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Reconstructing South China in Phanerozoic and Precambrian supercontinents

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Abstract

The history of the South China Craton and the constituent Yangtze and Cathaysia blocks are directly linked to Earth's Phanerozoic and Precambrian record of supercontinent assembly and dispersal. Exposed Archean rocks are limited to isolated fragments in the Yangtze Block that preserve a record of Meso- to Neo-Archean magmatism, sedimentation and metamorphism associated with a period of global craton formation and stabilization that corresponds with the assembly of the Kenor supercontinent/supercraton. However, there are insufficient data to link its history with other similar aged cratons. The tectonostratigraphic record in South China in the Paleoproterozoic, corresponding with the assembly of Nuna, suggests that rock units in the Yangtze Block were spatially linked with northwestern Laurentia and possibly Siberia, whereas Cathaysia was joined to northern India. During the formation of Rodinia at the end of the Mesoproterozoic through to that of Pangea in the mid-Paleozoic, Cathaysia remained joined to northern India. Early Neoproterozoic supra-subduction zone magmatic arc-back arc assemblages ranging in age from ~1000 Ma to 810 Ma occur within Cathaysia, along its northwestern margin, and along the southeastern margin of the Yangtze Block. These rocks provide a record of convergent plate interaction, which continued along the western margin of the Yangtze Block until around 700 Ma and correlates with similar along strike subduction zone magmatism in northwest India, Seychelles and Madagascar. During the final assembly of Gondwana in the early Paleozoic suturing of India-South China with the Western Australia-Mawson blocks along the Kuunga Orogen resulted in the accretion of the Sanya Block of Hainan Island with the rest of Cathaysia. The accretion of Laurussia to Gondwana in the mid-Paleozoic to form Pangea corresponds with the initiation of lithospheric extension along the northern margin of Gondwana and the separation of a number of continental blocks, including South China, which then drifted northward across the Paleo-Tethys to collide with the Asian segment of Pangea in the Permo-Triassic.

Keywords: supercontinent; Pangea; Gondwana; Rodinia; Nuna

1. Introduction

Asia is an amalgam of continental fragments that have been accreted onto the Siberian craton from the Neoproterozoic to recent (Fig. 1). The affinities of these building blocks include peri-Siberian terranes that formed along or outboard of Siberia (e.g., Zhou et al., 2011), but the majority are continental fragments allochthonous to Siberia that were transferred across ocean basins (e.g. Paleo-Asian, Tethys), prior to accretion into Asia (e.g., North and South China cratons, Tarim Craton, Indochina, India; Cocks and Torsvik, 2013; Han et al., 2016; Metcalfe, 2013). Each of these blocks is itself an amalgamation of arc and continental crustal fragments with their own unique histories. The timing of incorporation of these blocks into Asia is relatively well constrained by the age of the faults and orogenic belts that bound the blocks (Metcalfe, 2013). However, the paleogeographic disposition of these blocks, and their constituent fragments, prior to Asian assembly is less well constrained with uncertainty increasing with increasing age due to the incompleteness of the geologic record. In this paper, we look at the geological evolution of one of these Asian blocks, the South China Craton, reviewing the formation of its oldest components in the Archean to its accretion into the developing Asia landmass in the Mesozoic, and discuss its relationship with the supercontinents cycles of Pangea, Gondwana, Rodinia and Nuna. The craton is considered to have formed by collision of the Yangtze and Cathaysia blocks in the early Neoproterozoic, but the paleogeographic position of the craton and these blocks prior to their incorporation in Pangea is controversial. Our analysis of the craton history, based on the integration of lithostratigraphy, geochronology, geochemistry, and provenance information, constrains the development, assembly, and relative and absolute positions of the constituent components of South China over time.

2. Geological Setting of South China

The South China Craton is separated from the North China Craton to the north by the Qinling-Dabie-Sulu orogen, from the Indochina Block to the south by the Ailaoshan-Song Ma suture zone, and from the Songpan-Gantze terrane to the west by the Longmenshan Fault (Fig. 2). It is bounded to the east by the Pacific Ocean but extends beyond the Chinese mainland and includes the rocks on Hainan Island. The craton is divided into the Yangtze Block to the northwest and the Cathaysia Block to the southeast separated by the Jiangnan Orogen (Cawood et al., 2013; Li et al., 2009; Li et al., 2008b; Li et al., 2002b; Li et al., 2008c; Shu, 2012; Shu et al., 2014; Wang et al., 2007; Wang et al., 2008b; Wang et al., 2006; Wang et al., 2004; Wang et al., 2008c; Zhao, 2015; Zhao and Cawood, 1999, 2012; Zhao et al., 2011; Zhou et al., 2009). The orogen (Fig. 2, inset), which is also known as the Sibao Orogen, is a broad zone dominated by early to mid-Neoproterozoic rock units and interpreted to represent an accretionary belt that records the assembly of the two blocks into a unified South China Craton (Cawood et al., 2013).

The South China Craton consists of spatially limited and generally poorly exposed Archean and Paleoproterozoic basement assemblages unconformably overlain by variably deformed and metamorphosed Neoproterozoic, Paleozoic and Mesozoic igneous and sedimentary successions (Zhao and Cawood, 2012, and references therein). Late Archean, Paleoproterozoic, early Neoproterozoic, mid-Paleozoic, and early Mesozoic tectonothermal events resulted in variable deformation, metamorphism and igneous activity across the craton.

2.1. Mesoproterozoic and older rock units and events

Archean and Paleoproterozoic rock units crop out in the northern and southwestern portions of the Yangtze Block of the South China Craton (Fig. 2). Archean outcrops are restricted to the northern part of the Yangtze Block and are represented by the Kongling Complex, Huangtuling granulites, and Yudongzi Group (Fig. 2). They are spatially restricted and intruded, or surrounded, by Paleoproterozoic and younger igneous and sedimentary successions (Zhao and Cawood, 2012). The Archean rocks include tonalite, trondhjemite, and granodiorite (TTG) gneisses locally containing minor mafic granulite lenses and boudins, and metasedimentary rocks. The protoliths of the TTG gneisses at Kongling were emplaced at 3.3-2.7 Ga, metamorphosed at 2.73 Ga and 2.0 Ga and intruded by A-type plutons at 1.85 Ga (Fig. 3; Gao et al., 1999; Gao et al., 2011; Guo et al., 2014; Peng et al., 2012). The gneisses contain an inherited zircon population with ages of 3.45-3.2 Ga (Gao et al., 2011; Guo et al., 2014; Qiu et al., 2000). Metasedimentary rocks contain detrital zircons as young as 2.87 Ga (Gao et al., 2011). Hf model ages for the TTG igneous and metasedimentary detrital zircons are as old as 4.0-3.5 Ga and Nd whole rock model ages on the gneisses are as old as 4.2 Ga (Gao et al., 2011; Guo et al., 2014, and references therein). Magmatic zircons within the Huangtuling granulites were dated at 2.78-2.74 Ga with metamorphic rims yielding ages of ca. 2.0 Ga (Wu et al., 2008a). Metasedimentary rocks accumulated sometime between 2.7 Ga and 2.0 Ga, based on the ages of the youngest detrital zircons and of the metamorphic overprint (Sun et al., 2008). Amphibolites within a metasedimentary and igneous gneiss succession of the Yudongzi Group are not well dated but have yielded a zircon upper intercept age of ca. 2.7 Ga (Zhang et al., 2001).

Paleoproterozoic units in the Yangtze Block include a supracrustal assemblage (Houhe Complex, Figs. 2, 3) that contains grey gneiss with arc geochemical affinities dated by U-Pb zircon at ca. 2080 Ma (Wu et al., 2012). In the southwestern portion of the Yangtze Block, low-grade volcanic and sedimentary rocks include the Dahongshan, Dongchuan and Hekou groups (Fig. 2). Tuffs within these units have yielded U-Pb zircon ages in the range 1740-1503 Ma (Greentree and Li, 2008; Sun et al., 2009b; Zhao et al., 2010). These units are in fault contact with the ca. 1.0 Ga Kunyang and Huili groups, and the Ailaoshan shear zone (Sun et al., 2009a).

Archean rock outcrops have not been recognized in the Cathaysia Block but Paleoproterozoic and younger sedimentary and igneous rocks have yielded detrital, inherited and xenocrystic zircons with U-Pb ages of 2.7-2.5 Ga and ranging back to as old as 4.1 Ga (Li et al., 2014; Xu et al., 2013; Yao et al., 2011; Zhao and Cawood, 2012, and references therein). Liu et al. (2014) noted that the complex types and compositions of the Paleoproterozoic granites in the northeastern Cathaysia Block suggest that the lower crust in the area was heterogeneous. Furthermore, they argued that the discovery of Paleoproterozoic I-type granites, coupled with the ~2.8 Ga model ages and inherited Archean zircons in these granites, demonstrates the existence of Archean basement rocks in the Cathaysia Block at depth.

Paleoproterozoic basement rocks in Cathaysia are sparsely distributed, largely in the Wuyishan region, occurring within a NE-SW trending structural block bounded by the Chenzhou-Linwu-Jiangshan-Shaoxing fault to the northwest and the Zhenghe-Dapu fault zone to the southeast (Fig. 2). The Paleoproterozoic rocks include granitoids and the Badu supracrustals (and equivalents) consisting of paragneiss and minor amphibolite (Yu et al., 2009). The granitoids are also caught within the Zhenghe-Dapu fault system (Liu et al., 2014). Igneous zircons from granitoids and amphibolites yield U-Pb zircon ages in the range 1910-1780 Ma (Liu et al., 2014; Xia et al., 2012). Metamorphic zircons from the supracrustal succession yield ages around 1890-1880 Ma and 250-235 Ma (Hua et al., 2008; Yu et al., 2012) and the Paleoproterozoic granites show evidence for both early Mesozoic (250–230 Ma) and late Mesozoic (110–90 Ma) metamorphism (Liu et al., 2014).

Mesoproterozoic rocks were once considered to be widespread in South China (e.g., Yang et al., 1994) but the application of modern methods of radiometric dating has revealed that the bulk of these units are Neoproterozoic. Dated Mesoproterozoic rocks in the Yangtze Block are limited to the southwest corner where a tuff from the Laowushan Formation yielded a U-Pb zircon age of ca. 1140 Ma (Greentree et al., 2006). The tuff is interstratified with sandstone, siltstone, breccia and alkali basalts with the latter displaying a continental rift geochemical signature. Also in the southwest corner of the Yangtze Block, a bentonite from the middle units of the Kunyang Group was dated by U-Pb zircon at 1030 Ma (Zhang et al., 2007) and basalt from the lower Julin Group yielded an age of 1050 Ma (Chen et al., 2014a). Recently, an alkaline rhyolite from the southeastern margin of the Yangtze Block has been dated at 1159 ± 8 Ma (Li et al., 2013b). In Cathaysia, dated Mesoproterozoic rocks are limited to Hainan Island, where variably metamorphosed tuff and volcaniclastic rocks of the Baoban Group have yielded zircon ages of between 1440-1430 Ma (Fig. 3; Li et al., 2008b). Deformed granodiorites associated with the metasedimentary succession yield similar ages (Li et al., 2002b) and the succession was metamorphosed in period 1.3-1.0 Ga (Yao et al., 2017).

2.2. Neoproterozoic and younger rock units and events

Neoproterozoic successions are widespread across the South China Craton and, where stratigraphic relations are preserved, are unconformable on older rock units. Lithostratigraphic associations and spatial relationships enable the division of the early Neoproterozoic units into a number of belts, the age range and distribution of which provide important insights into the character and assembly history of the South China Craton (Fig. 3).

The Yangtze and Cathaysia blocks along with the intervening Jiangnan Orogen contain discrete lithotectonic domains of early Neoproterozoic and older rocks associations that were assembled in the early Neoproterozoic (Zhao and Cawood, 2012). These domains are Hainan Island, eastern (mainland) Cathaysia, Wuyi-Yunkai (western Cathaysia), Jiangnan, eastern and central Yangtze, and Panxi-Hannan, which developed on a basement of older Yangtze rocks along the northern, western and southern margins of the block (Figs. 2, 3; Wang et al., 2013b; Xu et al., 2007b; Yu et al., 2009; Zhao and Cawood, 2012). The Wuyi-Yunkai domain of the Cathaysia Block is separated from Eastern Cathaysia by the Zhenghe-Dapu fault system and from the Jiangnan Orogen by the Shaoxing-Jiangshao-Pingxiang-Guilin Fault system. The Jiangnan Orogen is internally disrupted by faults into several structural blocks (e.g. Shuangxiwu). Although these domains are differentiated on the basis of Neoproterozoic and older rock units, they show evidence for modification during mid-Paleozoic and Mesozoic tectonothermal events (Wang et al., 2013a). The contact between the Jiangnan Orogen and the Yangtze Block is ill-defined and corresponds approximately with the western limit of early to mid-Neoproterozoic strata.

