ages were calculated using the dating results of the same spots.

4. Results

4.1 Zircon U-Pb geochronology

The LA-ICP-MS U-Pb dating results of zircons for the studied samples are listed in Table S1. Most analyses were plotted on or near the concordia curve (Fig. 3). The detrital zircon U-Pb ages from the Eastern Yidun subterrane in this study show different age distribution patterns with unimodal detrital zircon pattern for the Neoproterozoic samples but multimodal pattern for the Ordovician ones (Fig. 3).

Zircon grains from all the Neoproterozoic samples in the Eastern Yidun subterrane are primarily euhedral and partly subeuhedral. All of them show magmatic oscillatory zoning in CL images (Fig. S1). 278 of 280 analyses produced 90-100% concordant ages, which were considered to be available for the following discussion. They gave an age spectrum ranging from 960 Ma to 574 Ma, and each sample displays a similar unimodal pattern with a single major age population at 800-760 Ma

(Table S1 and Fig. 3). Only one older age of ca. 960 Ma is present in the sample 10YD-97 (Table S1 and Fig. 3).

Most of zircon crystals from the Ordovician samples in the Eastern Yidun subterrane are subeuhedral to subround while some grains are rounded. All the analyzed zircon grains show magmatic oscillatory zoning in CL images (Fig. S1). 163 out of 165 analyses are less than 10% discordance, which are available for the following discussion. The two Ordovician samples yielded U-Pb age varying from 3093 to 447 Ma. They share similar multimodal distribution patterns, with major age populations at 600-500 Ma and 860-700 Ma and a subordinate age group at 2500-2400 Ma (Fig. 3). One difference is that the schist sample (10YD-99) has an alternative Grenvillian age population at 1100-900 Ma (Fig. 3).

4.2 Zircon Hf isotopic compositions

A total of 230 analyses for these three Neoproterozoic samples of the Eastern Yidun subterrane exhibit a wide range of initial $^{176}Hf/^{177}Hf$ ratios from 0.282248 to 0.283031 (Table S2). Among them, 215 spots have positive $\varepsilon_{Hf}(t)$ values between +0.1 and +24.0 with T_{DM}^{C} ages at 1.57-0.77 Ga (Table S2 and Fig.4), compatible with those of the Neoproterozoic igneous rocks along the western and northern margins of the Yangtze Terrane (Zhao et al., 2011). Only two Neoproterozoic zircons gave slightly negative $\varepsilon_{Hf}(t)$ values of -2.1 and -1.2, respectively (Table S2 and Fig.4).

In the case of the Ordovician samples in the Eastern Yidun subterrane, a total of 75 analyses exhibit a wide range of initial $^{176}Hf/^{177}Hf$ ratios from 0.280824 to

0.282793, corresponding to large variations of $\varepsilon_{Hf}(t)$ values (-25.9 to +35.0), indicating a mixing products of the juvenile ($\varepsilon_{Hf}(t)>0$) and old ($\varepsilon_{Hf}(t)<0$) crustal rocks (Table S2 and Fig. 4). The main age group of 650-500 Ma have similar $\varepsilon_{Hf}(t)$ values (-25.0 to +6.1) with those of the magmatic rocks in the Kuunga Orogen (Zhu et al., 2011, and references therein), while the age cluster at 830-700 Ma yield similar $\varepsilon_{Hf}(t)$ values (-13.4 to +16.5) to those of the coeval igneous rocks in the Jiangnan Orogen in South China (Fig. 4; Yao et al., 2019). The 1100-900 Ma detrital zircons from the schist sample (10YD-99) show $\varepsilon_{Hf}(t)$ values ranging from -8.5 to +13.2, compatible with those in the Eastern Ghats Orogen and CITZ (Bhowmik et al., 2012; Zhu et al., 2011; and references therein). Minor ca. 2400 Ma zircons have variable $\varepsilon_{Hf}(t)$ values between -11.4 and +35.0.

5. Discussion

5.1. Sedimentary provenance

By comparison, a unimodal age distribution pattern of the Neoproterozoic schists in the Eastern Yidun subterrane similar to those in the western Yangtze Terrane reflect a common provenance for the late Tonian-Ediacaran strata (Fig. 5). Owing to the absence of the Neoproterozoic moderate-felsic magmatic rocks within the Yidun Terrane (Tian et al., 2020), these Neoproterozoic detrital materials cannot be sourced from the interior of this terrane. In contrast, voluminous 0.86-0.70 Ga igneous rocks are exposed along the northern and western margins of the Yangtze Terrane, such as the Neoproterozoic Panxi-Hannan arc (Zhao et al., 2018b; Zhou et al., 2006). Moreover, the Hf isotopic compositions of detrital zircons from these Neoproterozoic samples are in a good agreement with those of magmatic zircons of the Neoproterozoic igneous rocks from the Panxi-Hannan arc (Fig. 4). In addition, these detrital zircons of our Neoproterozoic samples are euhedral with magmatic zoning (Fig. S1), indicating a short-distance transport from its provenance. Hence, we suggest that the Neoproterozoic detritus in the Eastern Yidun subterrane could be mainly sourced from the coeval igneous rocks in the Panxi-Hannan arc along the western and northern margins of the Yangtze Terrane.

In the case of the Ordovician samples, they show a multimodal pattern distinguishable from the unimodal one of the Neoproterozoic samples (Fig. 3). Except for a similar major age of ca. 0.83-0.70 Ga to those Neoproterozoic samples, for instance, they possess main age groups at ca. 0.65-0.50 Ga, ca. 1.00-0.90 Ga and a subordinate age group at ca. 2.40 Ga (Fig. 3). Alternatively, the 0.83-0.70 Ga zircons of the Ordovician samples have distinguishable $\varepsilon_{Hf}(t)$ values (-16.1 to +15.7) from those of the Neoproterozoic samples (Table S2), but are similar to those of the coeval igneous rocks in the Jiangnan Orogen in South China as mentioned before (Fig.4; Yao et al., 2019). Taken together, it is obvious that the 0.83-0.70 Ga zircons of the Ordovician samples could not originate mainly from the erosion of the Panxi-Hannan arc magmatic rocks in the western Yangtze Terrane. In contrast, it is possible that most of the 0.83-0.70 Ga zircons in the Ordovician sediments in the Eastern Yidun subterrane were derived from the Jiangnan Orogen. Concerning the 1.00-0.90 Ga and

0.65-0.50 Ga detrital zircons, they were impossibly sourced from the coeval igneous rocks in the interior of South China due to the absence of synchronous magmatic rocks within South China. Therefore, they could be exotic by a long distance transport or recycled from the old strata in South China (Cawood et al., 2018), which are consistent with the subrounded and rounded attributes of these detrital zircons (Fig.S1). Indeed, the Ordovician sediments in the Eastern Yidun subterrane share a similar age spectrum and zircon Hf isotopic compositions to the Cambrian unit in the western Yangtze Terrane (Chen et al., 2021), indicating that the former could be primarily derived from the recycling of the latter, although their ultimate sources include the Eastern Ghats-Rayner Complex and the Kuunga Orogen located in the eastern India region, and the Jiangnan Orogen in South China.

5.2. Tectonic link between South China and India

Two contrasting reconstruction models have been proposed for the paleogeographic position of South China in Rodinia: an internal location within the Rodinia supercontinent versus an external setting along the margin of the Rodinia supercontinent (e.g., Cawood et al., 2018; Li et al., 1999, and references therein; Zhao & Cawood, 1999). For the internal model, South China was located between the Laurentia and Australia blocks (e.g., Li et al., 1999; Li et al., 2002). In the peripheral model, South China was attached to India in the Early to Mid-Neoproterozoic (e.g., Cawood et al., 2018; Zhao et al., 2018b).

In fact, increasing lines of evidence including magmatic, paleomagnetic, and sedimentary data (e.g., Cawood et al., 2018; Chen et al., 2021; Gregory et al., 2009; Wang et al., 2017a, 2021; Yang et al., 2004; Yao et al., 2014; Zhao et al., 2018b), have demonstrated that South China could be located to the periphery of Rodinia rather than an intra-cratonic position during Neoproterozoic time. Nonetheless, the spatio-temporal evolution of South China within these peripheral models from Rodinia to Gondwana by different researchers is also different. For example, based on the paleomagnetic studies on the Middle Cambrian sediments from the western Yangtze Terrane, Yang et al. (2004) proposed that South China was connected with NW Australia during latest Proterozoic and Early Paleozoic times, until its breakup from Australia in the Middle Devonian. In contrast, by comparison of detrital zircon age spectra between the Gondwana-derived blocks/terranes, Yao et al. (2014) suggested that the Cathaysia side of South China was closely linked with the northern margin of India (the Himalaya region) by the Ediacaran-Cambrian collision between South China and India and persisted until the opening of the Paleo-Tethys Ocean during Devonian time. In recent years, by comparisons of magmatism, sedimentation, bio-stratigraphic affinity and paleomagnetic pole of South China with India and Australia, some researchers concluded that South China was most likely close to northern India during Neoproterozoic and even Early Cambrian times but was progressively separating from the latter, and rotating and migrating along the Gondwana margin toward northeastern India and NW Australia during latest Ediacaran or Early Cambrian time (e.g., Chen et al., 2021; Jiang et al., 2003; Wang et al., 2021).

