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Neoproterozoic geology and reconstruction of South China

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ABSTRACT

The South China Craton, as one of the largest continental blocks in China, has been considered as a key element in the Rodinia supercontinent. Its Precambrian rocks record a long-term and complicated tectonic history. In the past few decades, scientists obtained massive geochronological and geochemical data, as well as many structural and geophysical data, and proposed different percussive interpretations and models for the nature of the basement, formation of the unified South China Craton, and secular evolution of the lithospheric mantle and continental crust during Precambrian. In recent years, many new results have been available because of the development of in-situ analytical techniques. In this special issue, we compile new research outcomes about the Precambrian geology in South China. Totally twenty papers in the special issue covers fields in geophysics, igneous and sedimentary petrology and geochronology with a focus on unresolved and controversial issues. Our new special issue provides a timely addition to the understanding of the Precambrian geology of South China for the international geological community.

Key words: Neoproterozoic; Geology; reconstruction; South China

1. Introduction

South China comprises the Yangtze and Cathaysia blocks that were welded together along the Jiangnan Orogen (alternatively named as Sibao Orogen or Jiangnan Fold Belt) during the Neoproterozoic (Zheng et al., 2013; Zhao and Cawood, 2012; Zhao, 2014), and is considered as the key element in the Rodinia supercontinent (Zheng, 2004; Li et al., 2008; Cawood et al., 2013). In the past few decades, large volume of data have been published, primarily focusing on geochronology, geochemistry and petrogenesis of the igneous and sedimentary rocks in South China, as well as their relationships with the Neoproterozoic rocks in the neighboring continental blocks (e.g. India and Australia). A number of tectonic scenarios, such as plume model (Li et al., 2003, 2008a, b), plate-rift model (Zheng et al., 2007, 2008) and slab-arc models (Zhou et al., 2002, 2006, 2014; Wang et al., 2004, 2014; Zhao et al., 2011) have been proposed to interpret the tectonic settings and possible geodynamics. However, the positions of South China in Rodinia, assemblage between and Yangtze and Cathaysia blocks, and heat sources for melting of the continental crust are still a hot topic of debate.

In recent years, more and more lines of geological evidence have been presented in support of the hypothesis that the magmatism and sedimentation in South China were controlled by a series of subduction systems during the Neoproterozoic, and thus many scientists speculated that South China was probably located at a marginal position in the Rodinia supercontinent (Zheng, 2004; Zhou et al., 2006; 2014; Cawood et al., 2013). They also found that the Neoproterozoic magmatic and sedimentary successions are different in western and southeastern margins of the Yangtze Block, whereas the detailed geological processes are not clear. It is thus timely to have this special issue entitled "*Neoproterozoic geology and reconstruction of South China*", in which twenty papers were collected in order to clarify the tectono-magmatic evolution of the igneous rocks, provenance characteristics of the sedimentary rocks, and possible correlation between South China and the other neighboring blocks in Rodinia.

2. Grenvillian rift-related magmatism in South China

Late Mesoproterozoic igneous rocks in South China have been traditionally thought to mark Grenvillian orogens and are widely used for reconstruction of Rodinia (Li et al., 2008b). A few locations preserve late Mesoproterozoic to early Neoproterozoic volcano-sedimentary sequences, such as the Kunyang, Huili and Juling groups in the western (Greentree et al., 2006; Sun et al., 2009) and the Shennongjia and Dagushi groups in the northern Yangtze Block (Qiu et al., 2011; Du et al., 2016). However, these volcanic rocks are suggested to have been formed in rift settings. The two papers included in this special issue also support this hypothesis.