We consider the Zhenghe-Dapu fault system to constitute a major structural boundary within the Cathaysia Block as it delineates the southeast extent of exposed Paleoproterozoic rock units. However, others have suggested it is simply an internal fracture within the Cathaysia Block based on similarity of detrital zircon age peaks observed across the fault (Yu et al., 2010). The fault records a long history of multiple phases of deformation and reactivation (Shu et al., 2011; Shu et al., 2008a) and the region to the southeast of the fault is dominated by Mesozoic rock units (Fig. 2). The fault zone, in addition to incorporating Paleoproterozoic granites (Liu et al., 2014), contains 970 Ma rhyolite with arc-type geochemical affinities and ca. 850-800 Ma mafic-ultramafic suites with within plate geochemical signatures (Shu et al., 2011; Shu et al., 2008b). The fault zone records evidence for early Paleozoic dextral strike-slip ductile shearing (ca. 430 Ma; Xu et al., 2011), and Early Cretaceous southeast dipping normal faulting (Shu et al., 2009). At depth the Zhenghe-

Dapu fault may join with the subparallel trending FuAn - NanJing fault, which lies to the southeast within the Mesozoic volcanic rock succession of the eastern Cathaysia Block and corresponds with a decrease in crustal thickness as delineated by regional gravity data (Ma and Xu., 2010).

The early Neoproterozoic successions in South China consist of mafic to silicic volcanic rocks and their intrusive equivalents, tuffs, clastic sandstones and siltstones, along with lesser amounts of ophiolite related mafic-ultramafic assemblages, limestone and chert (Li et al., 2009; Wang et al., 2013b; Yao et al., 2016a; Yao et al., 2016b; Yao et al., 2014b; Zhou et al., 2006; Zhou et al., 2002). Estimates on the timing of assembly of the Yangtze and Cathaysia blocks range from 980 Ma to 810 Ma (Li et al., 2014; Wang et al., 2016b; Zhao, 2015; Zhao and Cawood, 1999, 2012). This uncertainty in the age range for assembly of the South China Craton is due in large part to differing interpretations of the geochemical affinities and resultant tectonic setting of rocks younger than 980 Ma, and in particular those within the 860-810 Ma Sibao Group and equivalents (e.g., Lengjiaxi, Shuangqiaoshan, Xikou; Ma et al., 2016; Wang et al., 2012c; Wang et al., 2016b; Wang et al., 2007; Wang et al., 2014b; Zhao and Cawood, 2012). One group of models favour a mantle plume origin related to lithospheric extension and others a supra-subduction zone setting (e.g., compare Cawood et al., 2013; Li et al., 2014). A younger age limit on assembly is provided by the Banxi Group and other units (e.g., Xiajiang, Danzhou, Cangshuipu; Zhang et al., 2015b; Zhao and Cawood, 2012), which unconformably overlie the older successions, and have a maximum depositional age of around 810-800 Ma on the basis of the volcanic rocks within the lower Banxi Group and equivalents (e.g., 814 ± 12 Ma, Cangshuipu volcanics; 803 ± 9 Ma, Taoyuan rhyolite; 802-794 Ma Shangshu volcanics; Wang et al., 2003; Wang et al., 2015a). S-type granites emplaced into the early Neoproterozoic successions yield ages in the range 830-815 Ma (Wang et al., 2016b; Yao et al., 2014b).

The Yangtze Block, including the Paleoproterozoic and older basement units (Figs. 2, 3) are enveloped along the northern, western and southern margins of the block by the Panxi-Hannan Belt of mafic to intermediate volcanic rocks and volcaniclastic sedimentary rocks, and associated plutonic complexes (Dong et al., 2012a; Dong et al., 2011). Along the southern margin, the belt is disrupted by the Ailaoshan fault zone (Cai et al., 2014; Cai et al., 2015; Wang et al., 2016c). Rock units range in age from latest Mesoproterozoic (ca. 1030 Ma) to as young as 710 Ma but with most in the range 830-760 Ma (Cai et al., 2014; Dong et al., 2012a; Geng et al., 2007; Sun et al., 2009a; Zhang et al., 2007; Zhou et al., 2006; Zhou et al., 2002). As with the Jiangnan Orogen, the tectonic setting of the Panxi-Hannan Belt, especially for the younger time frame (post-830 Ma) is disputed with both convergent plate margin and intra-plate rift settings proposed (Li et al., 2003c; Zhao and Cawood, 2012, and references therein; Zhou et al., 2002).

The Banxi Group and equivalents (age range 810-730 Ma) are characterized by bi-modal magmatism and associated sedimentary successions, and are thought to have accumulated in an intracontinental rift environment (i.e., Nanhua rift; Wang and Li, 2003; Wang et al., 2012d; Zhu et al., 2008). Upper Neoproterozoic and Lower Paleozoic strata conformably overlie the older Precambrian successions in Cathaysia and nonconformably overlie strata in the Yangtze Block and Jiangnan Orogen. The strata show significant facies variation across the craton. The Cambrian-Ordovician succession ranges from siliciclastic dominated in the Cathaysia Block to a mixed carbonate and siliciclastic succession that in part represents a platform environment on the Yangtze Block (Wang et al., 2010c). Silurian successions occur in the Yangtze Block and are siliciclastic dominated, but are generally absent from the Cathaysia Block, except for the region from Qinzhou to Fangchenggang near the southern margin of the block within the Qin-Fang Trough (Xu et al., 2012). The craton was subsequently overprinted by the early Paleozoic (460 - 420 Ma) Kwangsian Orogeny

(Ting, 1929; Wang et al., 2013a; Xu et al., 2016), also termed the Caledonian (Faure et al., 2009) or the Wuyi-Yunkai Orogeny (Li et al., 2010), the effects of which are mainly focused in the Cathaysia Block (Shu et al., 2015; Shu, 2012). Orogenesis resulted in extensive metamorphism and deformation of pre-Devonian rocks along with granite intrusions and emplacement of minor basalts (Li et al., 2010; Shu et al., 2015; Wang et al., 2012e; Wang et al., 2013c; Wang et al., 2010c; Yao et al., 2012; Zhao et al., 2015). Metamorphism was largely at greenschist facies, but locally reached amphibolite to granulite facies (Yu et al., 2005). Coeval structures occur throughout pre-Devonian strata in Cathaysia, with development of sub-E-W trending folds accompanied by regional-scale ductile thrusting, shear foliation and stretching lineations (Shu et al., 2015; Shu, 2012). Dip and sense of motion on thrusts vary across strike and display an overall fan pattern with the northwest margin of the Wuyi-Yunkai domain thrust northwest-ward towards the Yangtze Block and southeast margin of the domain thrust southeast-ward towards east Cathaysia (Charvet et al., 2010; Shu et al., 2014). Post-tectonic Devonian strata unconformably overlie older units and mark a period of post-orogenic transgression that evolved into a Carboniferous to Permian carbonate platform consisting of limestone, dolomite, black chert, and minor sandstones and mudstones, with no coeval magmatism (Shu et al., 2008a; Shu et al., 2015). In the Triassic, the Indosinian Orogeny, manifested by deformation and magmatism at 250-200 Ma, and a regional unconformity between Late Triassic and underlying strata, terminated carbonate sedimentation across the craton (Hu et al., 2015; Shu et al., 2015; Wang et al., 2013a). Orogenesis generated large scale fold and nappe systems in Jiangnan belt and Cathaysia Block, which partially overprinted the pre-Mesozoic structures in South China (Shu, 2012; Wang et al., 2013a).

3. Supercontinent cycles and South China

A variety of paleogeographic positions have been proposed for the South China Craton within Gondwana and older supercontinents as well as positions independent of, external to, the supercontinents (Li et al., 2008c; Wu et al., 2010; Yang et al., 2004; Zhao and Cawood, 1999, 2012). In addition, some reconstructions have not included South China (e.g., Collins and Pisarevsky, 2005; Dalziel, 1997), perhaps reflecting the uncertainty in its paleogeographic position. Much of the disagreement revolves around the position of South China in Rodinia and whether it occupied an internal or peripheral location within the supercontinent, or whether it was even part of Rodinia (cf., Cawood et al., 2013; Li et al., 2008c; Merdith et al., in press). This, in turn, impinges on its position in both older and younger supercontinents as South China and its constituent fragments must migrate into and away from mutually exclusive internal and external locations in, or beyond, Rodinia. The nature, age and paleogeographic setting of the early to mid-Neoproterozoic (ca. 900-730 Ma) rocks along the Yangtze-Cathaysia boundary zone (Jiangnan Orogen) and western Yangtze (Panxi-Hannan Belt), and in particular whether they developed in an accretionary orogenic setting or within a post-collisional extensional setting are key elements in constraining the role of South China in the supercontinent cycle (Cawood et al., 2013, and references therein; Li et al., 2002b; Zhao, 2015). In Gondwana, the position of the South China Craton has been proposed to occupy a position on the margin of the supercontinent (Zhang and Piper, 1997; Zhao and Cawood, 1999), as part of a separate plate that then accreted to Gondwana (Li et al., 2008c; Li and Powell, 2001; Yao et al., 2014c), or was unrelated to Gondwana and joined to Laurentia (Li et al., 2013a; Wu et al., 2010). There is even more uncertainty in the position of South China in Nuna due to the incomplete nature of the Precambrian rock archive (Li et al., 2014; Wang et al., 2016a; Yu et al., 2012; Zhao et al., 2002).

Evaluating the myriad of competing models for the spatial and temporal distribution of South China, to arrive at a holistic integrated history from its formation as a craton to its assembly into its present location within Asia, requires critical evaluation and integration of all available data. This evaluation is undertaken in the following sections, commencing with its most recent history, where the data are most complete, and hence perhaps the least ambiguous in its interpretation, and then extending back though earlier supercontinent cycles.

4. South China in Pangea and Gondwana

Convergence between the South China Craton and Asia is recorded in the Devonian to Permian history of the Qinling–Dabie–Sulu Orogen, which lies along the northern margin of the craton (Fig. 2). Final collision and incorporation into the Asian segment of Pangea occurred during the late Paleozoic to early Mesozoic Indosinian Orogeny (Dong et al., 2012b; Dong and Santosh, 2016; Faure et al., 2003; Faure et al., 2009; Hacker et al., 2004; Metcalfe, 2013; Wang et al., 2013a). Integrated geochronologic, metamorphic and structural studies on diamond and coesite-bearing eclogites in the Dabie-Sulu segments of the orogen indicate subduction of the northern edge of South China to depths of > 150 km in the Late Permian to Early Triassic as it collided with the North China Craton (Hacker et al., 2004; Hacker et al., 2009; Hacker et al., 2006; Ratschbacher et al., 2003).

Prior to its migration across the Paleo-Tethys and collision with Asia, South China lay along the northern margin of Gondwana. Early Paleozoic shallow marine faunas in South China are similar to those in the Himalayan-Iranian region of north Gondwana, as well as with the Sibumasu Block and the North China Craton that were also located along this segment of the Gondwana margin at this time (Cocks et al., 2005; Fortey and Cocks, 2003; Hughes, 2016; Li, 1994; McKenzie et al., 2011; Yang, 1994). In contrast, Devonian faunas are endemic suggesting that South China had by then separated from Gondwana (Metcalfe, 2013). Northward drift of South China across the Paleo-Tethys continued throughout the remainder of the Paleozoic prior to collision with Asia in the Permian to Triassic (Cocks and Torsvik, 2013; Metcalfe, 2013). Paleomagnetic data for South China in the early Paleozoic are limited but at least for the Cambrian suggest a low-latitude position consistent with a setting along, or near, North Gondwana (Cocks and Torsvik, 2013; Yang et al., 2004).

South China was one of a series of blocks that rifted off northern Gondwana in the early to mid-Paleozoic, resulting in the formation of the Paleo-Tethys Ocean (Fig. 4), the remnants of which are represented by the Changning-Menglian-Inthanon suture in SE Asia (Arboit et al., 2016a; Arboit et al., 2016b; Hara et al., 2012; Kamata et al., 2012; Metcalfe, 2013; Zhang et al., 2016). The Jinshajiang-Ailaoshan-Song Ma suture (Jian et al., 2009; Khin et al., 2014; Sone and Metcalfe, 2008), which defines the southeastern margin of the South China Craton (Fig. 2), represents a branch, or back-arc basin, of the Paleo-Tethyan Ocean (Fig. 1; Zi et al., 2012a; Zi et al., 2012c), and was the site for rifting and breakup of the craton from Gondwana (Zi et al., 2012b). The suture zone is a belt up to 30 km wide composed of disrupted and discontinuous Proterozoic to Cenozoic rock units. The early history of the zone has been extensively modified by late Paleozoic to early Mesozoic reactivation during closure of the Paleo-Tethys Ocean and accretion of the Indochina Block to the southeast (Cai et al., 2014; Lin et al., 2012; Zi et al., 2013). Subsequent Cenozoic strike-slip deformation associated with the India-Asia collision further reactivated the suture zone (Tapponnier et al., 2001, and references therein). Evidence for the breakup history of South China from Gondwana may be preserved in the Qin-Fang Trough, which trends orthogonal to the suture zone. Basal Silurian and overlying Devonian clastic strata within the trough are interpreted as forming within an aulacogen during rifting and drifting respectively, associated with Paleo-Tethys ocean opening along the southern margin of South China (Xu et al., under review).