However, keeping a consistently main age group from the Tonian to Cambrian strata on the Cathaysia Terrane and on the western Yangtze Terrane although their main age groups are different, such as ca. 960 Ma for the former and ca. 800 Ma for the latter, respectively (Fig. 5; Wang et al., 2021; Yao et al., 2014), indicate that their detrital provenances did not change with time. In other words, they each shared a common source from the Tonian to Cambrian although the provenance is different between them. This, in turn, hints that the tectonic setting for the Tonian to Cambrian sedimentation in these two terranes did not change. Accordingly, it is unlikely that the Yangtze Terrane commenced to rift from northwestern India since the late Tonian and South China was migrating towards NW Australia. Moreover, the absence of diagnostic ca. 1170 Ma age group of NW Australia in the Tonian to Early Paleozoic strata in the Cathaysia Terrane (Fig. 5; e.g., Wang et al., 2010; Yao et al., 2014) also argues against a close proximity to NW Australia during Tonian to Early Paleozoic time. By contrast, the presence of a predominant age population of detrital zircons at ca. 960 Ma from the Tonian to Cambrian strata in the Cathaysia Terrane (Fig. 5; e.g., Wang et al., 2010; Yao et al., 2014), suggests that a common northern Indian (the Tethyan sequences) detrital provenance had continuously provided the detritus input into the Cathaysia Terrane from the Tonian to Cambrian. In fact, the similarities in facies assemblages of the late Neoproterozoic-Early Cambrian sedimentary rocks between South China and India also lend strong support to this proposition. For example, the Yangtze Terrane of South China and NW India share similar late Tonian rift-related siliciclastic-volcanic successions, Cryogenian glaciogenic diamictite successions, Ediacaran carbonate successions, Early Cambrian phosphorite and clastic successions (Jiang et al., 2003). Correspondingly, the Cathaysia Terrane and eastern India region contain similar Tonian siliciclastics, Cryogenian sandstones and diamictites, Ediacaran-Cambrian siliciclastics (Wang & Li, 2003; Wang et al., 2021). As a consequence, we propose that South China should keep a close linkage with India and form the South China-India Duo at least during late Tonian to Cambrian time as the connection model proposed by Cawood et al. (2018) and Zhao et al. (2018b). It was finally separated from Indian Gondwana likely after the Early Cambrian due to the opening of Proto-Tethys Ocean (ca. 510 Ma) rather than Paleo-Tethys Ocean after the Devonian (also see discussion in Section 5.4).

5.3. Double late Neoproterozoic rift systems developed in the South China-India Duo

Increasing lines of evidence, such as comparable Neoproterozoic rift-related magmatism and sedimentation between the Nanhua tectonic zone in South China and the Aravalli-Delhi fold belt in NW India, illustrate the development of a Neoproterozoic intracontinental linear rift basin in the interior of the South China-India Duo (Fig. 6; Wang & Li, 2003; Wang et al., 2017a; Zhao et al., 2018b, and references therein). For example, from a sedimentation perspective, some coeval extension-related basins with similar lithological assemblages and sedimentary sequences had developed in the Sindreth and Punagarh basins along the western margin of the Aravalli-Dehli fold belt in NW India (Jiang et al., 2003; Zhao et al., 2018b, and references therein), the unnamed basin in the Lesser Himalaya north of the Aravalli-Dehli fold belt (i.e., the Jaunsar-Simla and Blaini sequences; Jiang et al., 2003; Zhao et al., 2018b, and references therein), and the Nanhua basin in South China (Wang & Li, 2003; Zhao et al., 2018b). In addition, the late Tonian-Ediacaran sedimentary sequences in the Nanhua and Aravalli-Dehli basins share similar detrital zircon age patterns and overlapping $\varepsilon_{Hf}(t)$ values (Fig. 5), which also favors the idea of depositional continuity among the Nanhua-Aravalli-Dehli basin at that time. Besides, similar Neoproterozoic rift-related magmatism, including the bimodal magmatic rocks and A-type granites that are generally produced in extension-related regimes, has been identified in the Malani Igneous Suite located to the western margin of the NE-trending Aravalli-Dehli fold belt of NW India (e.g., Wang et al., 2017a; Zhao et al., 2018b; and references therein) and the Nanhua basin in South China (e.g., Deng et al., 2016; Li et al., 2021; Wang & Li, 2003). More importantly, the recognition of Late Neoproterozoic lower $\delta^{18}O$ magmatic zircons (<5‰) than that of mantle values (5.3 ± 0.6‰; Valley et al., 1998) in these two aforementioned belts (Fig. 6; Li et al., 2021; Wang et al., 2017a; Zhang et al., 2020a; Zhao et al., 2018b; and references therein), indicates the development of a synchronous rifting in NW India and the interior of South China as pointed out by Zhao et al. (2018b).

In fact, an alternative Neoproterozoic extension-related tectonic zone had also developed simultaneously along the northern and western margins of the Yangtze Terrane of South China. For instance, the occurrence of some Neoproterozoic extension-related igneous rocks on the western margin of the Yangtze Terrane, including the Tiechuanshan (ca. 820 Ma) and Suxiong (ca. 800 Ma) bimodal volcanic rocks, and the Daxiangling (ca. 816 Ma), and Tiechuanshan, Huangguan and Mianning (780 Ma), and Panzhihua (750 Ma) A-type granites, and low-$\delta^{18}O$ magmatic rocks (Fig. 6; e.g., Li et al., 2002; Wu et al., 2020; and references therein), suggests an extensional setting at that time. Although a mantle plume setting has been invoked to account for such extension-related magmatism (Li et al., 2002; Wang et al., 2007a), this scenario fails to explain the presence of more voluminous 820-770 Ma magmatic rocks featured by typical arc geochemical signature in the Panxi-Hannan region on the northern and western Yangtze Terrane (Zhao et al., 2011; Zhao et al., 2018b; and references therein). In contrast, a prolonged subduction-related arc environment as proposed by some authors (Cawood et al., 2018; Zhao et al., 2018b; Zhou et al., 2006; and references therein) can have also developed at 820-770 Ma. Moreover, the arc-like geochemical characteristics and high proportion of younger detrital zircon age population (CA-DA<100 Ma in 30% of the zircon population; Fig. 7) of the Neoproterozoic metasedimentary samples from the Yidun Terrane also indicated the deposition in a convergent setting basin (Cawood et al., 2012; Tian et al., 2020). In this respect, a back-arc environment is likely a plausible interpretation for the coexistence of arc- and extension-type magmatic rocks on the western and northern margins of the Yangtze Terrane, as assumed recently by Luo et al. (2018). However, such a model is incompatible with their magmatic pattern dominated by arc-type magmatic rocks with some extension-related rocks in this region as mentioned before (Cawood et al., 2018; Zhao et al., 2018b). In other words, these Neoproterozoic arc-type magmatic rocks should represent the important component of simultaneous continental arc. Moreover, considering that a huge thickness of extension-related late Neoproterozoic volcaniclastic sediments (> 5 km) coexist with synchronous magmatic rocks on the northern and western margins of the Yangtze Terrane and the southeastern margin of the Ganzê and Yidun terranes (BGMRSP, 1984), we propose that an intra-arc rifting is the most feasible explanation for such a coupling of magmatism and sedimentation. In fact, intra-arc rifting has been established in different subduction zones, such as northeast Japan of west Pacific (Nakajima, 2013), and the Anglona region of northwestern Sardinia, Italy (Sowerbutts, 2000). In particular, the magmatic association and sedimentary pattern on the northern and western margins of the Yangtze Terrane are similar to those in the intra-arc rift basin in the Anglona region of northwestern Sardinia, Italy (Sowerbutts, 2000).