In the southeastern Yangtze Block, Wang et al. (2018a) conducted zircon U-Pb ages and Hf isotopes on the ore-related Liujia and Tieshajie basalts in the eastern Jiangnan Orogen. These volcanic rocks were formed during ca. 1.01 to 0.98 Ga. The basalts display typical OIB-like trace element patterns, high Ti contents, and positive zircon εHf values (+3.4 to +15.8), and are proposed to have been derived from a fertile asthenospheric mantle. The low Mg# values (36-58) indicate moderately to strong fractional crystallization of olivine and clinopyroxene. Zircon Hf isotopes of the ore-related porphyries in the Jurassic Dexing, Yinshan and Jiande deposits are plotted into the regime confined by the Liujia and Tieshajie basalts, supporting that melting of a metal-rich juvenile crust is likely responsible for the generation of the regional large scale Jurassic Cu-Au mineralization in South China. The Grenvillian-age sedimentary and igneous rocks are suggested to have been formed in an extensional setting, rather than related to continental collision.

Chen et al. (2018b) also conducted an integrated geochronological, geochemical and Nd-Hf isotopic study on the ~1050 Ma dacite, rhyolite and granites from Yunnan Province in the southwestern Yangtze Block. These felsic rocks show geochemical features similar to A-type granitoids formed in an intra-plate rifting setting, thus arguing against their existence of the so-called Grenvillian Orogen in the region. Instead, these A-type felsic rocks and the subsequent Neoproterozoic arc-related igneous rocks in the region record a tectonic change from a continental-rifting basin to a compression setting in the western Yangtze Block.

3. New advances about the Jiangnan Orogen of South China

It is widely accepted that Neoproterozoic amalgamation of the Yangtze and Cathaysia Blocks led to the formation of the unified South China Craton, following rifting that resulted in formation of the Nanhua Basin. However, the range and evolution history of the Jiangnan Orogen still remains unclear.

Due to the poor outcrops and multiple tectonic overprints, the range of the Jiangnan Orogen has never been precisely defined. Generally, the

Jiangshan-Shaoxing Fault is widely accepted as the boundary between the Jiangnan Orogen and the Cathaysia Block, although its western part remains unclear. To constrain the tectonic boundaries of the central and western Jiangnan Orogen, Guo and Gao (2018) performed a NW-trending deep seismic reflection profile, which is part of SinoProbe-02 project. Seismic data analysis and 2-D gravity modeling reveal that crustal structures of the Yangtze and Cathaysia Blocks are different. Together with the regional gravity and magnetic anomalies analysis, Guo and Gao (2018) proposed that the northern and southern boundary of the Jiangnan Orogen is Shitai – Jiujiang – Dayong – Tongren – Hechi - Baise and Shaoxing - Jiangshan – Pingxiang – Qidong – Yongzhou – Guigang - Nanning lines, respectively.

The previous tectonic models favored northwestward subduction and subsequent collision between the Yangtze and Cathaysia blocks, giving rise to the Jiangnan Orogen. More details are necessary for refining the amalgamation history. Based on the geochronological and geochemical data of the Neoproterozoic igneous rocks from the Jiangnan Orogen, Xia et al. (2018) proposed a modified amalgamation model: (1) closure of an ocean basin through oceanic-oceanic subduction and bidirectional oceanic-continental subduction that caused the development of the intra-oceanic arc and the active continental margins of Yangtze and Cathaysia, (2) continent-arc-continent collision that formed the Jiangnan Orogen, and (3) subsequent tectonic collapse led to the Nanhua rifting. The new model expands our future studies on the Neoproterozoic orogenic processes in the Cathaysia Block. This new model also supports the South China's marginal position in Rodinia due to lack of the Grenvillian Orogeny or mantle plume imprints.

The subduction beneath the southeastern margin of the Yangtze Block is well exemplified by the Northeast Jiangxi ophiolite (NJO) and the South Anhui ophiolite (SAO) which have been dated at ca. 1.0-0.9 Ga and ca. 840-820 Ma, respectively (Ding et al., 2008; Li and Li, 2003; Zhang et al., 2012). The SAO is considered as the suprasubduction zone (SSZ)-type ophiolites (Zhang et al., 2013 and references therein). In this study, Sun et al. (2018) gave new SHRIMP zircon U-Pb ages of 831 ± 5 Ma for the SAO. They used whole-rock and mineral compositions, PGE and Os isotopes, and revealed that the NJO complex underwent low degrees of partial melting and was formed in a fore-arc setting, whereas the SAO mantle experienced high melt extraction and was formed in a back-arc extensional setting. These two suits of ophiolites shed light on the tectonic evolution of the Jiangnan Orogen and record the orogenic evolution from the early oceanic subduction to the late back-arc extension and finally the back-arc basin closure.