Most reconstructions for South China in the early Paleozoic place it along, or nearby, the northern margin of Gondwana and are based on some combination of faunal, provenance and paleomagnetic data sets. In general, South China is positioned near India (e.g. Fig. 4) but specific locations range from close to the Arabian Peninsula on India's northwestern side to off Western Australia, northeast of India (Burrett et al., 2014; Cawood et al., 2013; Cocks and Torsvik, 2002; Hughes, 2016; Metcalfe, 2013; Wang et al., 2010c; Xu et al., 2013; Zhu et al., 2012). Cocks and Torsvik (2013) suggested that through the early Paleozoic South China migrated along Gondwana's north margin by a combination of sea-floor spreading and dextral strike-slip motion. In this model, South China initially lay outboard of the Afghan terrane and Arabia finishing its migration off northwest Australia, prior to opening of the Paleo-Tethys Ocean. Paleocurrent and detrital zircon provenance data for early Paleozoic strata in South China (Fig. 5) indicate derivation of detritus from the south or southeast (present-day coordinates), and beyond the present day limits of the craton from a site in northern Gondwana (Wang et al., 2010c; Xu et al., 2013). In particular, the early Paleozoic units are characterized by input from late Mesoproterozoic (1150-1100 Ma) and early Neoproterozoic (960-900 Ma) aged zircon detritus interpreted to be derived from Wilkes-Albany-Fraser belt between southwest Australia and Antarctica and from the Rayner-Eastern Ghats belt between India and Antarctica, respectively (Fig. 5). Derivation of detritus from these sources beyond the craton required South China to be joined rather than separated from northern Gondwana, and at a location off northeastern India (Cawood et al., 2013; Xu et al., 2013).

Additional constraints on the position of South China along the Gondwana margin are provided by rock relations on Hainan Island. Provenance and faunal data for early Paleozoic sandstones from the Sanya Block, suggest this region only became part of South China in the early to mid-Ordovician (Xu et al., 2014b). U-Pb ages and Hf isotope compositions of detrital zircons from Cambrian sandstones in the Sanya Block are consistent with derivation of detritus from late Paleoproterozoic and Mesoproterozoic units along the western margin of the West Australia Craton or the Albany-Fraser-Wilkes orogen, and contrasts with the provenance record of equivalent strata in mainland South China, whose provenance record is similar to that of strata in the Tethyan Himalaya of northeastern India (Fig. 5). Linking the Sanya Block with Australia is further supported by faunal evidence with morphologically distinct middle Cambrian trilobites of the block also occurring in Australia and Antarctica but sparse or absent in mainland South China (Xu et al., 2014b). The Cambrian strata in the Sanya Block are unconformably overlain by Ordovician to Silurian rock units that contain prominent late Paleoproterozoic to early Mesoproterozoic aged zircon grains as well as early Paleozoic grains, all of which could have been sourced from the the Qiongzhong Block or other parts of South China (Xu et al., 2014b). The Qiongzhong Block remained part of the southeastern convergent plate margin of the South China Craton in the early Paleozoic. This suggests that by the mid-Ordovician the Sanya Block was accreted to the Qiongzhong Block, and presumably the rest of South China (Fig. 6). Again faunal data is supportive of this sequence of events with similar early Ordovician trilobites in both South China and Australia (Torsvik and Cocks, 2009) and Early Devonian fresh water fish in South China, Vietnam, and Western Australia (Burrett et al., 1990). The evolving provenance and faunal record of the Cambrian and Ordovician strata in Hainan Island suggests that the juxtaposition of a combined Sanya Block and West Australia with the rest of South China and India occurred in the early to mid-Ordovician. This region lies at the northern continuation of Kuunga Orogeny and the recorded events correspond with the final assembly of Gondwana (Fig. 6). The provenance record of late Neoproterozoic strata from Cathaysia (Fig. 5; Yu et al., 2008) are consistent with derivation from east India with both showing a prominent early Mesoproterozoic peak and lacking a late Mesoproterozoic age peak (ca. 1200-1150 Ma), which is inferred to have been sourced from southwestern Australia and adjoining regions in Antarctica, thus suggesting that Australia and India were separate at this time.

5. South China in Rodinia

The transition from Rodinia to Gondwana in the Neoproterozoic involves the breakout of Laurentia from a keystone location within Rodinia (Hoffman, 1991) and is associated with the closure of the pan-Rodinian Mirovoi Ocean (Fig. 4) and the development of the proto-Pacific, paleo-Asian and Iapetus oceans around Laurentia (Cawood, 2005; Cawood et al., 2016; Dalziel, 1997). Two end-member models have been proposed for the paleogeographic setting of South China in Rodinia; an internal location within the supercontinent versus an external setting along the margin of Rodinia (Cawood et al., 2013; Li et al., 2008c). In addition, if Cathaysia was linked to northern India through the Mesoproterozoic and early Neoproterozoic, then a third model in which these continental fragments were independent of Rodinia is also possible (Merdith et al., in press, and references therein). In reconstructions favouring an internal location within Rodinia, the South China craton has been invoked as providing a key link between Laurentia and Australia (Li et al., 2002b; Li et al., 2008c). In these models, the amalgamation of the Cathaysia and Yangtze blocks is envisaged as occurring in an end Mesoproterozoic to early Neoproterozoic collisional orogen (ca. 1000-890 Ma; Li et al., 2009; Li et al., 2007), but possibly as young at ca. 860 Ma (Shu and Charvet, 1996), and is associated with the overall assembly of Laurentia and East Australia-Antarctica, resulting in an assembled South China Craton occupying an interior intra-continental position in an assembled Rodinia (Li et al., 2014; Li et al., 2008c). Subsequent breakout of South China from this internal location is proposed to have involved pulses of bi-modal mantle plume magmatism between ca. 830-745 Ma and associated rift related sedimentation (Li et al., 2003c). After breakup South China constituted a separate plate that is inferred to have migrated around Australia to collide with northern India in the late Neoproterozoic to early Paleozoic (Yao et al., 2014c) causing the Bhimphedian Orogeny (ca. 530-470 Ma; Cawood et al., 2007) as well as the Wuyi-Yunkai/Kwangsian Orogeny in South China (460-420 Ma; Li et al., 2010).

In models favouring an external location for South China in Rodinia (Yang et al., 2004; Zhao and Cawood, 1999), assembly of the Cathaysia and Yangtze blocks occurred in an overall accretionary orogenic setting through assembly of one or more convergent plate margin arc systems (e.g., Fig 4c; Cawood et al., 2013; Yao et al., 2016b; Zhao, 2015). Final assembly of the Yangtze and Cathaysia blocks was not complete until around 830-810 Ma in the accretionary model and subduction is inferred to have continued along the western margin of the Yangtze Block until at least 730 Ma (Zhou et al., 2002). Subduction in the western Yangtze is inferred to have occurred in an overall retreating plate scenario resulting in lithospheric extension in the overriding South China lithosphere (Zhao et al., 2011).

Merdith et al. (in press) have recently proposed a full plate global reconstruction for the Neoproterozoic. They follow Cawood et al. (2013) in positioning Cathaysia on the northern margin of India but, building on the earlier work of Pisarevsky et al. (2003) and Collins and Pisarevsky (2005), argue that neither were part of Rodinia and lay on a separate plate. In this model, the Rayner-Eastern Ghats orogen, along with inferred outboards regions that are no longer preserved, are considered to be an accretionary orogen in which subduction did not terminate until the late Neoproterozoic when India joined Antarctica and Australia in Gondwana (Merdith et al., in press, and references therein). This contrasts with ‘traditional’ models (e.g., Li et al., 2008c, and references therein) in which the Rayner-Eastern Ghats region is considered to be a late Mesoproterozoic to early Neoproterozoic collisional orogen responsible for suturing India within the supercontinent. The geology of South China alone cannot differentiate between whether India (and South China) were part of, or independent from, Rodinia. Both models are similar in requiring the two continental fragments to be linked throughout the Mesoproterozoic and Neoproterozoic, and for the purposes of the following discussion the model in which India and Cathaysia constitute a separate plate to Rodinia (Merdith et al., in press) is considered to be equivalent to that in which the two are joined on the margin of Rodinia (Cawood et al., 2013).

Internal and external models for the position of South China in Rodinia have contrasting consequences for the Neoproterozoic geological history of South China. The internal model requires subduction to be completed by 890 Ma (Li et al., 2002b; Li et al., 2008c) or 860 Ma (Shu and Charvet, 1996) and subsequent magmatism is related to lithospheric extension associated with a mantle plume, whereas the external model has subduction continuing until as late as 830-810 Ma (Wang et al., 2016b) between Yangtze and Cathaysia and 730-700 Ma on the western margin of Yangtze (Dong et al., 2012a; Zhou et al., 2002). Similarly, movement of South China from an internal location within Rodinia to an external location in Gondwana implies a different provenance record than a peripheral Rodinian model in which the position of South China with respect to India is essentially fixed through the Neoproterozoic, which is also similar to the model in which South China and India are independent of Rodinia.

The character and provenance record of the Cryogenian Nanhua Basin has been used to support both internal and external models for the position of South China. The Nanhua sequences and equivalents (e.g., Kangdian sequences) represent sediment accumulation during lithospheric extension (Wang and Li, 2003; Zhao et al., 2011). Proponents of the internal model for the paleogeographic position of South China in Rodinia suggest extension was associated with a “super-plume" that caused the breakup of Rodinia and correlates with contemporaneous rift systems in eastern Australia and western Laurentia, providing evidence for placement the Yangtze Block between Australia and Laurentia in Rodinia (Li et al., 2002b; Li et al., 2008c; Li et al., 2003c). U-Pb age patterns and Hf isotopic signatures of detrital zircons from the Danzhou, Xiajiang and Banxi groups indicate that sedimentary detritus supplied to the Nanhua Basin sequences were largely sourced from Neoproterozoic rocks within South China (Wang et al., 2010a; Wang and Zhou, 2012; Wang et al., 2012d). The absence of late Mesoproterozoic aged detritus, as well as only minor input from Archean and Paleoproterozoic cratonic sources, in the Nanhua sequences is distinct from the detrital age patterns of time-equivalent strata in Laurentia and Australia, but is similar to that of Cryogenian strata in the Lesser Himalaya of northwest India (Fig. 7). Flood basalts related to the inferred ‘super-plume’ are documented in Australia but are not present in the Yangtze Block (Zhou et al., 2008). The absence of basalts has been attributed to erosion during sedimentation of the Neoproterozoic sedimentary basins in the Yangtze Block, similar to that which occurred in the Adelaide Fold Belt (Barovich and Foden, 2000; Wang et al., 2011). However, sedimentary rocks from the Nanhua sequences have trace elemental and Sm-Nd isotopic signatures indicative of sources dominantly composed of granitic to dioritic end-members from the interior of the Yangtze Block (Fig. 8) (Wang et al., 2012b; Wang and Zhou, 2012; Xu et al., 2007a), arguing against derivation of sedimentary detritus from a large basalt province. Thus, the detrital zircon age spectra and the felsic composition of the igneous source rocks for the Nanhua sequences do not support development in association with mantle plume located between western Laurentia and Australia-Antarctica.

Early Neoproterozoic rock units along the southeastern margin of the Yangtze Block and the western Cathaysia Block consist of volcanic and sedimentary rocks deformed and metamorphosed at greenschist facies. This succession was intruded in the mid-Neoproterozoic by massive, peraluminious granites, and unconformably overlain by a mid- to late Neoproterozoic sedimentary and volcanic cover succession (Li et al., 2003a; Wang et al., 2012d; Wang et al., 2013b; Wang et al., 2014c; Zhao, 2015; Zhao and Cawood, 2012, and references therein). The early Neoproterozoic rock units include the Sibao Group and equivalents in the Yangtze Block (e.g., Fanjingshan, Lengjiaxi, Shangxi and Shuangxiwu groups, Zhao and Cawood, 2012) and the Longquan Group in the Cathaysia Block (e.g., Zhao and Cawood, 2012). These succession consists of volcanic and pyroclastic rocks and tuffs, with a range of basaltic, andesitic, dacitic and rhyolitic compositions, along with volcaniclastic sedimentary rocks, and minor intrusive mafic and ultramafic rocks, siliciclastic rocks, chert and carbonate.

Overall age range of the successions in the Jiangnan Orogen developed along the southeastern margins of the Yangtze Block and the northwestern margins of the Cathaysia Block is from 1000-810 Ma but with variation in spatial distribution of the age data: in the eastern Jiangnan Orogen dated igneous rocks range from 970-890 Ma (Li et al., 2009; Ye et al., 2007) and from 870-850 Ma (Yao et al., 2016b; Yao et al., 2015), in the central Jiangnan Orogen the age of rock units is more restricted in range from 850-840 Ma (Zhang and Wang, 2016; Zhang et al., 2013b). In the western part of the orogen dated rocks have yielded ages in the range 855-830 Ma (Chen et al., 2014b; Yao et al., 2015; Zhao and Zhou, 2013), and in the northwestern Cathaysia Block rocks are dated at 1000-970 Ma and ca. 840 Ma (Li et al., 2010; Shu et al., 2008b; Wang et al., 2013b; Zhang et al., 2012a). Thus, available age data suggest that periods of magmatic activity may be restricted in their spatial distribution (Wang et al., 2013b; Wang et al., 2014c) and that future additional data, in combination with field and geochemical constraints, may enable further structural subdivisions, especially within the Jiangnan Orogen.

Geochemically the volcanic rocks from Jiangnan Orogen mostly resemble those in modern magmatic arcs with enrichment in Th and light rare earth elements (LREE) and depletions in Nb, Ta, Zr, Hf and Ti, and whole rock εNd and zircon εHf values are variable but generally positive indicating input from juvenile sources (Fig. 9; Li et al., 2013c; Zhao and Asimow, 2014). Minor ca. 850 Ma N-MORB type igneous suites with LREE depleted patterns and enrichment in Sr and highly incompatible elements, along with moderate depletion in incompatible elements and Ti, have also been observed (Fig. 9; Wang et al., 2008b; Zhang et al., 2013b).