As the important parts of the Neoproterozoic subduction system on the western margin of Rodinia (e.g., Cawood et al., 2018; Wang et al., 2021; Zhao et al., 2018b), the coexistence of coeval extension-related magmatic rocks and sedimentary basins together with a large number of subduction-related arc-type igneous rocks in Madagascar and Seychelles likewise indicates the development of an intra-arc rifting at that time, resembling those on the western and northern margins of the Yangtze Terrane as stated above. For instance, the recognition of some mafic-ultramafic plutons with layered Fe-Ti-V oxide mineralization, A-type granitoids with a strongly alkaline composition and bimodal magmatic suite in the Imorona-Itsindro Suite of central Madagascar (Archibald et al., 2017; Nédélec et al., 2016; Zhou et al., 2018a; and references therein), coupled with the same extensional structural signature between the ca. 790 Ma Imorona-Itsindro rocks and their country rocks (Nédélec et al., 2016, and references therein), has been recently interpreted as the products of continental rifting by Zhou et al. (2018a). Furthermore, from a variation of isotopic composition perspective, especially for zircon Hf and O isotopes of the 850-750 Ma magmatic rocks in the central Madagascar, Zhou et al. (2018a) believed that synchronous continental rifting had been involved in their petrogenesis. On the other hand, these central Madagascar rocks are dominated by calc-alkaline series and geochemically show an affinity to volcanic or continental arc magmatic rocks, most researchers ascribed their generation to the results of prolonged Andean-like arc magmatism (Archibald et al., 2017; Handke et al., 1999; Kröner et al. 2000; Tucker et al. 1999b). In Seychelles, the 810-700 Ma magmatic rocks also display the coupling of a typical Andean-type arc and rift-type (low-$\delta^{18}O$ granites) geochemical signatures (e.g., Ashwal et al., 2002, and references therein). Taken together, we propose that a late Neoproterozoic intra-arc rift system could have developed along the northern and western margins of the Yangtze Terrane, through the Marwar Terrane of western India, and then into Seychelles and Madagascar, although such lines of evidence from western India are still absent so far (Fig. 6). Such an intra-arc rift system along the western margin of the South China-India Duo is different from the contemporaneous intracontinental one (the Nanhua-Aravalli-Delhi rift system) within it (Fig. 6). Moreover, it can also account for the contradiction about the common presence of coeval arc-type and extension-related magmatic rocks coupled with some extension-related sedimentation in the same area.

The most plausible mechanism responsible for the development of such double synchronous rift systems should be attributed to the rollback of subducting oceanic slab beneath the South China-India Duo (Fig. 6), which would result in the asthenospheric upwelling and subsequent lithospheric extension at that time. As the old suture belts, the Jiangnan fold belt between the Yangtze and Cathaysia terranes in South China (Zhao et al., 2011) and the Aravalli-Dehli fold belt between the Marwar and Bundelkhand terranes in NW India (Zhao et al., 2018b) are the most ideal areas to produce lithospheric extension. As a result, it is the most effective mechanism to induce an intracontinental rifting. An alternative region apt to trigger lithospheric extension is the continental arc, especially the intra-arc where arc magmatism develops frequently and trans-lithospheric faults widely occur. Such a scenario can also be an important mechanism for the fragmentation of some micro-continents/terranes/blocks from a big continent by the intra-arc rifting.

5.4. Implication for breakup of South China from Gondwana

Different researchers have proposed different breakup times for South China from Gondwana. For example, earlier studies suggested the separating time from the Early Cambrian to Silurian in light of the variation of biogeography and stratigraphy in South China (Jiang et al., 2003, and references therein). Subsequently, considering the opening of Paleo-Tethys Ocean between the South China and Indochina blocks, most workers believed that South China had broken up from Gondwana in the Devonian (e.g., Cawood et al., 2013; Chen et al., 2021; Metcalfe, 2013; Wang et al., 2021). The critical evidence is the dating results of the remnant oceanic components, the oldest plagiogranites of which at Shuanggou from the Jinshajiang-Ailaoshan Paleo-Tethys suture yielded zircon U-Pb ages of ca. 383-376 Ma (Jian et al., 2009). More recently, by comparison of the Neoproterozoic to Early Paleozoic detrital zircon age spectra of South China with India and Australia, Wang et al. (2021) and Chen et al. (2021) proposed the initial separation time of South China from NW India in the Cryogenian and Early Cambrian, respectively. Moreover, based on the opening of Paleo-Tethys Ocean, they both concluded that South China should have finally drifted away from the northern margin of Australian Gondwana in the Devonian (Chen et al., 2021; Wang et al., 2021).

Regardless of how South China broke up from Gondwana, all the views ignore a crucial fact that the Proto-Tethys Ocean between South China and other Gondwana-derived blocks had also developed in the Early Paleozoic. The opening of the Proto-Tethys Ocean should have ever led to the separation of South China from northern Gondwana. For instance, the Early Paleozoic oceanic relics, including 477-460 Ma MORB-type clinopyroxenite, gabbro and amphibolite, and 519-502 Ma plagiogranites in the Tam Ky-Phuoc Son suture of Vietnam (Gardner et al., 2017; Nguyen et al., 2019, and references therein), indicate the presence of an Early Paleozoic Ocean between the South China and Indochina blocks or South

China-northern Indochina and southern Indochina blocks (Faure et al., 2018; Nguyen et al., 2019). On the other hand, another Proto-Tethys Ocean (518-438 Ma) between the South Qiangtang-Baoshan and North Qiangtang-Indochina terranes has been also documented in recent years (e.g., Hu et al., 2014; Wu, 2013). In particular, the identification of the Cambrian ophiolites (ca. 517-490 Ma; Hu et al., 2014; Wu, 2013) implies the development of a Tethys Ocean at least in the Middle Cambrian. In this regard, it is suggested that the Indochina Block had rifted away from the northern margin of Gondwana in the Middle Cambrian-Early Silurian interval. It is, in turn, the most plausible to infer that South China had been ever separated from the northern Gondwana at least from the Middle Cambrian to Early Silurian (Fig. 8; Liu et al., 2020a).

Whether South China had been assembled together with northern Gondwana by continent-continent collision similar to the collision between the South China and Indochina blocks in the Late Silurian remains unknown. Although Zhang et al. (2014) proposed a continent-continent collision time at 427-422 Ma based on the study of high-pressure basic granulites in the Central Qiangtang of Tibet, the identification of coeval (438±11 Ma) oceanic cumulate gabbro in the same ophiolitic complex belt of central Qiangtang likely indicates that the Early Paleozoic Proto-Tethys Ocean had not been closed (Wu, 2013). In fact, no age-equivalent collision-related records have been discovered so far in the Changning-Menglian ophiolite belt that represents the southern continuation of the central Qiangtang Proto-Tethys Ocean. More importantly, the identification of the Early and Late Paleozoic oceanic OIB-type mafic rocks that had commonly experienced a same Late Triassic ultrahigh-pressure metamorphism (Fan et al., 2015), indicates that the Proto-Tethys Ocean could have developed persistently from the Early Paleozoic to the end of the Paleozoic (Liu et al., 2020a, and references therein). Therefore, it is most likely that the Central Qiangtang high-pressure granulites within Tibet (Zhang et al., 2014) could be the products of Early Paleozoic arc-continent collision during the tectonic evolution of a single Proto- and Paleo-Tethys Ocean. Combing with all data (Chen et al., 2021, and references therein), we propose that the South China and Indochina blocks were separated from Indian Gondwana after the Early Cambrian and were not welded with Gondwana again, although they were likely amalgamated together during Late Silurian time (Faure et al., 2018; Nguyen et al., 2019) until the opening of the Paleo-Tethys Ocean between them (Jian et al., 2009).

6. Conclusions

Our new zircon U-Pb dating and Hf isotope analysis for the Neoproterozoic-Early Paleozoic (meta-) sedimentary sequences from the Eastern Yidun subterrane that belongs to part of the Yangtze Terrane of South China, coupled with a detailed compilation of big data published from South China, India and some blocks/terranes separated from them, can draw the following conclusions:

(1) The Neoproterozoic sediments in the Eastern Yidun subterrane were sourced mainly from the Panxi-Hannan magmatic arc on the northern and western margins of

the Yangtze Terrane while the Ordovician sequences were recycled from the Cambrian strata in the western Yangtze Terrane.

(2) South China kept a connection with India and formed the South China-India Duo located at northwestern margin of Rodinia during late Tonian (ca. 800 Ma) to Early Cambrian time.

(3) Double late Neoproterozoic rift systems had developed in the South China-India Duo owing to the rollback of subducting oceanic slab beneath it, including an intra-arc rift along the northern and western margins of the Yangtze Terrane, through the Marwar Terrane of western India, and then into the Seychelles and Madagascar, and another coeval intracontinental one (the Nanhua-Aravalli-Delhi rift) separating the Yangtze-Marwar from Cathaysia-Bundelkhand terranes within the interior of the South China-India Duo.