Yu et al. (2018) further studied the exposed metamorphic rocks and xenolithic rocks from the Xiangshan-Yuhuashan area in central Jiangxi Province to examine the possible tectonic movement. The detrital zircon U-Pb ages reveal that the protolith and xenolith rocks were deposited during the Neoproterozoic. The xenoliths display similar patterns of detrital zircon U-Pb ages and chemical compositions to those of components from the Wuyi terrane in the Cathaysia Block that consists mainly of Neoarchean, Paleoproterozoic and Neoproterozoic detritus. In contrast, the protoliths of the exposed metasedimentary rocks are similar to those of the southern Yangtze Block that consists mainly of Neoproterozoic detritus with minor Neoarchean and Paleoproterozoic fragments. If the interpretation is correct, that means the subduction was to the northwest beneath the Yangtze Block and the surface metasedimentary rocks were overthrusted from its southern margin.

4. New advances about rift-related magmatism in South China

South China underwent extensive extension during 820 Ma to 720 Ma as indicated by the Nanhua rift basin (Wang and Li, 2003), bimodal volcanic rocks (Li et al., 2005, 2008a) and A-type granites (Wang et al., 2010, 2012) along the Jiangnan Orogen. It is well known that the mantle source and the continental crust were melted and interacted during the Neoproterozoic. However, the detailed processes underneath the orogenic belt are not clear.

Chen et al. (2018c) evaluated petrogenesis of the two generations of the

Neoproterozoic mafic rocks in the western Jiangnan Orogen. The ca. 830-Ma Baotan mafic rocks are synchronously with the widespread peraluminous granitoids. They have unradiogenic and decoupled Nd-Hf compositions, suggesting their derivation from a subduction-modified mantle source in an active continental margin setting. A lot of volatiles, released from the underplating mafic magmas, facilitated crustal melting and thus generated the associated granitoid rocks. However, the ca. 770-Ma Longsheng mafic rocks were formed without granitic magmatism. They show radiogenic and coupled Nd-Hf isotopes and steep rare earth element patterns, indicating that the magmas were sourced from a deep mantle source (up to 120 km) in a post-orogenic extensional setting. This work emphasized that diverse mantle-crust melting processes in orogenic belts can serve as an indicator of tectonic transition in Precambrian orogenic belts.

Zhang et al. (2018) carried out zircon and apatite U-Pb dating by LA-ICP-MS method for the mafic dykes that intruded the Shuangxiwu and Heshangzhen groups in the eastern Jiangnan Orogen of Zhejiang Province. These mafic dikes were previously dated at ca. 850 Ma using SHRIMP zircon method (Li et al., 2008a). The subhedral to euhedral zircons in this study exhibit fine oscillatory zoning and display a wide range of ages (767 Ma to 2545 Ma), and thus are suggested to have been introduced from country rocks. The authors did not get concordant U-Pb ages for the apatites, and considered the lower intercept ages of ca. 760 Ma as the emplacement time. All the rocks are tholeiitic in compositions and divided into three subgroups. Synthetic geochemical and Sr-Nd isotopic data indicate that depleted asthenospheric mantle and metasomatized lithospheric mantle were involved in the formation of the three types of mafic dykes. They suggested that asthenosphere upwelling at ca. 760 Ma led to partial melting of the pre-existed enriched lithospheric mantle and thus generated arc-like mafic rocks. Continued extension resulted in low-degree partial melting of asthenospheric mantle and subsequent interaction with the lithospheric mantle-derived magmas. Based on these new results, the rifting of southern China from Rodinia should have not been happened before ca. 820 Ma. It should be noted that differences of U-Pb ages between or among minerals probably have different meanings, and needs to be carefully examined.