Mafic volcanic rocks with ages in the range ca. 1000-960 Ma from western Cathaysia display arc geochemical characteristics with depletion in Nb and Ta (Fig. 9; Shu et al., 2008b; Wang et al., 2013b). Others yield LREE depleted or flat REE patterns derived from the N-MORB and E-MORB-like sources modified by the addition of an arc-like component, and ascribed to fore- and back-arc settings (Wang et al., 2013b; Zhang et al., 2012a). Rhyolite dated at 972 Ma from the southeast margin of western Cathaysia is also characterized by depletion of Nb and Ta and an inferred magmatic arc origin (Shu et al., 2008b). The composition and provenance record of the sedimentary rocks is also consistent with derivation from a magmatic arc source (Wang et al., 2016b). Supra-subduction zone ophiolite rocks, which overlap with the overall duration of arc magmatism have also been recognized in the eastern Jiangnan Orogen (Wang et al., 2015b; Yao et al., 2016a; Zhang et al., 2013a; Zhang et al., 2015a).

The geochronological and geochemical data suggest a long lived convergent plate margin setting within South China extending from around 1000 Ma to 810 Ma (e.g., Fig. 4c). Critically, in terms of evaluating internal versus external models for South China in Rodinia, a supra-subduction zone setting for rocks from the boundary between the Yangtze and Cathaysia blocks is maintained until ca. 830-810 Ma (Li et al., 2013c; Wang et al., 2016b; Zhang et al., 2012b; Zhao, 2015). This age relationship indicates that accretion of these blocks was not complete until this time and is consistent with an external location for South China, either within an already assembled Rodinia or as part of independent plate separated from Rodinia. Early Neoproterozoic (ca. 860-820 Ma) bimodal basalt-rhyolite rock assemblages occur within Cathaysia (e.g., Li et al., 2005; Shu et al., 2011) but overlap with the overall age range of the rock associations with supra-subduction zone affinities (Chen et al., 2013; Yao et al., 2016b; Zhang and Wang, 2016; Zhao and Cawood, 2012, and references therein). We consider that such rocks reflect lithospheric extension within an overall convergent plate margin setting related to the southeast directed subduction of oceanic crust beneath northwest margin of the Cathaysia Block. Peraluminous, S-type granitoids in Jiangnan dated at 830-815 Ma may mark final accretion of the Yangtze and Cathaysia blocks and the termination of subduction in the region (Wang et al., 2006; Yao et al., 2014b). Earlier pulses of peraluminious granites have been recognized, such as those in the Wuyi-Yunkai domain of Cathaysia that range in age from 985-913 Ma (Wang et al., 2014c). These likely reflect periodic arc accretion events or coupling between the down-going and overriding plates within an evolving convergent plate margin framework (cf., Cawood et al., 2011). After assembly of the craton, a pulse of lithospheric extension is recorded in the Jiangnan Belt and the Cathaysia Block on the basis of lithostratigraphic records and bimodal magmatism characterized by within plate geochemical signatures (Wang et al., 2012a; Yao et al., 2014a; Zhao and Cawood, 2012).

The tectonic setting of Neoproterozoic igneous activity within the Panxi–Hannan Belt, along the western margin of the Yangtze Block, is also disputed with both convergent plate and within-plate settings proposed (Dong et al., 2012a; Dong et al., 2011; Li et al., 2003c; Zhou et al., 2006; Zhou et al., 2002). The bulk of the geochemical data for the plutonic and volcanic rocks of the belt indicate low-K tholeiitic to calc-alkaline and minor alkalic compositions along with enrichment in LREE and depletion in Nb, Ta, Zr and Hf, similar to rocks emplaced in magmatic arc settings (Cai et al., 2015; Dong et al., 2011; Wang et al., 2016c; Zhou et al., 2002). On the Hf-Th-Ta diagram, the majority of the rocks from the Panxi-Hannan Belt plot in volcanic arc field, with a minor component of samples displaying MORB features (Fig. 9). The geochemical affinities of these rocks in combination with the overall protracted, 300 Ma, duration of this igneous activity from ca. 1000-700 Ma (Fig. 3) is best accounted for through a long lived convergent plate margin setting on the periphery of Rodinia (Dong et al., 2012a; Dong et al., 2011; Zhao et al., 2011; Zhou et al., 2006; Zhou et al., 2002). Minor mafic igneous rocks with ages around ca. 800 Ma yield within-plate geochemical features with enrichment in Th, Ta, Nb, Zr, Hf and smooth LREE-enriched patterns (Fig. 9; Li et al., 2002a). However, given the protracted age range of magmatic arc signatures, extending from ca. 1000 Ma to ca. 700 Ma, we consider these ca. 800 Ma volcanic rocks were emplaced in a back arc or intra-arc extensional setting.

Models invoking lithospheric extension either above a mantle plume or though asthenospheric upwelling driven by orogenic collapse and lithospheric delamination suggests that at least some of the supra subduction zone geochemical signature relates to remelting of older rock with arc signatures or assimilation of pre-existing arc components (Li et al., 2006; Li et al., 2003b; Li et al., 2003c). The overall low grade of rock units in the Panxi-Hannan Belt argue against extensive orogenic collapse and associated exhumation, and the protracted record of magmatic activity within the belt is at odds with a fixed mantle plume emplaced into mobile lithosphere. As with the Jiangnan belt, we envisage any plume related geochemical signatures (Zhou et al., 2000) within the belt to reflect plume interaction within an overall supra subduction zone environment.

Mafic to silicic igneous rocks within the Ailaoshan tectonic zone, along the southern margin of the South China Craton range in age from 830-760 Ma (Wang et al., 2016c, and references therein). The geochemical signature of the rock units suggest derivation from a mantle wedge modified by slab-derived melt (Cai et al., 2014; Cai et al., 2015; Wang et al., 2016c). They are considered to represent the contemporaneous along strike extension of the Panxi-Hannan belt that has been subsequently disrupted and strung out along the southern margin of the South China Craton by tectonic activity along the Ailaoshan-Song Ma suture zone.

5.1. Was South China a separate plate in the Neoproterozoic?

Detrital zircons from late Neoproterozoic (Nanhua & Sinian, 710-540 Ma) sedimentary rocks in the Cathaysia Block range in age from 3755 Ma to 544 Ma with prominent age peaks at 950 Ma and 2.5 Ga and subordinate peaks at 1100 Ma, 835 Ma, 750 Ma and 584 Ma (Fig. 5; Yu et al., 2008; Yu et al., 2010). Early to mid-Neoproterozoic detrital zircons overlap with igneous activity recognized in South China and hence could be locally derived but other age components (e.g. 1100 Ma and 584 Ma) have not been recognized in South China and, along with evidence for abrasion of zircons, suggest long distance transport through one or more sedimentary cycles from sources beyond the craton. The overall age signature is similar to that in sedimentary rocks in northern India and suggest derivation from a common source consistent with South China attached to India at the time of sediment accumulation. Yao et al. (2014c) invoked a model in which South China collided with North India at ca. 580 Ma to account for the input of detritus derived from North India in the Cambrian sandstones of South China, but there is no evidence for tectonothermal event in South China, which is inferred to have lain on the lower, downgoing plate during this inferred collision event. Given the similarity in the stratigraphy, sedimentology and detrital age patterns of Cryogenian to Ediacaran rock units of South China and North India (Hofmann et al., 2011; Jiang et al., 2003), a more plausible explanation is that South China was attached to North India from (at least) the early Neoproterozoic (Cawood et al., 2013; Merdith et al., in press).

5.2. *Subduction polarity and along strike extension of magmatic arc in Rodinia*

The number and polarity of subduction zones involved in accretion of the Yangtze and Cathaysia blocks are unresolved (Fig. 10). Proposed tectonic models include southeast-directed subduction of oceanic lithosphere beneath Cathaysia (Cawood et al., 2013), northwest-directed subduction either beneath an intraoceanic arc between Cathaysia and Yangtze or directly beneath the Yangtze Block (Li et al., 2009; Yao et al., 2016b; Zhao et al., 2011), multiple arc-back arc systems developed above east and locally west dipping subduction systems (Wang et al., 2013b), intra-Cathaysia subduction between proposed western and eastern portions of the block (Wang et al., 2013b), and two-sided divergent subduction beneath both the Yangtze and Cathaysia blocks (Zhao, 2015). Northwest directed subduction beneath SE Yangtze is inferred from northwest dipping structures that are truncated and overlain by undeformed Banxi Group and its equivalents (Shu and Charvet, 1996; Yao et al., 2016a), whereas southeast directed subduction is inferred from a spatial distribution of ophiolite and arc magmatism (Dong et al., 2011; Sun and Vuagnat, 1992; Wang et al., 2016c; Zhou et al., 2006; Zhou et al., 2002). On the other hand, southeast directed subduction beneath northwest Cathaysia is proposed based on the distribution of magmatism with arc or MORB dominated geochemical signatures (Wang et al., 2013b; Zhang et al., 2012a; Zhao, 2015).

The diversity of proposed subduction polarities and potential numbers of subduction zones reflects in part uncertainty in establishing unequivocal links between the discrete elements that constitute a supra-subduction zone system (e.g. magmatic arc, backarc basin, forearc basin). Recognition of individual supra-subduction zone elements does not, in and of itself, establish subduction direction; individual elements must be linked in an assemblage (e.g., magmatic arc with contemporaneous back-arc basin or magmatic arc and linked forearc basin) or the magmatic arc lies on the edge of a continental margin. Only then can subduction direction for that individual assemblage be established and only when multiple assemblages are shown to be contemporaneous and to have lain across strike at their time of formation can multiple subduction zones be defined. Given limitations in present day exposure, and uncertainties in establishing both the original tectonic setting of individual elements of the arc system and in determining the precise age and relations between Neoproterozoic rock units, then constraining the original relationships between the various supra-subduction zone elements has proved challenging.

A peripheral setting for South China adjacent to India in the early to mid-Neoproterozoic is supported by analysis of the tectonic setting of rock assemblages in other continental fragments that are inferred to have lain along strike to the magmatic activity developed in the Panxi-Hannan Belt (Fig. 11). Geochronological and geochemical data for Neoproterozoic volcanic and plutonic rocks ranging in age from 800-700 Ma from the Seychelles, Madagascar and northwestern India (Malani Igneous Suite) are considered to have formed part of a continuous continental margin arc (Archibald et al., 2016; Archibald et al., 2017; Ashwal et al., 2002; Ashwal et al., 2013; Thomas et al., 2009; Tucker et al., 2001; Zhou et al., 2006).

6. South China at the time of Nuna

A number of models have been proposed for the position of South China in Nuna, the late Paleoproterozoic supercontinent (Wang et al., 2017; Wang et al., 2016a; Yin et al., 2013b; Yu et al., 2012; Zhou et al., 2014). Zhao et al. (2002) tentatively incorporated a coherent South China on the margin of Nuna within an embayment bounded by Australia and Siberia but subsequent workers have recognized the discrete and independent histories of Cathaysia and Yangtze during this period.

The rarity of Paleoproterozoic to Mesoproterozoic rocks in the Cathaysia Block has impeded understanding of its position and role in the Nuna supercontinent (e.g., Zhao and Cawood, 2012 and references therein). The recognition of ca 1430 Ma magmatism on Hainan Island (Li et al., 2008b) and southern Laurentia (Nyman et al., 1994; Whitmeyer and Karlstrom, 2007), as well as the presence within these regions of similar ca 1800 Ma basement and Archean protoliths, has been used to argue that Cathaysia represented a western extension of southwestern Laurentia by the early Mesoproterozoic. This proposed link has resulted in models in which Cathaysia occupies an internal location between Laurentia and a combined East Antarctica-Australia within Nuna (Li et al., 2008b; Zhang et al., 2012c). The 1430 Ma magmatic activity is also invoked as the source for detritus of this age in 1.0 Ga sedimentary successions in the Yangtze Block and hence cited as evidence it has collided with Cathaysia by this time (Li et al., 2002b). In contrast, Yu et al (2012) placed Cathaysia outboard of Northern India on the margin of Nuna on the basis of similar detrital zircon patterns from inferred synchronous Paleoproterozoic (ca. 1.9-1.8 Ga) sedimentary sequences as well as similar ages of Paleoproterozoic orogenic belts between the two regions (Fig. 12). A detailed comparison demonstrates that the Paleoproterozoic sedimentary sequences in the Cathaysia Block show detrital age patterns similar to synchronous sequences from northern India and Lesser Himalaya, but different from those of the North China Craton and Northwestern Laurentia (Fig. 13; Wang et al., 2017). Furthermore, the record of metamorphic-magmatic-sedimentary events in northern India (including the Aravalli-Fold belt and the Lesser Himalaya) and the Cathaysia Block indicates a close linkage between the two during Nuna assembly. Synchronous Paleoproterozoic (1.9-1.8 Ga) sedimentary sequences, represented by the Badu complex in Cathaysia, the Udaipur Formation in the Aravalli Delhi Belt, and the Jutogh and

Rampur Formations in Lesser Himalaya, contain similar detrital age peaks at ca. 2.5 Ga and ca. 1.88 Ga (Long et al., 2011; McQuarrie et al., 2008; Yu et al., 2012). In addition, 1.88-1.86 Ga granulite facies metamorphism, 1.90-1.81 Ga syn- and post-collisional felsic igneous rocks, and ca. 1.83-1.80 Ga within plate mafic volcanic rocks occur in both the Cathaysia Block and northern India (Chambers et al., 2008; Richards et al., 2005; Yu et al., 2012; Yu et al., 2009). In further support of locating Cathaysia adjacent to northern India, we note that 1430 Ma igneous activity is not limited to Hainan Island and Laurentia but is also known from India and is proposed as a potential source for detritus of this age in younger sedimentary rocks deposited across northern India (Myrow et al., 2010, and references therein). Thus, Indian, rather than Laurentian, derived material could act as a source for detritus of this age in Cathaysia.