(4) South China was finally separated from northern India during Middle Cambrian-Ordovician time due to the opening of the Proto-Tethys Ocean (ca. 510 Ma) but was not welded with Gondwana again.

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Captions

Table 1. Location and stratigraphic information of samples analyzed

Figure 1. Simplified geological maps of (a) the Tibetan Plateau (after Tian et al., 2020), (b) the Yidun Terrane (after Peng et al., 2014), (c) the Gongling region of the Eastern Yidun subterrane (after BGMRSP, 1980, 1984) and (d) the Cryogenian-Ordovician strata and samples in the Gongling region (after BGMRSP, 1980, 1984). Abbreviations: ADFB, Aravalli-Delhi fold belt; CITZ, Central Indian tectonic zone; EGB, East Ghats belt; EYD, Eastern Yidun subterrane; WYD, Western Yidun subterrane.

Figure 2. Photographs of the representative (meta-)sedimentary samples from the Eastern Yidun subterrane. (a and b) the schist samples, (c) the sandstone sample, and (d) the slate sample. Abbreviations: Qtz, quartz; Pl, plagioclase; Mca, mica.

Figure 3. Concordia and detrital zircon age histogram-probability density distribution diagrams of the Neoproterozoic-Ordovician samples from the Eastern Yidun subterrane.

Figure 4. Plots of zircon $\varepsilon_{Hf}(t)$ versus U-Pb age of the Neoproterozoic (a) and Ordovician (b) detrital sediments in the Eastern Yidun subterrane. The detrital zircons $\varepsilon_{Hf}(t)$ data from the Yidun terrane (this study and Tian et al., 2020). The igneous zircons $\varepsilon_{Hf}(t)$ values of the Panxi-Hannan arc (data sources: Ao et al., 2019; Li et al., 2018; Qi & Zhao, 2020; Zhao et al., 2008a, 2010, 2017; Zhao et al., 2008b; Zhu et al., 2019a); The igneous zircons $\varepsilon_{Hf}(t)$ values of the Jiangnan Orogen

(data sources: Yao et al., 2019, and references therein).

Figure 5. Detrital zircon age distributions for late Tonian to Ordovician rocks from Yidun, South China, India and Australia terranes. Compilation of zircon age distribution of Neoproterozoic-Early Paleozoic sedimentary rocks from (A1-3) the Yidun terrane (This study and Tian et al., 2020), (B1-5) western Yangtze terrane (This study and Chen et al., 2016, 2018, 2021; Han et al., 2017; Hofmann et al., 2016; Liu et al., 2019c; Liu et al., 2020b; Luo et al., 2020; Sun et al., 2008, 2009; Tian et al., 2020; Wang et al., 2012a; Wang et al., 2014; Xia et al., 2016; Yuan et al., 2017; Zhang et al., 2019b; Zhao et al., 2021), (C1-5) the Nanhua basin (Cui et al., 2015; He et al., 2020; Liu et al., 2019a; Liu et al., 2019b; Ma et al., 2019; Sun et al., 2018; Qi et al., 2018; Wang et al., 2012b, 2013a; Wang et al., 2007b; Wang et al., 2017b; Wang et al., 2018a; Yan et al., 2019; Yang et al., 2015; Zhang et al., 2019a; Zhang et al., 2020b; Zhao et al., 2018c; Zhou et al., 2018b; Zhu et al., 2019b), (D1-5) the Cathaysia terrane (Qi et al., 2018, 2020; Wang et al., 2010; Wang et al., 2012b; Wang et al., 2015; Wang et al., 2018a; Wang et al., 2018b; Wang et al., 2018c; Wu et al., 2010; Xiang & Shu, 2010; Xiong et al., 2019; Xu et al., 2013, 2014; Xue et al., 2019; Yan et al., 2015; Yang & Jiang, 2019; Yao et al., 2011; Yao et al., 2014, 2015; Yu et al., 2010; Zhang et al., 2018; Zhou et al., 2018b), (E1-3) the western India terrane (Hughes et al., 2019; Lan et al., 2020; Malone et al., 2008; McKenzie et al., 2013; Myrow et al., 2010; Qasim et al., 2018; Turner et al., 2014; Wang et al., 2019a), (F1-5) the Aravalli-Delhi basin (DeCelles et al., 2000; Gehrels et al., 2006; Hofmann et al., 2011; Malone et al., 2008; Mukherjee et al., 2019; Myrow et al., 2010), (G1-5) the eastern India terrane (DeCelles et al., 2000; Gehrels et al., 2006, 2011; Hughes et al., 2011; Lan et al., 2020; Long et al., 2010; Malone et al., 2008; Mckenzie et al., 2011;

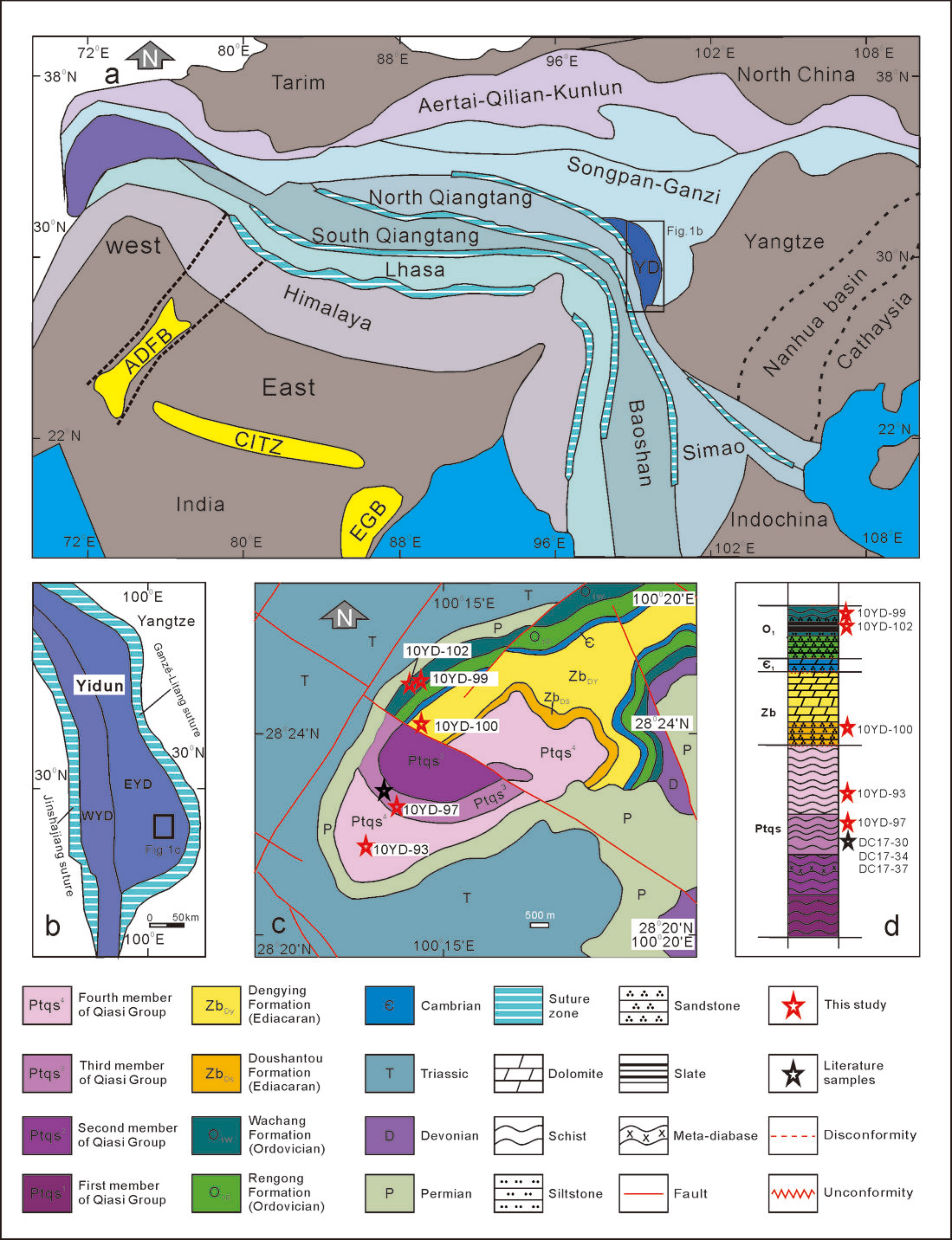
McQuarrie et al., 2013; Myrow et al., 2010; Turner et al., 2014), (H1-5) the Australia terrane (Haines et al., 2016; Johnson et al., 2016; Keemana et al., 2020; Mulder et al., 2020; Verdel et al., 2021).