The rift-related felsic igneous rocks along the Jiangnan Orogen are dominated by the 820-Ma peraluminous granitoids associated with minor 780-Ma diorites and A-type granitoids (Li et al., 2003; Zheng et al., 2007). Liu and Zhao (2018) selected two typical felsic intrusions from Hunan Province in central Jiangnan Orogen. The 821± 6 Ma Meixian diorites have high V (102-137 ppm) and Cr (47.1-58.7 ppm), and nearly zero εNd (-0.6 to -0.1) and high εHf values (+2.3 to +10.6), and are suggested to have been formed by fractional crystallization of basaltic melts followed by 10-30% crustal contamination. However, the 823 ± 7 Ma Lantian granitoids are classified as fractionated I-type peraluminous granites that have negative εNd (-2.3 to -1.4) and positive εHf values (+0.4 to +9.9), similar to those of the early Neoproterozoic arc-affinity mafic rocks in the region, and thus are considered to be partial melts of the mafic juvenile crust. Underplating of the mafic melts probably triggered crustal anatexis during or after the collision.

Li et al. (2018b) show that the rhyodacite and rhyolitic tuffs from the Jingtan Formation in the eastern part of the Jiangnan Orogen have SIMS zircon U-Pb ages of 784 ± 6 Ma and 788 ± 6 Ma, respectively. These volcanic rocks and their equivalents in the regions have been extensively studied (Li et al., 2018 and references therein). The volcanic rocks show A-type granite geochemical signatures, such as high total alkalis (K_2O + Na_2O = 5.3-7.64 wt.%) and Al_2O_3 content (12-15 wt.%), negative whole rocks εNd values (-4.2 to -1.0) but large variable positive zircon εHf values (+1.26 to +11.6), and thus are suggested to have been produced by melting of the Neoproterozoic to late Mesoproterozoic crustal materials due to tectonic collapse of the Orogen.

5. Neoproterozoic arc-like magmatism in the western Yangtze Block

The Neoproterozoic magmatism in the west margin of the Yangtze Block is characterized by voluminous granitoids and many mafic-ultramafic plutons that were continuously generated compared with its southeastern margin. These rock have been widely discussed in the past decades, the findings in this special issue gave some new insights for the duration of the subduction, nature of the mantle source, and the tectonic evolutions in the region.

Although the geologists totally agree with that the Yangtze Block was surrounded by the subduction systems during the early Neoproterozoic, very rare arc-affinity igneous rocks of this stage have been found on the periphery of the Yangtze Block, and thus restricting our understanding of the Neoproterozoic tectonic evolution of the Yangtze Block and its role within the Rodinia supercontinent. Li et al. (2018a) reported ca. 970 Ma interlayered spilite - keratophyre - quartz - keratophyre associations in the Tongmuliang Group at the NW margin of the Yangtze Block. The rocks show clear arc geochemical characteristics, such as enrichment of large ion lithophile elements and depletion of Nb-Ta-Ti, low Th/La, Nb/La and Nb/U ratios and highly depleted Nd and Hf isotopes. The spilites and keratophyres were originated from a mantle source that was modified by slab-derived fluids, whereas the quartz-keratophyres were partial melts of juvenile crustal materials. The authors further proposed that an early Neoproterozoic ocean-ocean subduction existed along the NW margin of the Yangtze Block. If that was the case, the Tongmuliang volcanic rocks are the oldest arc-affinity assemblages identified in the region, and the subduction may have started as early as 970 Ma, but this should be further tested.

Li and Zhao (2018) discussed the 830-Ma mafic dikes that emplaced into the 845-Ma Tongde gabbro-diorite intrusion. These dikes were previously considered as picrites that were derived from a mantle plume (Li et al., 2010). In this study, rocks from the dikes have variable Mg# (40-69) and SiO_2 (50.98-61.01 wt.%), Sr/Y (12-115) and $(La/Yb)_N$ ratios (3-21). They have positive εNd values (+0.6 to +2.0), similar to the rocks from the Tongde intrusion.

Calculations reveal that the dikes were produced by factional crystallization of olivine, clinopyroxene, garnet and hornblende from hydrous basaltic melts under high pressures.