A new paleomagnetic pole for the 1466 Ma Lakhna dykes from the Bastar Craton in India suggest it was tied to Baltica within the Nuna supercontinent (Pisarevsky et al., 2013; Pisarevsky et al., 2014). In this paleomagnetically constrained reconstruction, the Dharwar craton of southern India is positioned against the Sarmatia craton of southern Baltica bounded by the Central Indian Tectonic Zone and the inferred along strike 2.1 to 2.0 Ga Lipetsk-Losev-East Voronezh Belt on one side and ca.1.8-1.3 Ga accretionary orogens in the Eastern Ghats and southern Baltica on the other. Within this configuration, Cathaysia lay off northern India (present coordinates). The limited Paleo- and Mesoproterozoic history of Cathaysia suggests it lay inboard of the inferred accretionary orogens that developed along the margins of Baltic and India. Late Mesoproterozoic paleomagnetic data suggest that India (along with Cathaysia) and Baltica separated between 1120-1080 Ma (Pisarevsky et al., 2013). Geological evidence for this breakup event is limited due to subsequent overprinting events but data from southern Baltica that rifting and platform formation occurred in the late Mesoproterozoic at a location corresponding approximately with the younger Teisseyre-Tornquist line (Bogdanova et al., 2008; Nikishin et al., 1996; Poprawa and Pacze´sna, 2002)

Evidence for Paleoproterozoic metamorphism of parts of the Yangtze Block (ca. 2.0 Ga, Figs. 3, 12) has been considered as crucial evidence to demonstrate its involvement in the assembly of the Nuna supercontinent (Sun et al., 2008; Wu et al., 2008b; Yin et al., 2013a; Zhang et al., 2006). Nevertheless, the widespread distribution of orogenesis of this age within Nuna (Zhao et al., 2002), means that the presence of such a metamorphic event cannot by itself accurately constrain the position of the Yangtze Block within the supercontinent. Proposed links between the Yangtze Block and other continental fragments within Nuna include Western Australia, which is based on the presence of similar ca. 2.3 Ga detrital age peaks (Wang et al., 2012c). However, multiple Proterozoic tectonothermal events in Western Australia, including the ca 2.2 Ga Ophthalmian Orogeny, the 2.0–1.96 Ga Glenburgh Orogeny, the 1.83–1.78 Ga Capricorn Orogeny, the 1.79–1.76 Ga Yapungku Orogeny and the 1.68–1.62 Ga Mangaroon Orogeny (Cawood and Korsch, 2008, and references therein) lack counterparts in the Yangtze Block. The Yangtze Block has been conjoined with northern Australia and India on the basis of similar age and character of iron oxide copper gold (IOCG) deposits, represented by the late Paleoproterozoic to early Mesoproterozoic Dongchuan deposit in Yangtze, the Khetri deposit in India, and the Ernest Henry and Lightning Creek deposits in Australia (Zhou et al., 2014). Mineralization was inferred to occur during initial breakup of the supercontinent. The linkage between the India and Yangtze blocks, however, is challenged by the absence of ca. 2.7 and 2.3 Ga components in ca. 1.7 Ga sequences in northern India (Fig. 13), which constitutes distinct detrital compositions in synchronous rift basin successions related to early Nuna breakup in the Yangtze, northern Australia and northwestern Laurentia (Wang and Zhou, 2014). Furthermore, episodes of within plate magmatism in the southwestern Yangtze Block at ca. 1.71 Ga and 1.68-1.66 Ga are bimodal (Chen et al., 2013), and differ from the ca. 1.72 Ga felsic dominated magmatism and granulite facies metamorphism in the Aravalli-Dehli belt of India (Bhowmik and Dasgupta, 2012; Biju-Sekhar et al., 2003; Buick et al., 2006; Buick et al., 2010).

Recently, Wang et al. (2016a) noted that the record of magmatic events in the southern Yangtze Block at ca. 2.9 Ga and ca. 2.2 Ga along with metamorphic events at 1.97-1.96 and ~1.83 Ga, which were followed by rift and passive margin sedimentation in the period ca. 1.74-1.50 Ga, and related to an evolving history of Nuna assembly and breakup, is similar that in northwestern Laurentia. Systematic comparison of the timing and character of igneous, metamorphic events and provenance data for southwestern Yangtze Block, northwestern Laurentia and Siberia suggests a close linkage among these continental blocks within Nuna (Figs. 11, 13).

7. Discussion and conclusions

Figure 14 shows our preferred history of assembly and breakup of the Yangtze and Cathaysia blocks with other continental fragments prior to their amalgamation in the Neoproterozoic to form the South China Craton. In the mid-Paleozoic, South China rifted off northern Gondwana, drifting across the Tethys Ocean to collide with North China in the late Paleozoic to Mesozoic to form part of the Asian segment of Pangea.

The Archean record of the Yangtze Block indicates a period of Neoarchean continental lithospheric development and stabilization. The record is restricted spatially to isolated fragments, such as the Kongling complex, and their link to other Archean cratons is unknown. Late Archean and Paleoproterozoic magmatic and metamorphic events in the Yangtze in the period 2.9 Ga to 1.8 Ga are similar to in character to those in northwest Laurentia (Fig. 12) suggesting a common record of lithospheric formation culminating in accretion of the cratonic masses, and perhaps also involving Siberia, which show a similar tectonothermal record and suggest a spatial association (Wang et al., 2016a). Northern Laurentia and the Yangtze Block display a similar subsequent record of 1.8-1.6 Ga sedimentation and magmatism associated with lithospheric extension and continental breakup, which is taken to indicate separation of the two continental fragments. Younger Mesoproterozoic successions are largely absent from the Yangtze Block (Figs. 3, 12).

No Archean rocks are exposed in Cathaysia but their presence has been inferred on the basis of Archean Nd and Hf model ages and inherited zircons in Paleoproterozoic granites (Liu et al., 2014, and references therein). The composition of the granites changes from an earlier pulse of I- and S-types emplaced between ca. 1929-1875 Ma and interpreted to relate to a continental collisional environment, and later ca. 1880-1850 Ma A-types, along with minor mafic magmatism as young as 1760 Ma (Li et al., 2010) related to a post-collision collapse and extensional setting (Liu et al., 2014; Yu et al., 2009). The granites were emplaced into the Badu Complex which underwent high-grade granulite facies metamorphism around 1890 Ma (Yu et al., 2012). The record of Paleoproterozoic tectonothermal events in Cathaysia and ages of detrital zircons correlates well with events in northern India (Figs. 12, 13), suggesting that the two were linked. Thus, the record of metamorphism and granite magmatism in Cathaysia is taken to record its assembly with northern India around 1910-1875 Ma as part of the more general assembly of the Nuna supercontinent (Figs. 4, 12). The paleogeographic relations of Cathaysia prior to this time are unknown.

Assembly of the Yangtze and Cathaysia blocks occurred along the Jiangnan Orogen in the early Neoproterozoic (Figs. 3, 4, 10). Geochemical affinities of rock units within the orogen suggest formation in an overall supra-subductions zone environment (Fig. 9), which extended from ca 1000-810 Ma. An overall subduction-related accretionary orogen setting continued until almost 700 Ma along the western margin of the Yangtze and along strike equivalent belts in the Seychelles, northern Madagascar and northwestern India (Fig. 11). This protracted record of convergent plate margin activity establishes that the assembly of the Yangtze and Cathaysia blocks occurred on the margin of an already assembled Rodinia supercontinent (Fig. 4), or possibly on a tectonic plate separate from Rodinia (Merdith et al., in press). Bi-modal magmatism that overlaps in age with this period of convergent plate margin activity likely reflects lithospheric extension within backarc basin settings. The united South China Craton remained fixed to northern India during Rodinia breakup and Gondwana assembly from the mid-Neoproterozoic to early Paleozoic (Fig. 4). The final assembly of Gondwana took place in the early Paleozoic along the Kuunga orogen and resulted in amalgamation of the Sanya Block in southern Hainan Island, which at that time lay along the northwestern margin of Western Australia, with the rest of South China and India (Fig. 6). Breakup of South China from northern Gondwana commenced in the mid-Paleozoic coincident with the assembly of Pangea (Figs. 4, 14).

In summary, South China and its constituent lithotectonic fragments record a long history of assembly and dispersal within the major supercontinents of Earth history (Figs. 4, 14). The late Archean timing of crustal growth and reworking events in South China correspond with a period of widespread craton formation (Bleeker, 2003). This phase of continental growth has been termed the Kenor supercontinent or supercraton but it is unclear to which, if any, of the other temporally equivalent cratons that the various Late Archean elements in South China were linked. Assembly of Yangtze with Laurentia and Cathaysia with India were part of a series of events associated with the formation of the late Paleoproterozoic supercontinent of Nuna. The breakup of Yangtze and Laurentia corresponds with the partial breakup of Nuna but the core elements of Laurentia, Siberia and Baltica appear to have remained largely intact through the Mesoproterozoic (Cawood and Hawkesworth, 2014; Cawood et al., 2016; Evans and Mitchell, 2011; Pisarevsky et al., 2014) and Cathaysia remained attached to India throughout this timeframe (Yu et al., 2012) positioned along, or outboard of, the margin of the assembling Rodinia supercontinent. The position of the Yangtze Block after it separated from Laurentia for the remainder of the

Mesoproterozoic prior to assembly with Cathaysia is unknown. Limited paleomagnetic and geological evidence suggests that the combined India and Cathaysia broke away from southern Baltica in the late Mesoproterozoic (Pisarevsky et al., 2014, and references therein). The Yangtze Block was sutured to Cathaysia along the Jiangnan Orogen in the early Neoproterozoic, creating the combined South China Craton (Cawood et al., 2013; Zhao, 2015). Subduction continued along the western margin of the Yangtze until the mid-Neoproterozoic and extended through northwestern India to the Seychelles and northern Madagascar (Ashwal et al., 2013; Zhou et al., 2006). During Gondwana assembly India-Cathaysia collided with the Western Australia-Mawson block along the Kuunga orogen resulting in the accretion of the Sanya Block to the rest of South China (Xu et al., 2014b). The accretion of Laurussia to Gondwana in the mid-Paleozoic to form Pangea corresponded with lithospheric extension along the northern margin of Gondwana and the separation of a number of continental blocks including South China, which then drifted northward across the Paleo-Tethys to collide with the Asian segment of Pangea in the Permo-Triassic (Metcalfe, 2013).

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8. Figures

Figure 1. Tectonic map of Asia showing continental blocks and bounding sutures (adapted from Li, 2006; Metcalfe, 2013).

Figure 2. Geological map of South China. Uncolored areas depict Phanerozoic sedimentary and igneous rocks.

Figure 3. Time space plot showing age range of principal rock units and tectonothermal events within the South China Craton. Emieshan Large Igneous Province, dated at 260 Ma (Huang et al., 2016), and which overlies part of the southwestern Yangtze Province, is not shown. Abbreviations: BB – Baoban Group and equivalents; BG – Banxi Group and equivalents; BJ – Bikou and Julin groups and equivalents, and associated plutonic complexes; BS – Badu supracrustals; DG – Dongchuan Group; DP – Datangpo Formation; DS – Dahongshan Group; GC – Gucheng Formation; HC – Houhe Complex; HK – Hekou Group; HS – Huangling intrusive suite; JK – Jiangkou Formation; KC – Kongling Complex and equivalents; KY – Kunyang & Yanbian group and equivalents; LG – Longquan Group and equivalents along with associated intrusive rocks; LS – Lengjiaxi Group; NT – Nantuo Formation; QG – Quanyitang granite; SS – Sizhoushan Formation; SG – Shuangxiwu Group; LJG – Lengjiaxi Group and equivalents; SY – Shenshan and Yunkau groups and equivalents; TD – Tianzidong Formation; XM – Xiangmeng Formation; YG – Yunkai Group and equivalents; ZL – Zhengyuanling Formation.

Figure 4. Schematic paleogeographic reconstructions showing position of the Cathaysia, Yangtze blocks in various inferred supercontent reconstructions at: a) Nuna assembly at ca. 1.7 Ga (adapted from Pisarevsky et al., 2014); b) Nuna at 1.35 Ga (adapted from Pisarevsky et al., 2014); c) Rodinia assembly at ca. 900 Ma (adapted from Cawood et al., 2013); d) Gondwana assembly at 500-450 Ma (adapted from Cawood and Buchan, 2007); e) Pangea assembly at ca. 300 Ma (adapted from Metcalfe, 2013). Abbreviations: Am, Amazon; Aus, Australia; Co, Congo; Ba, Baltica; In, India; La – Laurentia; NC, North China; Ma, Mawson; WAf, west Africa; SF, San Francisco; Si, Siberia; Y: Yangtze Block, CA: Cathaysia Block, Mad: Madagascar; , IC: Indo-China Block.