Figure 6. Proposed tectonic framework and palaeogeographic position for South China, India, Seychelles and Madagascar in Rodinia during the Neoproterozoic (after Cawood et al., 2018; ; Wang et al., 2017a, 2021; Zhao et al., 2018b). Abbreviation: YD, Yidun Terrane. The Neoproterozoic igneous zircons $\varepsilon_{Hf}(t)$ and $\delta^{18}O$ data of the Madagascar terrane from (Armistead et al., 2019; Zhou et al., 2015, 2017); of the Seychelles terrane from (Harris & Ashwal, 2002; Shellnutt et al., 2020; Zhou et al., 2020); of the NW India from (Wang et al., 2017a); of the western Yangzte terrane from (Jiang et al., 2020; Qi & Zhao, 2020; Wu et al., 2020; Yang et al., 2016; Zou et al., 2020); of the Aravalli-Nanhua rift basin from (Huang et al., 2018; Wang et al., 2011, 2012c; Yuan et al., 2021; Zhao et al., 2018b).

Figure 7. Depositional setting of the Cryogenian Qiasi Group in the Eastern Yidun subterrane as inferred by discrimination plot of cumulative proportions vs. CA-DA of analyzed detrital zircons (after Cawood et al., 2012). Data are compiled from this study and Tian et al. (2020).

Figure 8. Tentative tectonic reconstruction models of South China (including the Yidun Terrane) along with other ambient terranes in Gondwana during Late Ediacaran-Early Cambrian (A) and Middle Cambrian-Early Ordovician (B) times (after Zhao et al., 2018a). Abbreviations: SC, South China; NC, North China.

Figure 1.



a
N
Tarim
North China
Aertai-Qilian-Kunlun
Songpan-Ganzi
North Qiangtang
South Qiangtang
Lhasa
Himalaya
west
East
India
ADFB
CITZ
EGB
YD
Fig.1b
Yangtze
Nanhua basin
Cathaysia
Baoshan
Simao
Indochina
b
Yidun
Yangtze
Ganzê-Litang suture
Jinshajiang suture
EYD
WYD
Fig.1c
0 50km
c
10YD-102
10YD-99
10YD-100
10YD-97
10YD-93
Ptqs2
Ptqs3
Ptqs4
ZbDY
ZbDs
500 m
d
O1
Є1
Zb
Ptqs
DC17-30
DC17-34
DC17-37
Fourth member of Qiasi Group
Third member of Qiasi Group
Second member of Qiasi Group
First member of Qiasi Group
Dengying Formation (Ediacaran)
Doushantou Formation (Ediacaran)
Wachang Formation (Ordovician)
Rengong Formation (Ordovician)
Cambrian
Triassic
Devonian
Permian
Suture zone
Dolomite
Schist
Siltstone
Sandstone
Slate
Meta-diabase
Fault
This study
Literature samples
Disconformity
Unconformity

Figure 2.

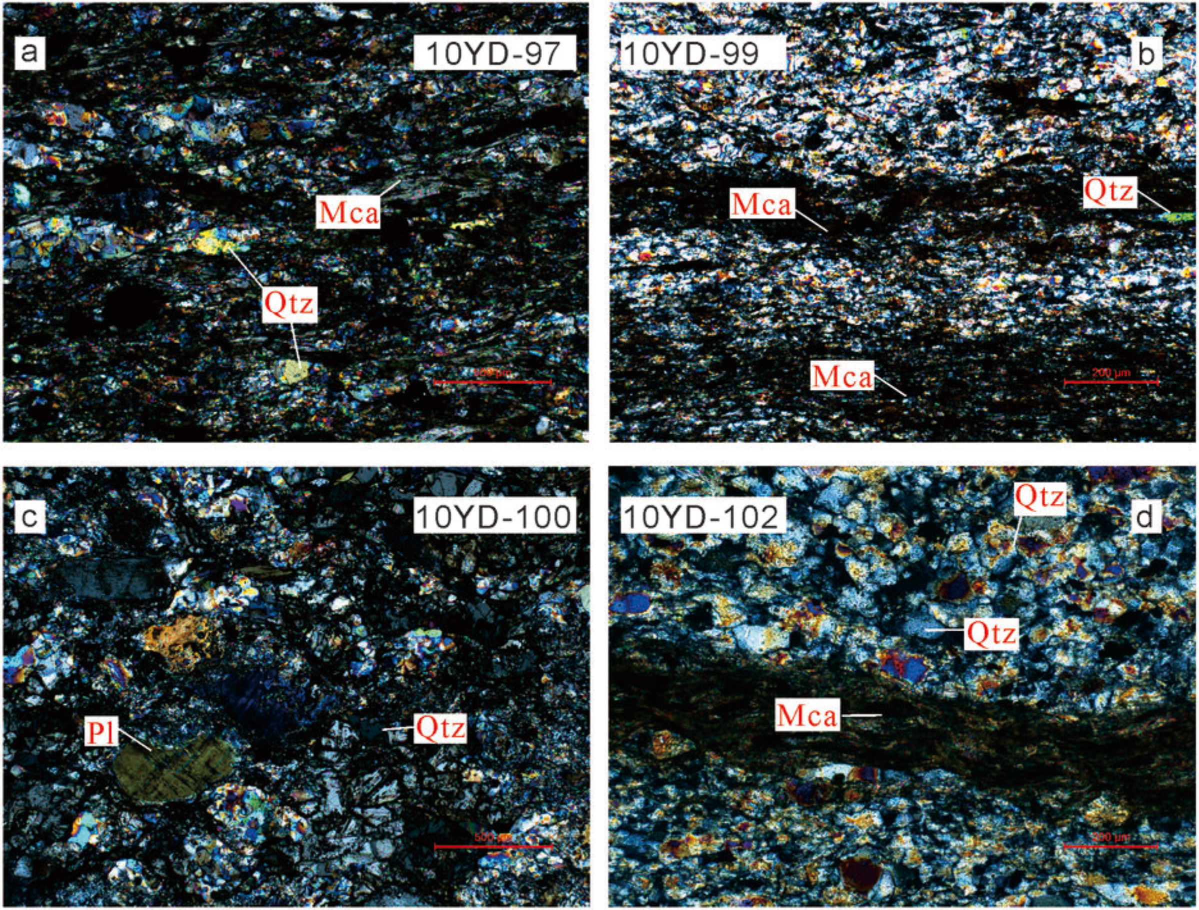
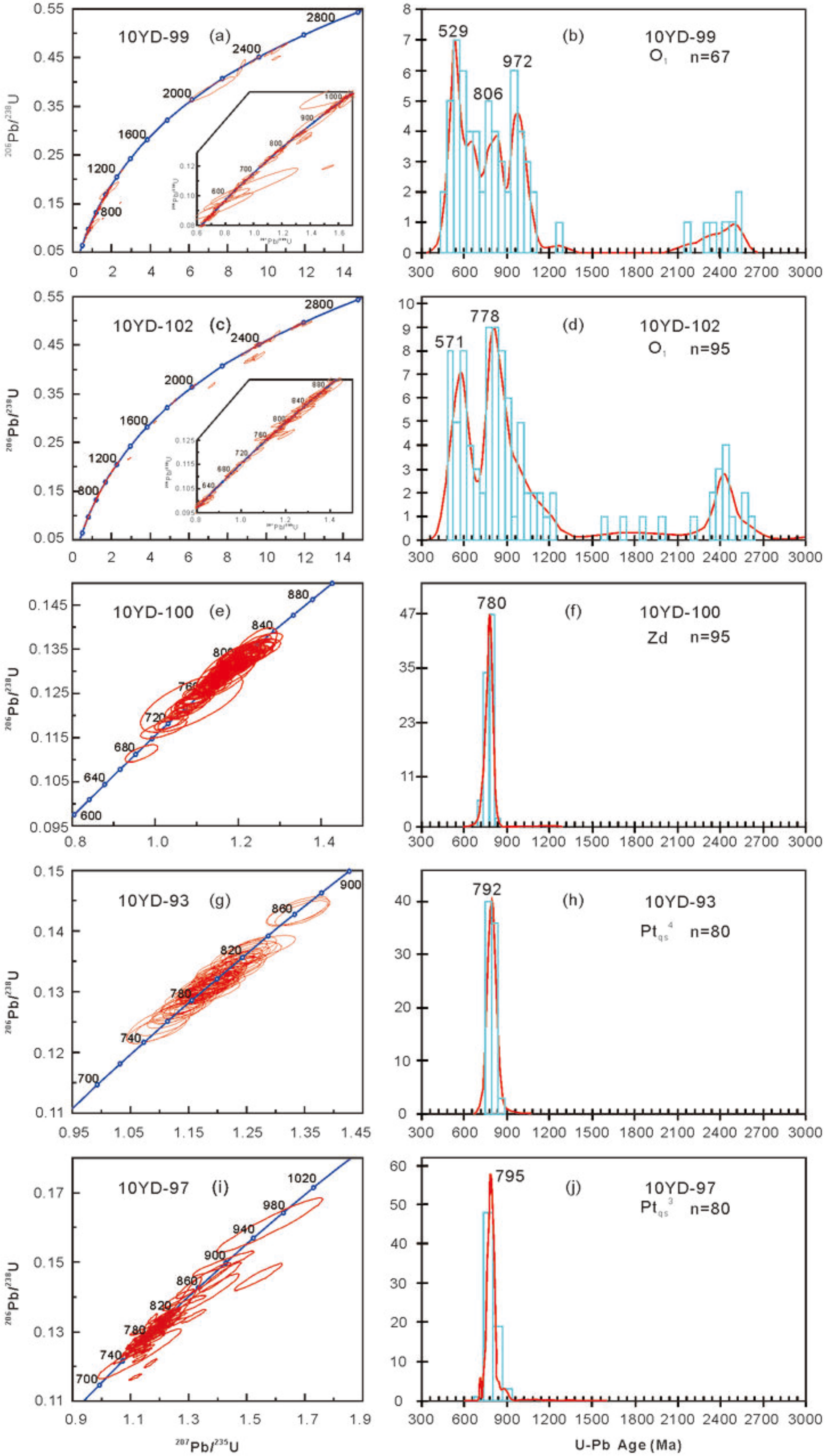
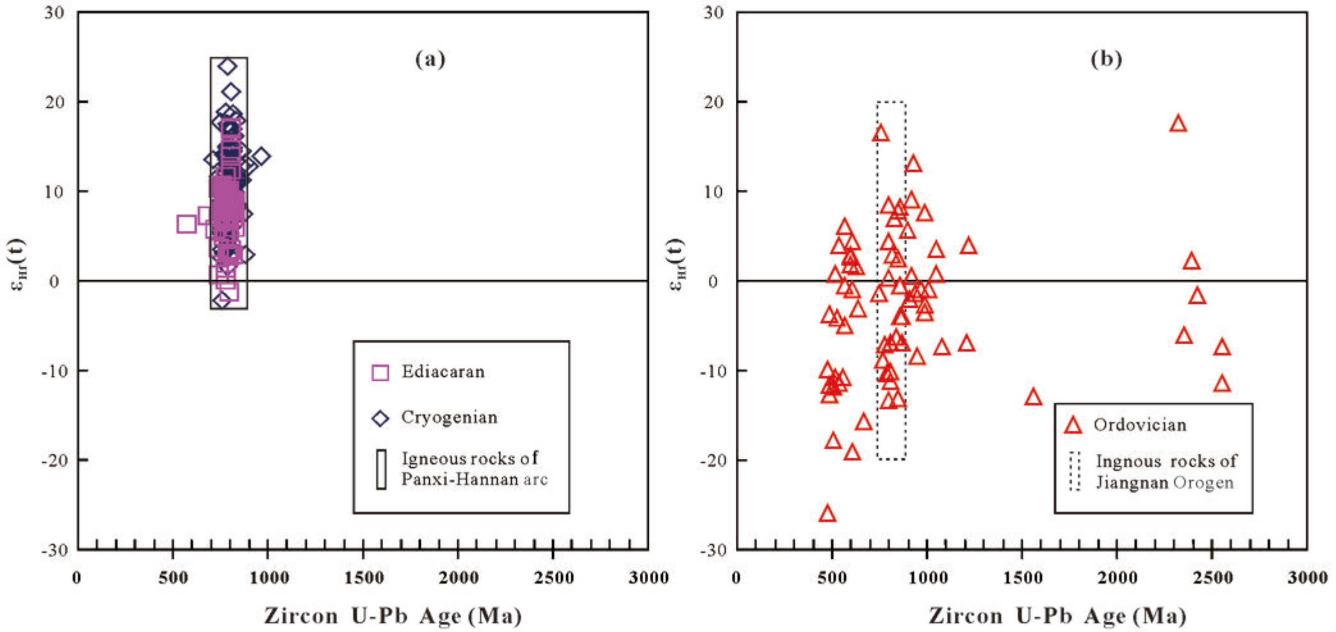