Li et al. (2018c) further identified a series of Neoproterozoic felsic intrusions in the Phan Si Pan belt, Northwest Vietnam. The rocks include syenogranite, monzogranite and granodiorite. The 824-Ma syenogranite has high SiO_2 (72.1-73.5 wt.%) and K_2O (5.14-5.52 wt.%), and negative εNd (-8.4 to -5.2) and εHf (-8.1 to -5.5) and high $\delta^{18}O$ (9.7-10.9‰), consistent their derivation from an ancient crustal source. The 758-736 Ma monzogranite and granodiorite also have high SiO_2 (68.2-76.7 wt.%) and (K_2O + Na_2O) (6.93-8.54 wt.%), and display negative εNd (-6.6 to 0.0) and large variable εHf values (-6.7 to +11.1), and thus are considered to have been produced by partial melting of ancient crust coupled with involvement of minor mantle- or juvenile crust-derived materials. The Neoproterozoic magmatism in the Phan Si Pan belt occurred in an arc setting that matches with the Panxi -Hannan arc system in South China, and thus is considered as the southern extension part of the subduction system of the Yangtze Block.

6. Structure and composition of the continental crust in South China

The structure and composition of the continental crust in South China is a very complicated question that has not been resolved. One of the most powerful ways is to study U-Pb age and Hf-isotope of detrital zircons from sedimentary rocks. Wang et al. (2018d) carried out detailed studies on the Meso- to Neoproterozoic sedimentary successions along the southeastern margin of the Yangtze Block. The sedimentary protolith of the Tianli Schists, deposited after 1524 Ma, received detritus from a wide range of cratonic sources in a passive scenario associated with the fragmentation of the Yangtze Block from the Columbia supercontinent. The uncomfortably overlying early-Neoproterozoic sedimentary successions were deposited after ~834 Ma and received syn-sedimentary magmatic (804 - 849 Ma) detritus in a continental arc setting. The late-Neoproterozoic Wengjialing Formation was deposited in the Nanhua rift basin with the maximum age of ~763 Ma, and the newly formed arc-related (≥820 Ma) and syn-rifting magmatic rocks (810-760 Ma) were the predominant sources. These features provide substantial evidences for the paleogoegraphic reconstructions of the Yangtze Block within the Proterozoic supercontinent configurations. The tectonic evolution model of South China during the Neoproterozoic based on sedimentary rocks is consistent with that on the igneous rocks as discussed above.

Yang et al. (2018) studied the detrital zircons in sandstones from the Neoproterozoic Huashan Group in the northern Yangtze Block. Two major peaks (1850-2050 Ma and 2650-2750 Ma) and four subordinate peaks (820 Ma, 2400-2500 Ma, 2800-2900 Ma and 3200-3300 Ma) have been identified in these samples. They collected more than four thousands of detrital zircon U-Pb age data from literature, and found that the western and eastern part of the Eastern Yangtze Block show different age peaks, 2.0 Ga, 2.67 Ga and 2.87 Ga for the west, 2.0 Ga and 2.5 Ga for the east, and thus inferred that the basement beneath the Yangtze Block were probably heterogeneous.

To constrain the position of the South China Craton in Gondwana, Chen et al. (2018a) studied detrital zircons in the early Paleozoic and Devonian sedimentary rocks from Danba-Longmenshan area at the western margin of the Yangtze Block. The detrital zircons show age peaks at 2.4-2.6 Ga, 1.75-1.95 Ga, 0.9-1.0 Ga, 0.75-0.85 Ga and 0.5-0.68 Ga. Zircons from the Cambrian sedimentary rocks are mostly euhedral, and show a U-Pb age peak at 550 Ma and positive zircon εHf values (+0.6 to +7.4), and are suggested to have been sourced from the late Neoproterozoic-early Cambrian accretionary orogen. The western margin of the South China was possibly connected with the North India margin of east Gondwanan in the very early Palozoic. On the other hand, the 500-680 Ma detrital zircons from the Silurian-Devonian strata are rounded and have negative εHf values (-27.8 to -0.3), and were possibly sourced from 'Pan-African' orogenic belts that formed during the amalgamation of the Gondwana.