Figure 5. Detrital zircon age distributions for Neoproterozoic and Phanerozoic sedimentary rocks from: a) the Ordovician strata above the unconformity in the Sanya region, Hainan Island (Xu et al., 2014b), b) the Cambrian strata below the unconformity in the Sanya region, Hainan Island (Xu et al., 2014b), c) Early Paleozoic strata in South China (Chen et al., in press; Wang et al., 2010c; Xu et al., 2013; Xu et al., 2014a), d) Tethyan Himalaya (Hughes et al., 2011; Myrow et al., 2010; Myrow et al., 2009), e) Ordovician, Permian and Triassic strata, Western Australia (Cawood and Nemchin, 2000; Kettanah, 2015; Veevers et al., 2006), f) Northampton Complex, Western Australia (Ksienzyk et al., 2012), g) Late Neoproterozoic strata, Cathaysia Block, South China Craton (Yu et al., 2008; Yu et al., 2010); h) Precambrian quartzite in the Qiongzhong Block, Hainan Island (Li et al., 2008b). Age ranges important in comparing data sets between the regions are highlighted in blue (1300-1100 Ma) and orange (1000-900 Ma) color bands; n—total number of analyses. All data based on analyses with <10% discordance. Ages older than 1000 Ma were calculated using ^{207}Pb/^{206}Pb ratios, and ages younger than 1000 Ma were calculated using ^{206}Pb/^{238}U ratios. Data used in plots given in Supplementary Table 1.

Figure 6. a) Simplified reconstruction showing the location of the South China Craton and other Asian continental blocks along the northern Gondwana margin at around 500 Ma (adapted from Xu et al., 2014b). The position of South China outboard of India is based on similarities of the detrital zircon record of the two regions (see figure 4). However, the Sanya Block from Hainan Island is detached from the rest of South China and placed close to Western Australia on the basis of the Cambrian provenance and faunal record. By the Ordovician the Sanya Block was joined to the rest of the South China Craton (see figure 5), and the region then became part of an accretionary orogen on the northern margin of Gondwana (Cawood et al., 2007); b) and c) Schematic cross-sections from India-South China to Australia for the Cambrian and Ordovician showing inferred suturing of Sanya Block with the rest of South China along the Kuunga suture.

Figure 7. Detrital zircon age distributions for Cryogenian rocks from: a) Southeastern Australia; b) western Laurentia; c) Lesser Himalaya of northwest India; and d) South China. Data compiled from Dehler et al. (2010) for The Unita Mountain Group and Big Cottonwood Formation, Laurentia; Gehrels et al. (1996) and Ireland et al. (1998)

for Adelaide Geosyncline, East Australia; Wang et al. (2012d) and Wang and Zhou (2012) for the Nanhua sequences of South China; and Hofmann et al. (2011) and McKenzie et al. (2011) for the Lesser Himalaya strata. Data used in plots given in Supplementary Table 2.

Figure 8. Initial $\varepsilon Nd_{(t)}$ value versus selected trace element diagrams for the Cryogenian (Nanhua, ~810-720 Ma) sedimentary rocks from the Yangtze Block of South China. Neoproterozoic felsic and mafic igneous rocks from South China and southeastern Australia are presented as potential sedimentary sources. Data sources: Nanhua Basin sequences (Wang et al., 2012d; Wang et al., 2011); 830-800 Ma mafic rocks from southern Australia Gardner Dyke Swarm and equivalent units (Wang et al., 2010b; Zhao et al., 1994); 820-760 mafic igneous rocks from South China (Li et al., 2002a; Lin et al., 2007; Ling et al., 2003; Wang et al., 2008a; Zhou et al., 2007); and 830-810 Ma granitic rocks from South China (Li et al., 2003a). Data used in plots listed in Supplementary Table 3.

Figure 9. Hf-Th-Ta diagram (after Wood, 1980) for Neoproterozoic igneous rocks from the Jiangnan, Panxi-Hannan and Cathaysia domains of the South China Craton. Sources of data, Jiangnan domain: Chen et al. (2014b), Li et al. (2008a; 2009), Wang et al. (2014a), Wang et al. (2008b; 2004), Yao et al. (2016a; 2016b; 2014a; 2015; 2014b), Ye et al. (2007), Zhang et al. (2013a), Zhang et al. (2012b), Zhang and Wang (2016), Zhang et al. (2012d; 2013b), and Zhao and Zhou (2013); Panxi-Hanna domain: Cai et al. (2014; 2015), Dong et al. (2011), Du et al. (2014), Li et al. (2002a), Ling et al. (2003), Wang et al. (2016c), and Zhou et al. (2006; 2002); Cathaysia domain: Li et al. (2005), Shu et al. (2011; 2008b), Wang et al. (2013b) and Zhang et al. (2012a). Data used in compiling diagram listed in Supplementary Data Table 4.

Figure 10. Diagram depicting distribution and direction of inferred convergent plate boundaries within and around the South China Craton. See text for discussion of data.

Figure 11. Proposed tectonic setting and paleogeographic links between Neoproterozoic Panxi-Hannan Belt in South China with time equivalent igneous activity in northwest India, Seychelles and Madagascar (Ashwal et al., 2013; Zhou et al., 2006). Extension in the upper plate of the convergent plate margin setting basin formation and sedimentation inboard of the magmatic arc in South China and northern India.

Figure 12. Time - space plot for principal early Paleoproterozoic to early Mesoproterozoic tectonothermal events within the northwestern Laurentia, Siberia South China and NW India. The tectnothermal events of Rae Craton include the Buffalo Head terrane and the Taltson - Thelon tectonic zone, which were accreted to or collided with the Rae Craton. The Wopmay orogen includes Coronation margin, Great Bear magmatic zone, Hottah terrane and Fort Simpson terrane. Abbreviations: AV - Aravalli Supergroup; BBS - Big Bear sequence; BBG - Baoban Group; BD - Badu complex; BG: Baker lake Group; DA: Damtha Group; DE: Deoban Group; HB - Hornby Bay Group; JU - Jutogh Group; L.AMs - Lower Amer Group and its equivalents including the Lower Murmac Bay, Ketyet River and Thluicho Lake groups; LD - Lower Dongchuan Group; LP - Lookout Point Formation; MK - Mukun Group; NDL - North Delhi Supergroup; PZ - Pitz Formation; RA - Rampur Formation; RO - Racklan Orogeny; SDL: South Delhi Supergroup; SL - Shilu Group; SQ - Sin Quyen Group; TD - Tangdan Group; TL - Thelon Formation; U.AMs - Upper Amer Group and its equvialents: the upper Murmac Bay, Ketyet River and Thluicho Lake groups; UD - Upper Dongchuan Group; UG - Uchur Group; WE - Wernecke Supergroup; WG - Whart Group. Data sources used in compilation of this diagram listed in Supplementary Figure 1.

Figure 13. U–Pb age spectra of zircons from Proterozoic metasedimentary rocks of: a) northern Aravalli orogen (Kaur et al., 2011; Wang et al., 2017); b) eastern Cathaysia Block, South China (Yu et al., 2012); c) Madagascar (Bauer et al., 2011; De Waele et al., 2011); d) inner Lesser Himalaya (Long et al., 2011; Martin et al., 2011; McKenzie et al., 2011; McQuarrie et al., 2008; Parrish and Hodges, 1996; Richards et al., 2005); e) southwestern Yangtze Block (Wang et al., 2012a; Wang and Zhou, 2014; Zhao et al., 2010); f) northwestern Laurentia (Rainbird and Davis, 2007); and g) northern margin of North China Craton (Ma et al., 2014; Zhong et al., 2015). Data used in compiling diagram listed in Supplementary Data Table 5.

Figure 14. Diagram highlighted principal craton blocks that South China and its constituent Yangtze and Cathaysia blocks have been associated with since the Archean and their relationship to supercontinent cycles. Blue lines connecting blocks represent inferred time range of continental rifting and drift, whereas red lines represent duration of convergence. Abbreviations: Cath – Cathaysia; GW – Gondwana; Pa – Pangea; La – Laurentia; Rodin – Rodinia; SC – South China; Sth – South; Yz – Yangtze.

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Cawood et al. Fig. 1

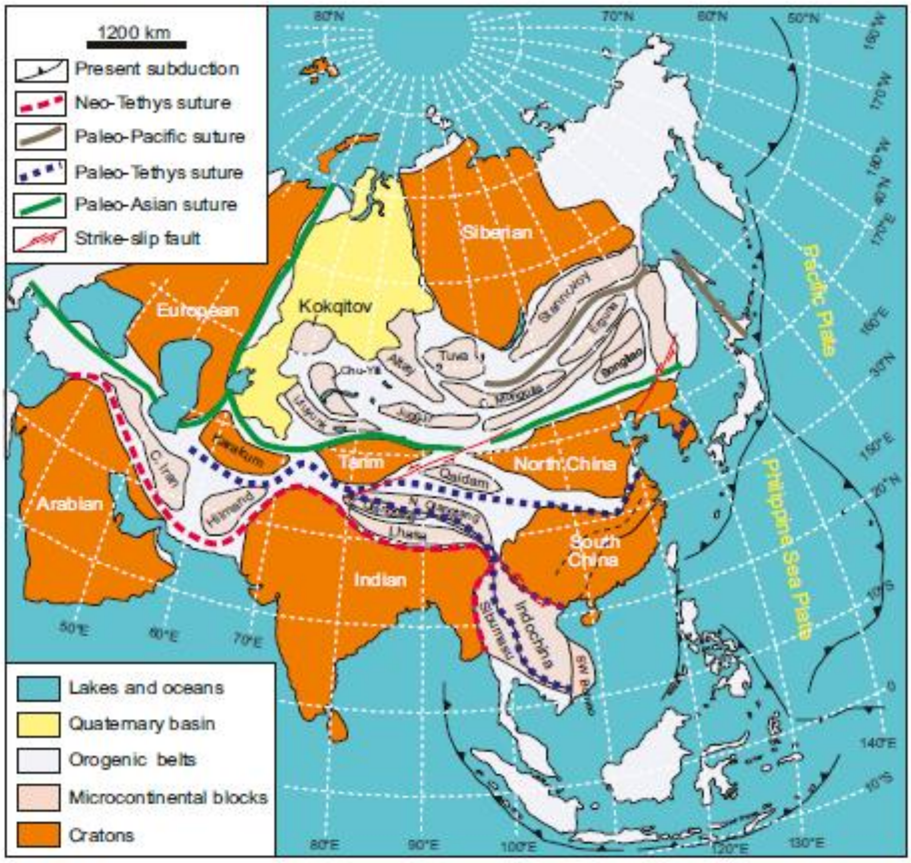
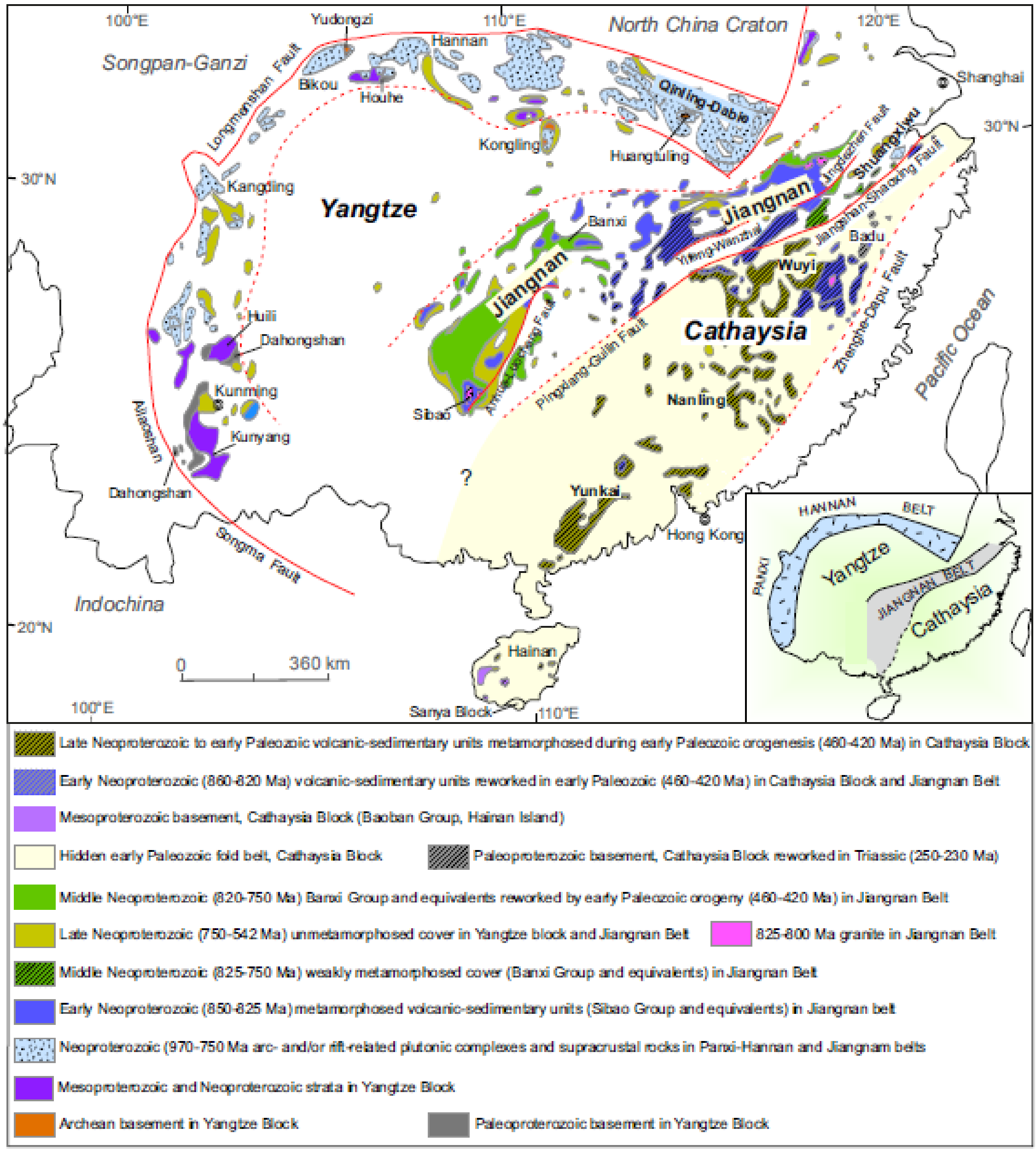


Figure 2 - Cawood et al.