a
10YD-97
Mca
Qtz
Qtz
500 μm
10YD-99
b
Mca
Qtz
Mca
200 μm
c
10YD-100
Pl
Qtz
500 μm
10YD-102
Qtz
d
Qtz
Mca
200 μm

Figure 3.



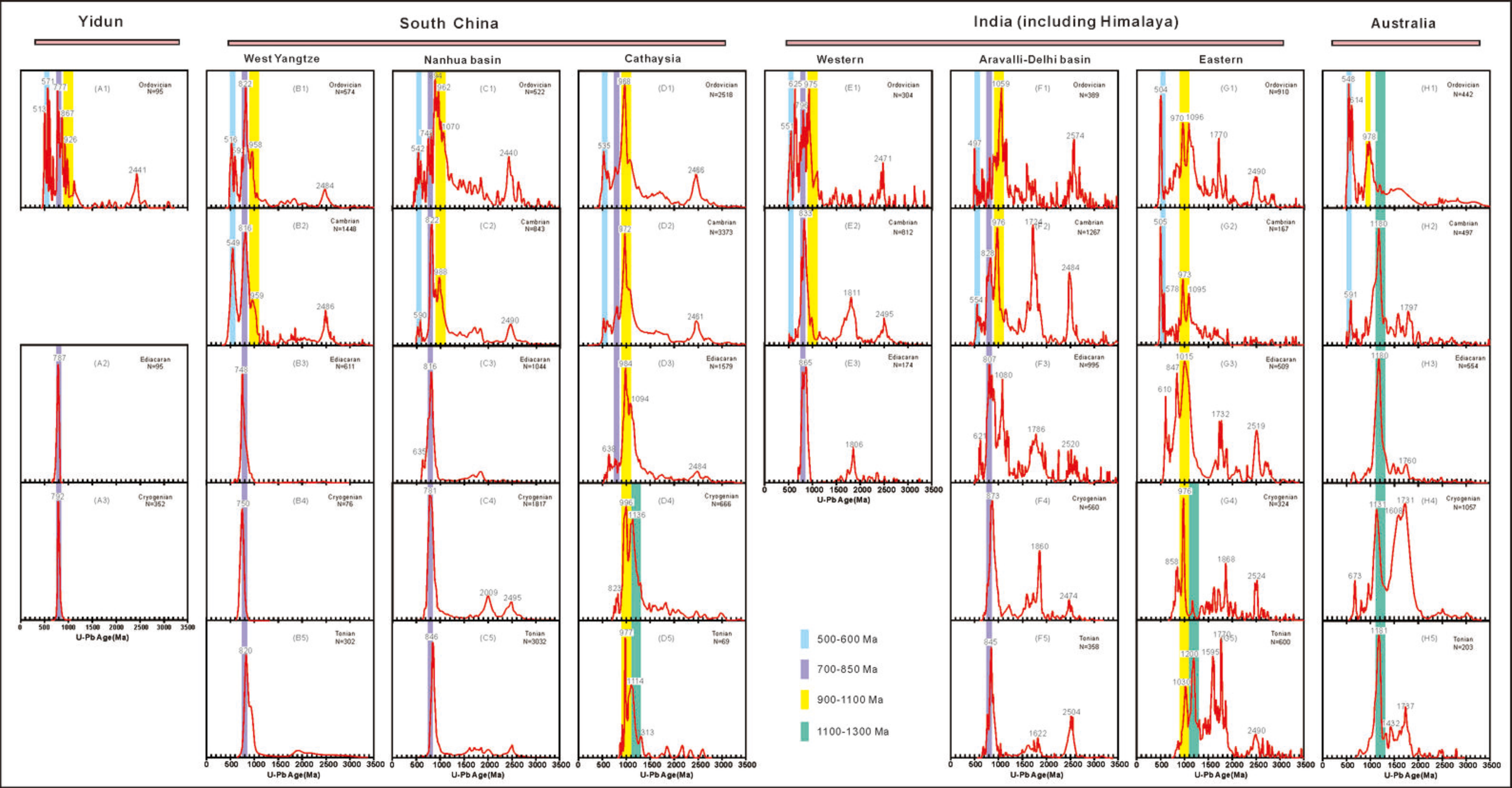
10YD-99 (a)
(b) 10YD-99 O1 n=67
529
806
972
10YD-102 (c)
(d) 10YD-102 O1 n=95
571
778
10YD-100 (e)
(f) 10YD-100 Zd n=95
780
10YD-93 (g)
(h) 10YD-93 Ptqs4 n=80
792
10YD-97 (i)
(j) 10YD-97 Ptqs3 n=80
795
206Pb/238U
207Pb/235U
U-Pb Age (Ma)

Figure 4.