Wang et al. (2018c) reported U-Pb-Hf isotopes for detrital zircons in sedimentary rocks from the Late Neoproterozoic to Early Paleozoic sequences in the Cathaysia Block. Detrital zircon U-Pb ages reveal that the lower and upper Louziba Groups were deposited at 655-635 Ma (Cryogenian) and 635-542 Ma (Ediacaran), respectively. Their patterns indicate that the lower Louziba Group was mainly sourced from the Windmill Islands-Bunger Hills (1300-1050 Ma) and Albany-Fraser Belt-Musgrave (1300-1050 Ma) regions in East Antarctica-western Australia associated with subordinate contribution from east Indian, while the upper Louziba Group was from the Eastern Ghats (ca. 990-950 Ma) in eastern India and North Prince Charles Mountains (ca. 990-950 Ma) in East Antarctica. This study built a linkage between the Cathaysia Block and the Grenvillian sources that started early than ca. 635 Ma during the assembly of Gondwana.

Zou et al. (2018) put their eyes on the two Precambrian successions (Shilu Group and Shihuiding Formation) in Hainan Island of South China. Their study is a follow-up work of Wang et al. (2015) who have reported detrital zircon U-Pb ages. Zou et al. (2018) analyzed Lu-Hf isotopes for detrital zircons from the same group. After data filting, 443 analyses are discussed. They used the two-stage Hf model ages to address the crustal growth and reworking history of Hainan Island. They also compared zircon U-Pb ages and Hf model ages between the Hainan Island and the Cathaysia Block and found some differences between them, and thus proposed that Hainan Island is not a part of the Cathaysia Block during the Precambrian time. However, we should remind the readers that the provenances of detrital zircons are unclear and the model ages are model-based.

7. Other advances

In the Yangtze Block, Paleoproterozoic igneous rocks are rare and thus most conclusions about the early history in South China are more speculative relative to the Neoproterozoic events. Han et al. (2018) identified new Paleoproterozoic metabasalt and metaandesite in the Kongling terrane that represents the continental nucleus of the Yangtze Block. Earlier studies show that most TTG rocks have ages about 2.9-3.0 Ga, and the Paleoproterozoic metasedimentary rocks and amphibolites preserve metamorphic age of 1.95-2.0 Ga (Qiu et al., 2000; Zhang et al., 2006a, b; Wu et al., 2009). In addition, 3.2 Ga, 3.3 Ga and 3.45 Ga felsic gneisses (Jiao et al., 2009; Gao et al., 2011; Guo et al., 2014) and 2.6-2.7 Ga A-type granitic gneiss have also been reported (Chen et al., 2013). One 2.0-Ga garnet-bearing granite sample was reported by Yin et al. (2013). Very luckily, the meta-andesite in this study occurred as small lenses in the metasedimentary rocks, and have zircon U-Pb ages of 2.1 Ga, and show negative to positive zircon εHf values (-0.2 to +3.3) and a negative whole-rock εNd value of -3.5 (Han et al., 2018). The authors interpreted that the andesites and basalts were formed by partial melting of subarc lithospheric mantle. The Kongling terrane is more complex than previously thought and deserves more detail study.

To the north of the Kongling terrane, there are numerous mafic and ultramafic dikes in the South Qinling Belt. These dikes are the youngest generation of the Neoproterozoic magmatism in South China. Wang et al. (2018b) carried out PGE and Sr-Nd-Os isotopes for the ca. 635 Ma mafic intrusions that are composed of troctolite, olivine gabbro and gabbronorite. These rocks show arc-affinity trace elemental characters and thus are proposed to have been derived from a metasomatized subcontinental lithospheric mantle (SCLM). They have radiogenic $^{187}Os/^{188}Os$ (0.137-0.247) and negative εNd values (-5.4 to -10.4), and commonly have <0.1 wt.% S and 0.08-17.5 ppb PGE. The low PGE concentrations probably resulted from sulfide retention in the metasomatized SCLM in the rift setting.

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Highlights

1. Grenvillian rift-related magmatism in South China
2. The Jiangnan Orogen is not part of Grenvillian orogens
3. Arc setting in the western margin and rift setting within South China
4. Long and complicated continental crustal evolution