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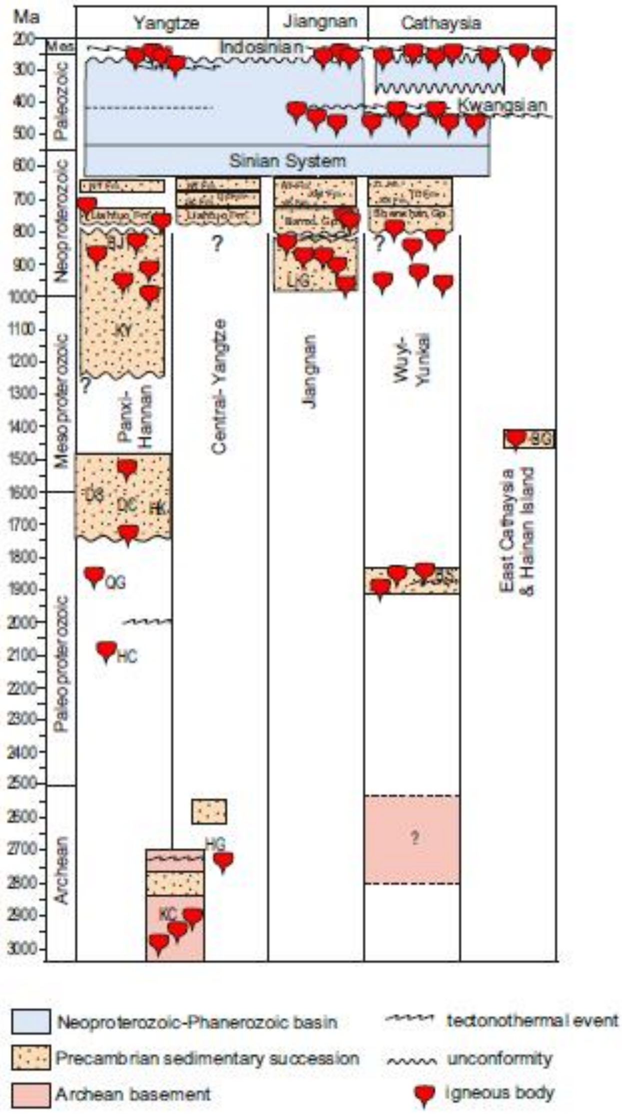

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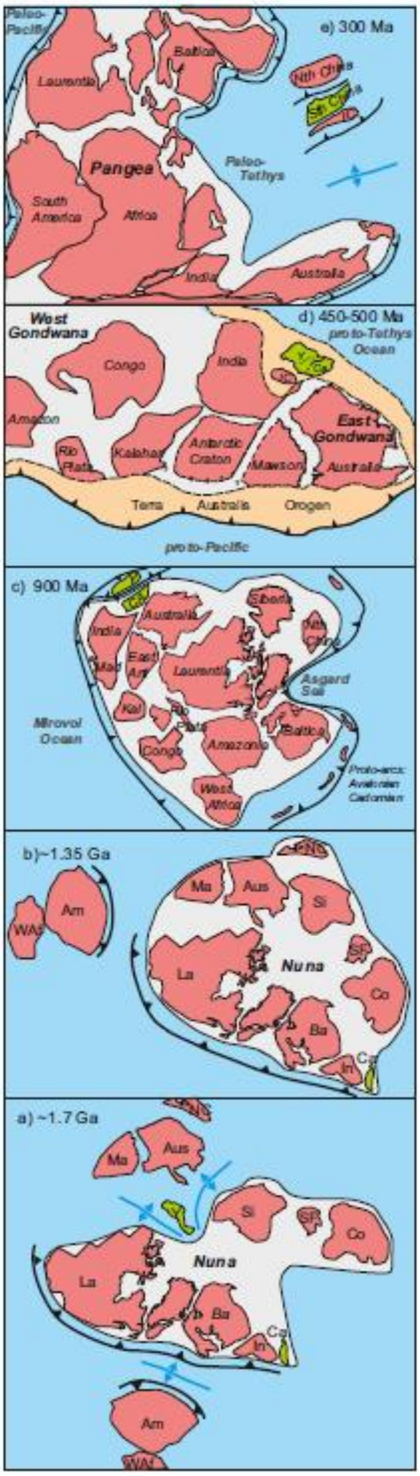

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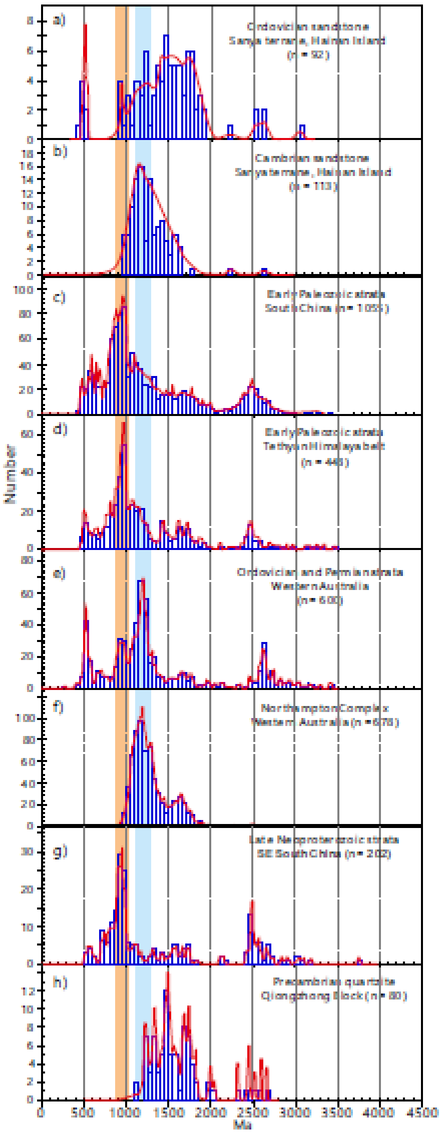

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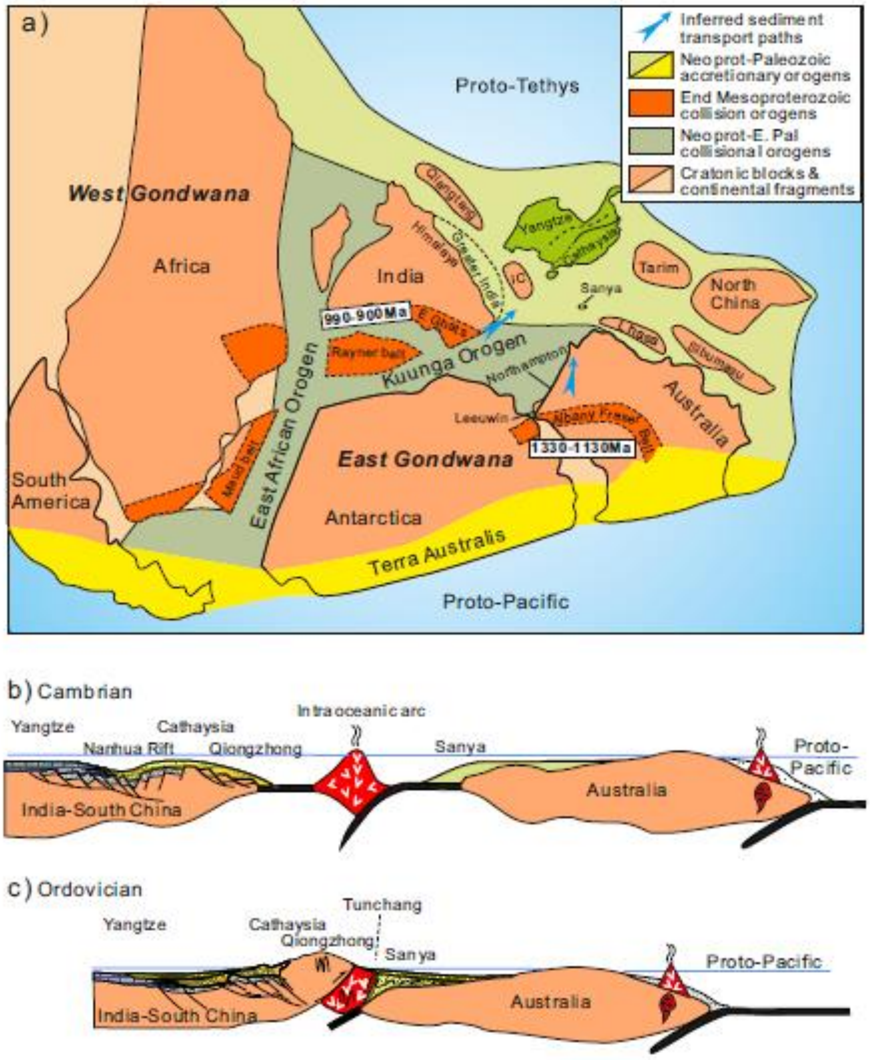

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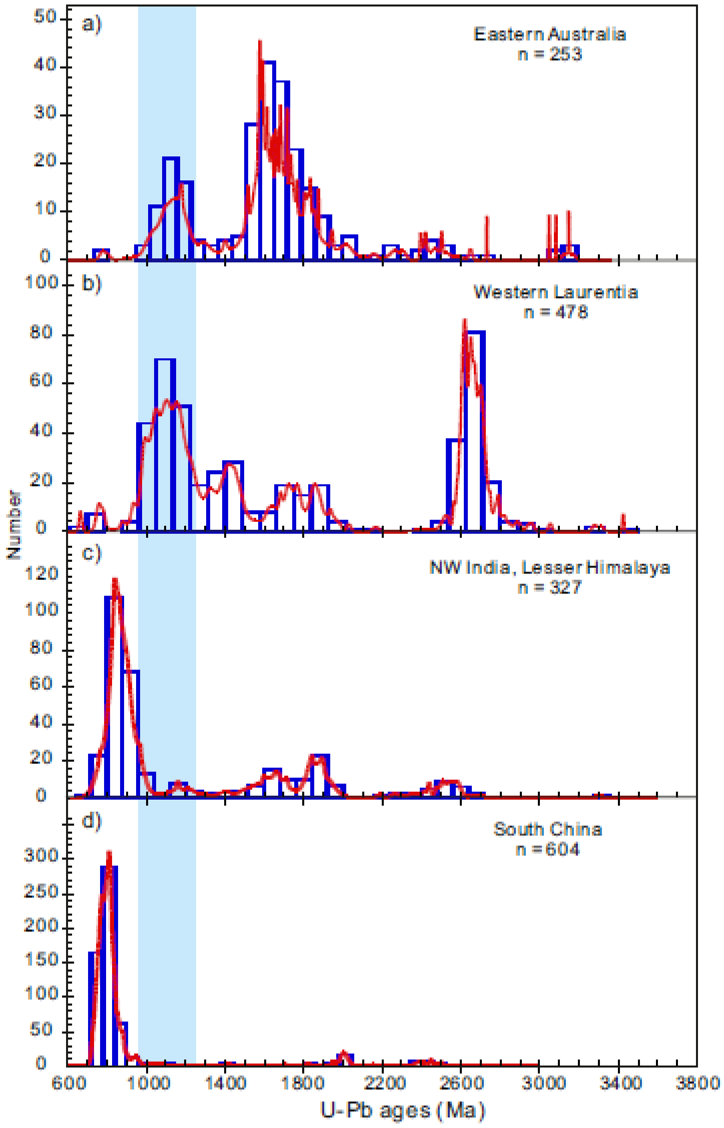