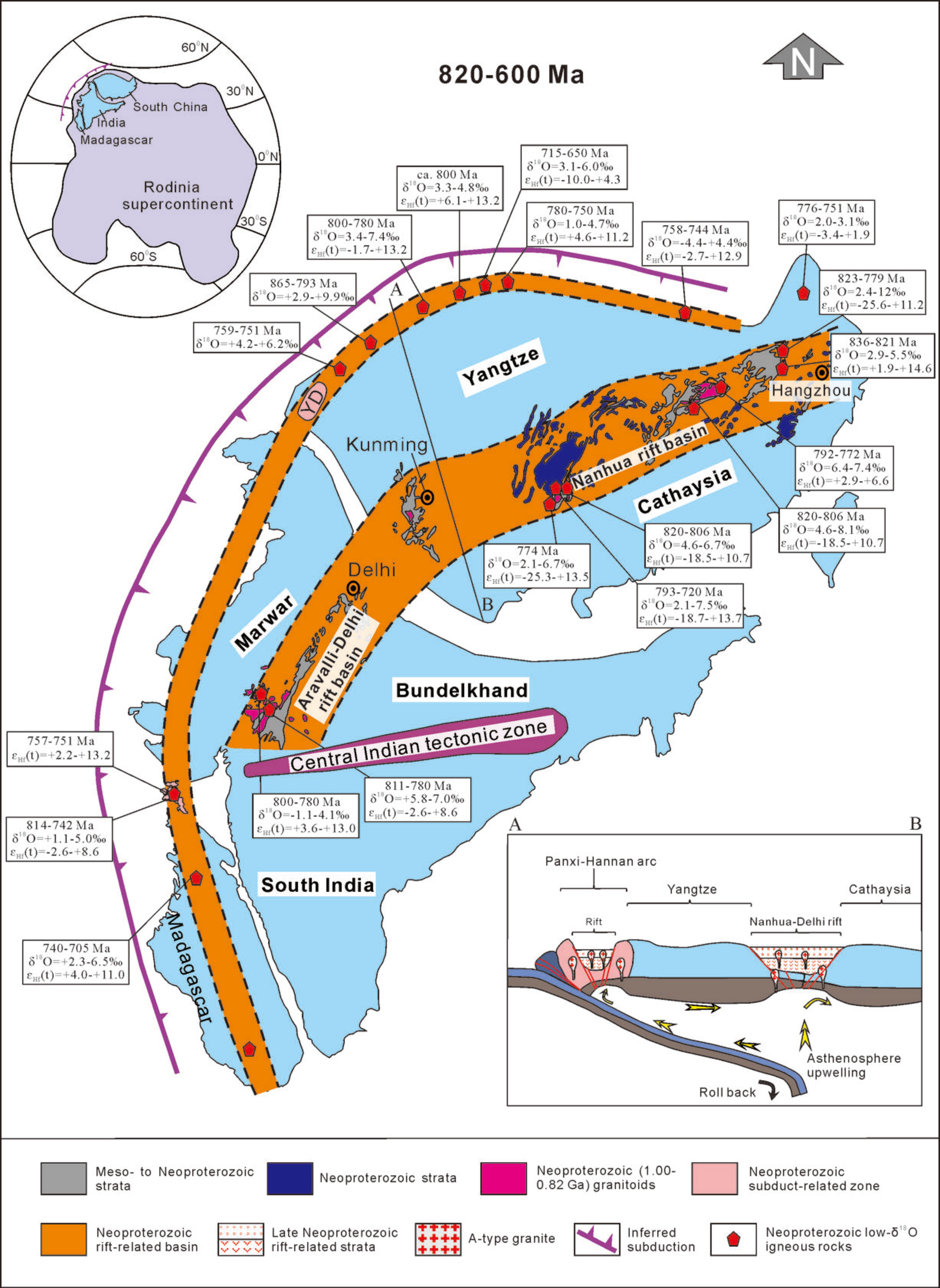
(a)
(b)
30
20
10
0
-10
-20
-30
$\varepsilon_{Hf}(t)$
0
500
1000
1500
2000
2500
3000
Zircon U-Pb Age (Ma)
Ediacaran
Cryogenian
Igneous rocks of
Panxi-Hannan arc
Ordovician
Ingnous rocks of
Jiangnan Orogen

Figure 5.



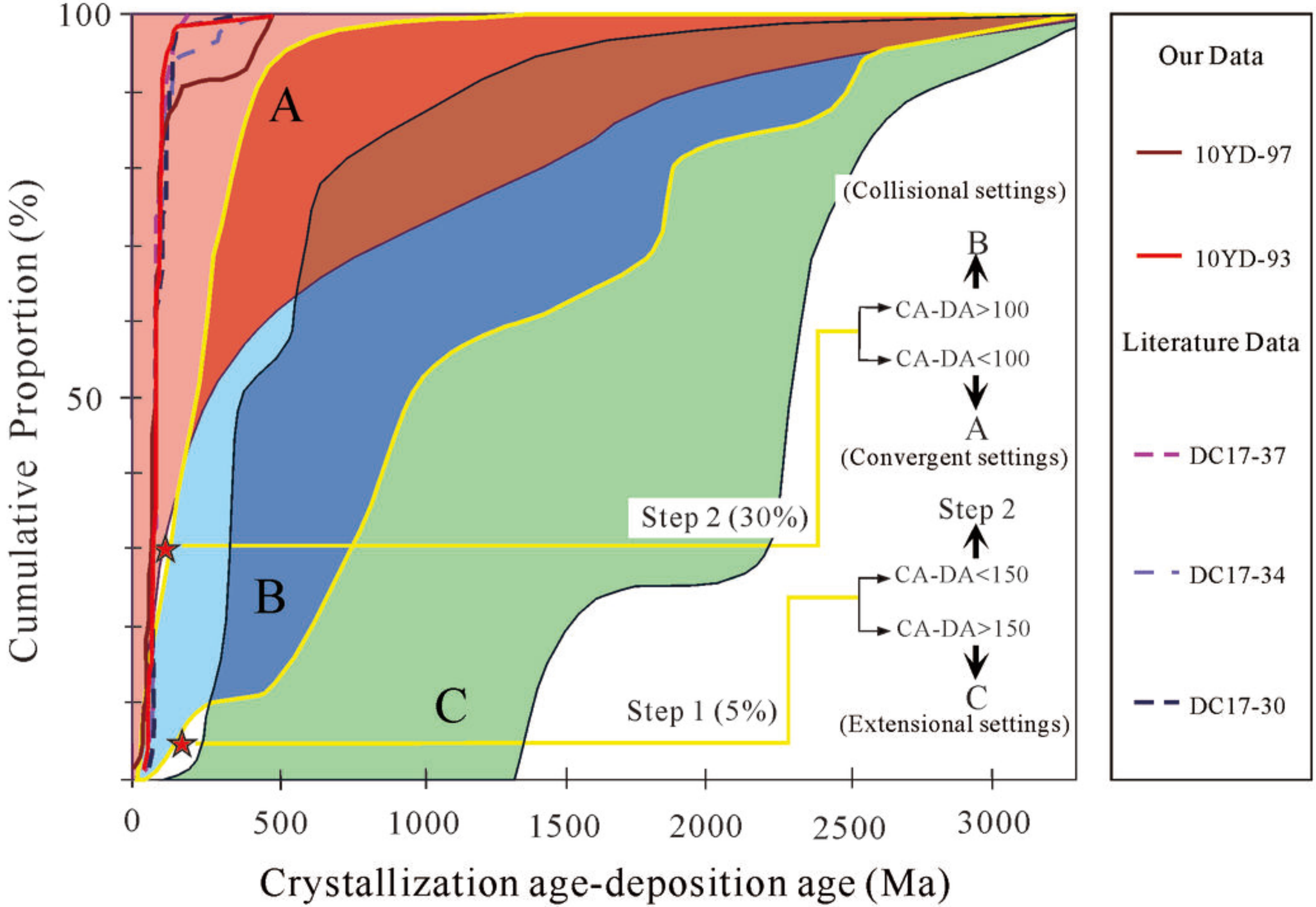
Yidun
South China
India (including Himalaya)
Australia
West Yangtze
Nanhua basin
Cathaysia
Western
Aravalli-Delhi basin
Eastern
500-600 Ma
700-850 Ma
900-1100 Ma
1100-1300 Ma
U-Pb Age(Ma)

Figure 6.