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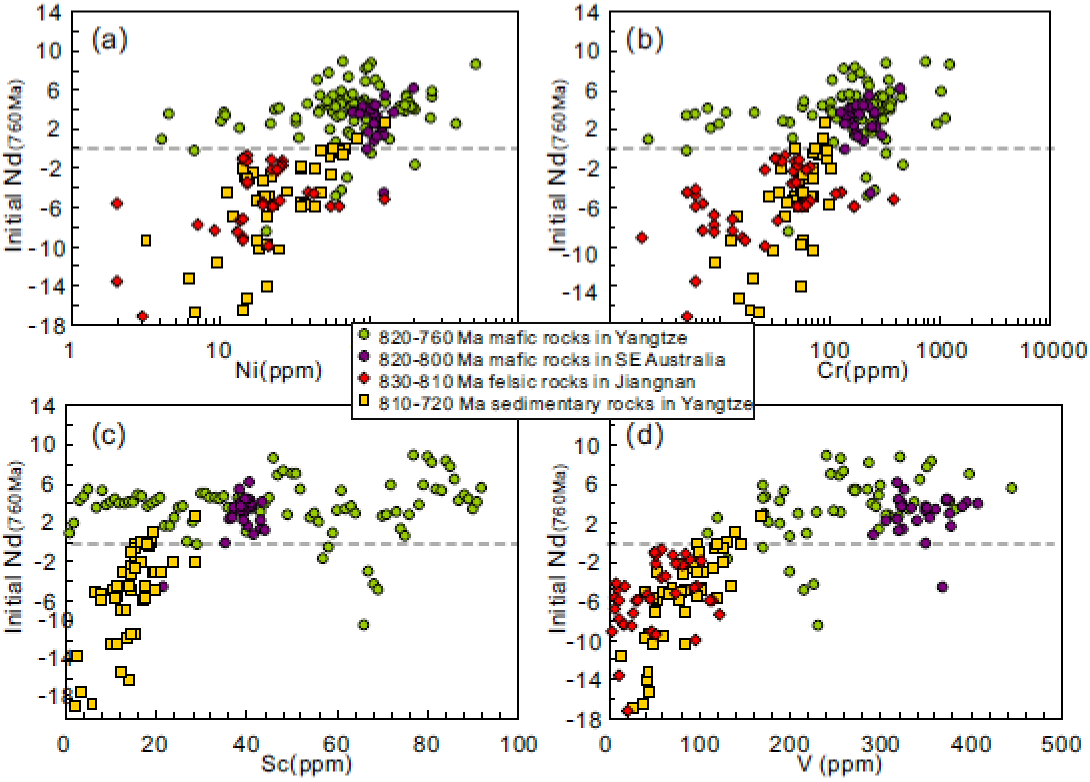

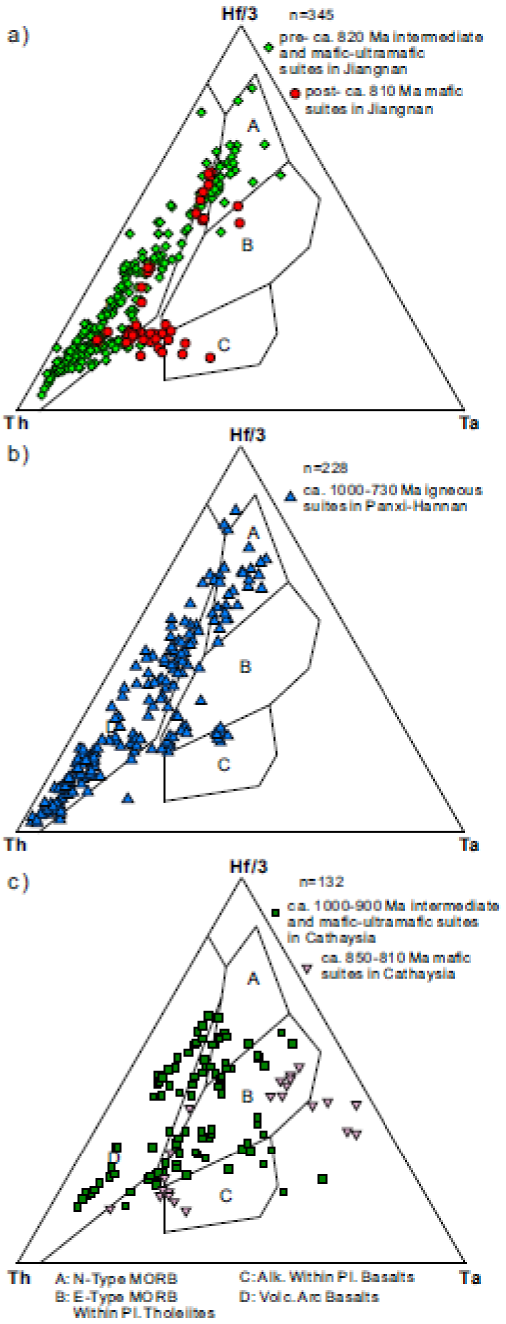

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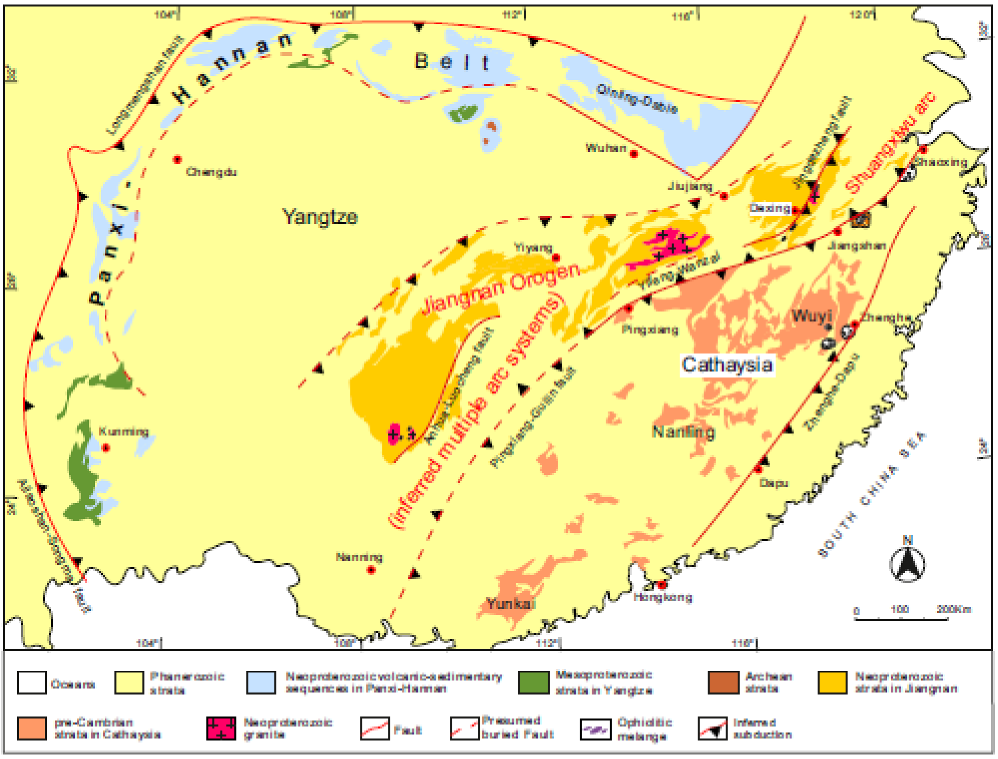

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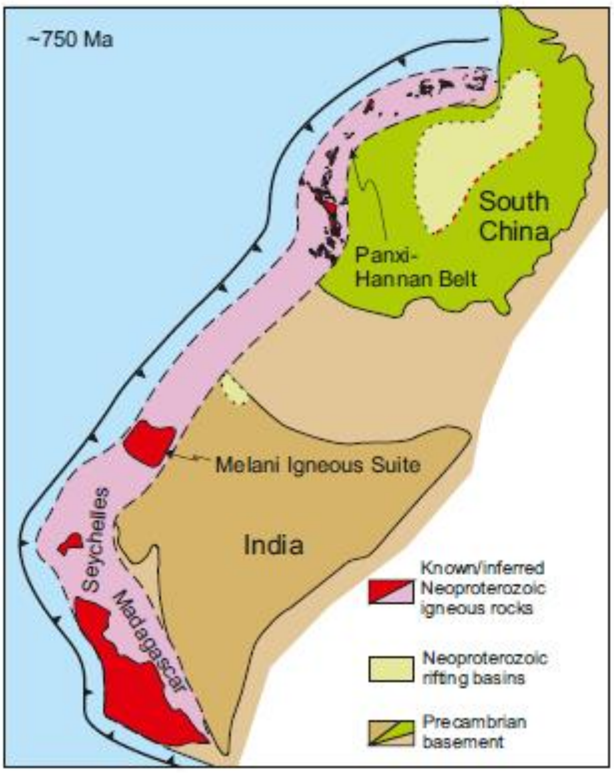

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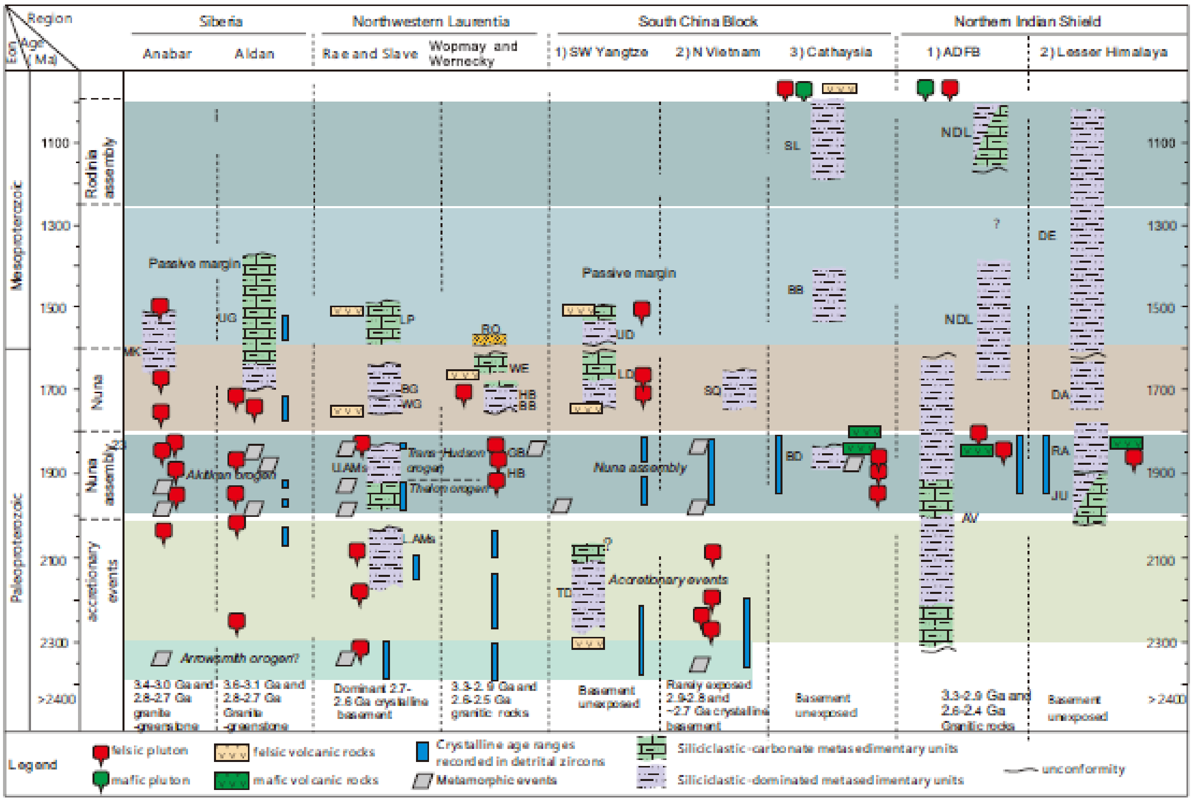

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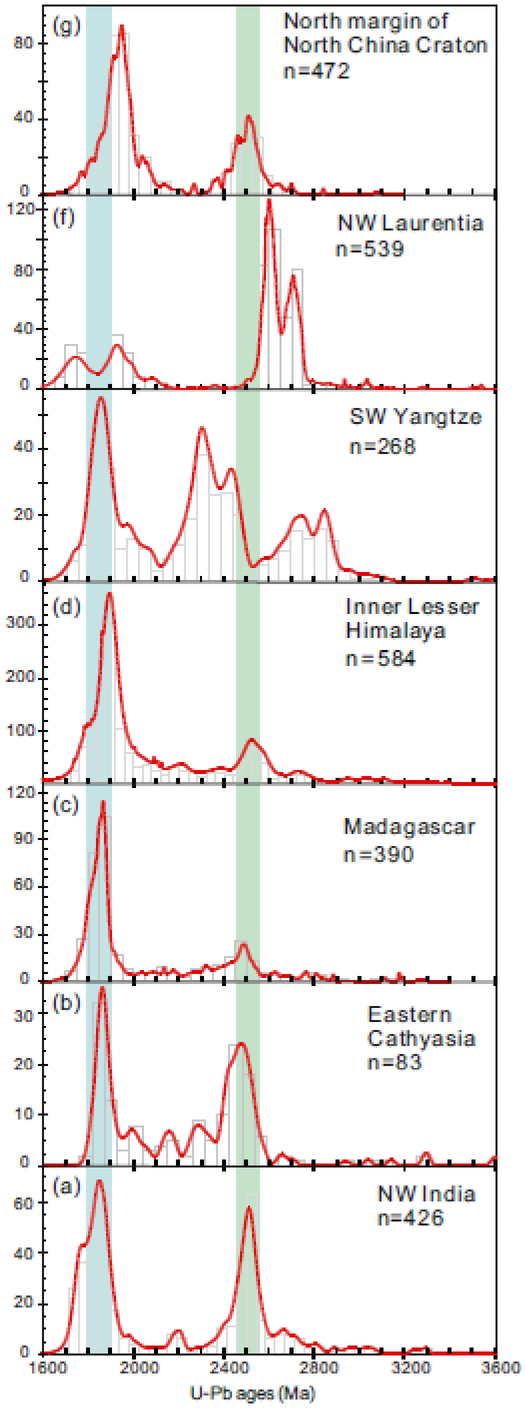

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