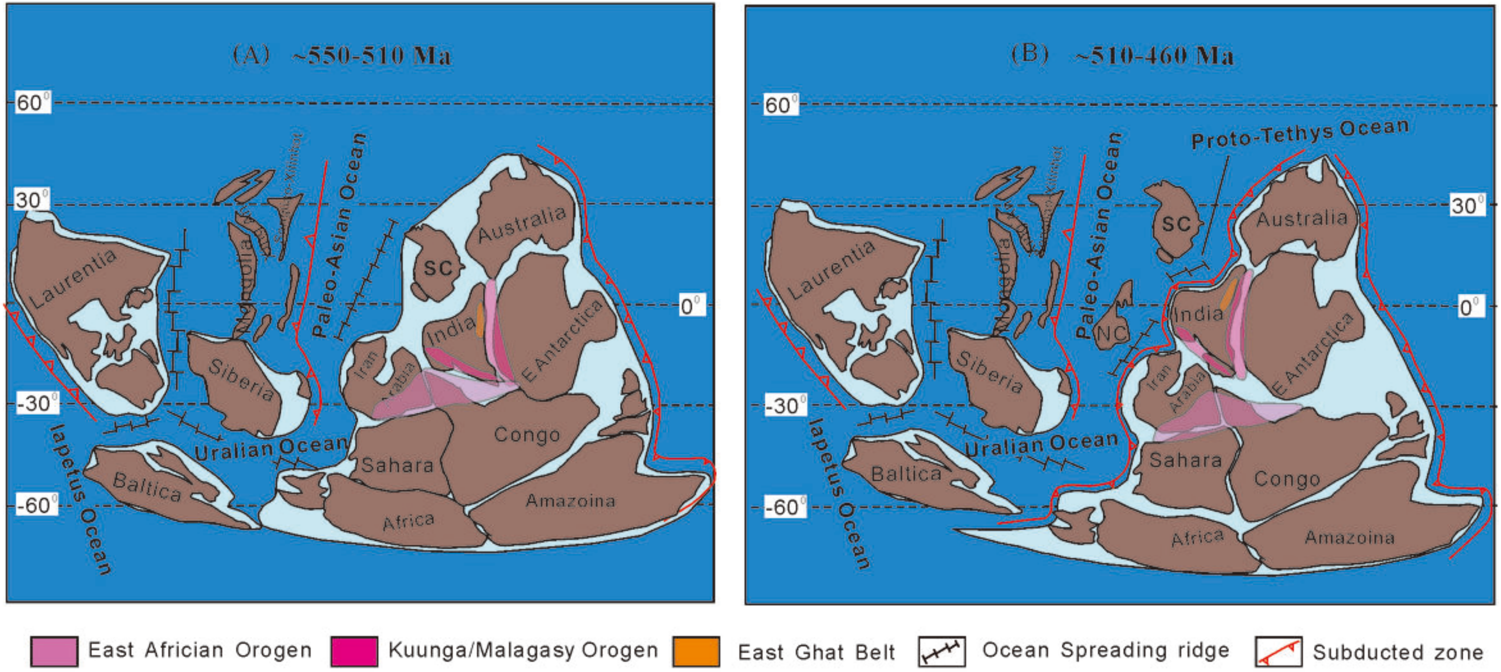
820-600 Ma
N
60°N
30°N
0°N
30°S
60°S
South China
India
Madagascar
Rodinia supercontinent
ca. 800 Ma δ18O=3.3-4.8‰ εHf(t)=+6.1-+13.2
715-650 Ma δ18O=3.1-6.0‰ εHf(t)=-10.0-+4.3
800-780 Ma δ18O=3.4-7.4‰ εHf(t)=-1.7-+13.2
780-750 Ma δ18O=1.0-4.7‰ εHf(t)=+4.6-+11.2
758-744 Ma δ18O=-4.4-+4.4‰ εHf(t)=-2.7-+12.9
776-751 Ma δ18O=2.0-3.1‰ εHf(t)=-3.4-+1.9
865-793 Ma δ18O=+2.9-+9.9‰
759-751 Ma δ18O=+4.2-+6.2‰
823-779 Ma δ18O=2.4-12‰ εHf(t)=-25.6-+11.2
836-821 Ma δ18O=2.9-5.5‰ εHf(t)=+1.9-+14.6
A
Yangtze
YD
Hangzhou
Kunming
Nanhua rift basin
Cathaysia
792-772 Ma δ18O=6.4-7.4‰ εHf(t)=+2.9-+6.6
820-806 Ma δ18O=4.6-8.1‰ εHf(t)=-18.5-+10.7
820-806 Ma δ18O=4.6-6.7‰ εHf(t)=-18.5-+10.7
774 Ma δ18O=2.1-6.7‰ εHf(t)=-25.3-+13.5
793-720 Ma δ18O=2.1-7.5‰ εHf(t)=-18.7-+13.7
Delhi
B
Marwar
Aravalli-Delhi rift basin
Bundelkhand
Central Indian tectonic zone
757-751 Ma εHf(t)=+2.2-+13.2
814-742 Ma δ18O=+1.1-5.0‰ εHf(t)=-2.6-+8.6
811-780 Ma δ18O=+5.8-7.0‰ εHf(t)=-2.6-+8.6
800-780 Ma δ18O=-1.1-4.1‰ εHf(t)=+3.6-+13.0
South India
740-705 Ma δ18O=+2.3-6.5‰ εHf(t)=+4.0-+11.0
Madagascar
A
B
Panxi-Hannan arc
Yangtze
Cathaysia
Rift
Nanhua-Delhi rift
Asthenosphere upwelling
Roll back
Meso- to Neoproterozoic strata
Neoproterozoic strata
Neoproterozoic (1.00-0.82 Ga) granitoids
Neoproterozoic subduct-related zone
Neoproterozoic rift-related basin
Late Neoproterozoic rift-related strata
A-type granite
Inferred subduction
Neoproterozoic low-δ18O igneous rocks

Figure 7.



100
50
0
500
1000
1500
2000
2500
3000
Cumulative Proportion (%)
Crystallization age-deposition age (Ma)
A
B
C
Step 2 (30%)
Step 1 (5%)
(Collisional settings)
B
CA-DA>100
CA-DA<100
A
(Convergent settings)
Step 2
CA-DA<150
CA-DA>150
C
(Extensional settings)
Our Data
10YD-97
10YD-93
Literature Data
DC17-37
DC17-34
DC17-30

Figure 8.



(A) ~550-510 Ma
(B) ~510-460 Ma
60°
30°
0°
-30°
-60°
Laurentia
Mongolia
Siberia
Baltica
Iapetus Ocean
Uralian Ocean
Paleo-Asian Ocean
Proto-Tethys Ocean
SC
NC
Australia
India
E Antarctica
Iran
Arabia
Sahara
Congo
Africa
Amazoina
East Africian Orogen
Kuunga/Malagasy Orogen
East Ghat Belt
Ocean Spreading ridge
Subducted zone

Table 1.Location and stratigraphic information of samples analyzed

Samples	Lithology	Latitude (N), Longitude (E)	Stratigraphic age	Mineral composition	Petrographical descriptions
10YD-93	Schist	N28°21.655, E100°13.619	The fourth member of Qiasi Group (Ptq^4; Cryogenian)	Quartz (80-85%), mica (5-10%), lithic fragment (1-5%) and minor heavy minerals	Fine-grained, subangular to subrounded, moderately to well sorted, grain-supported, moderately texture maturity
10YD-97	Schist	N28°22.453, E100°14.064	The third member of Qiasi Group (Ptq^3; Cryogenian)	Quartz (40-50%), mica (35-40%) and minor heavy minerals	Fine-grained, subangular to subrounded, moderately sorted, grain-supported, moderately texture maturity
10YD-99	Schist	N28°23.193, E100°14.410	Wachang Fm. (O_1)	Quartz (60-65%), mica (20-35%), and minor heavy minerals	Fine-grained, subangular to subrounded, moderately to well sorted, grain-supported, moderately texture maturity
10YD-100	Sandstone	N28°24.153, E100°14.546	Dengying Fm. (Ediacaran)	Quartz (70-80%), feldspar (10-15%) and minor heavy minerals	Middle- and fine-grained, angular to subangular, moderately to poorly sorted, grain-supported, moderately to low texture maturity
10YD-102	Slate	N28°24.958, E100°14.405	Wachang Fm. (O_1)	Quartz (ca.70%), mica (20-25%), and minor heavy minerals	Fine-grained, subangular to subrounded, moderately sorted, matrix-supported, moderately texture maturity