Early Precambrian Geological Signatures in South China Craton

Yuan-Sheng Geng

Abstract The South China Craton is formed through coalescence of the Yangtze and Cathaysian blocks in the Neoproterozoic and with 3 tectonic units included, the Yangtze and Cathaysia blocks and the intervening Jiangnan orogenic belt. As relatively young in formation time, the Yangtze craton is only sporadically distributed with Early Precambrian terranes. Some occurrences of Archean outcrop in northern Yangtze craton, such as the localities at Kongling, Yichang city, Huji, Zhongxiang city, of Hubei Province, and Yudongzi locality, Mian-Lue area, of Shaanxi Province. Among them, the Kongling terrane is well exposed, including the Meso–Neoarchean metamorphic supracrustal rocks of khondalite feature, the TTG gneiss series of 3.3, 2.9 and 2.7–2.6 Ga, and the metamorphism grade reached upper amphibolite to granulite facies. The Paleoproterozoic terranes are the Tangdan Group at southwestern margin, Houhe Complex at the northern margin of the Yangtze craton, the Badu Group, and the S-, I-granites at the northern margin of the Cathaysian block. Though the Archean and Paleoproterozoic rocks are sporadically exposed in South China Craton, the ubiquitous presence of the older detrital and inherited zircons suggests the once widespread occurrence of the Early Precambrian terranes on the craton. The zircon Hf-isotope compositions demonstrate three major magmatic events which were manifested substantially by the recycling of the crustal materials, accompanied by minor juvenile crustal accretion.

Keywords Archean · Paleoproterozoic · South China Craton · Yangtze block · Cathaysian block · Jiangnan (orogenic) belt · Dongchonghe complex

Y.-S. Geng (✉)
Institute of Geology, Chinese Academy of Geology Sciences, Beijing 100037, China
e-mail: ys-geng@cags.ac.cn

M. Zhai (ed.), *Precambrian Geology of China*,
Springer Geology, DOI 10.1007/978-3-662-47885-1_5

1 Introduction (Distribution of Precambrian Basement in South China)

South China Craton (SCC), located in the southeast part of China mainland, is formed through coalescence of the Yangtze and Cathaysian blocks in the Neoproterozoic and with 3 tectonic units included, the Yangtze and Cathaysia blocks and the intervening Jiangnan orogenic belt. The SCC is separated from the North China Craton by the central orogenic belt to the north and from the Tibetan Plateau by the Sanjiang Orogen to the west, and was developed from three Precambrian basements (or paleoplates) of the Yangtze basement, the Cathaysian basement, and the Indochina basement (Cheng 1994).

The SCC was developed on the Neoproterozoic-Caledonian orogeny, and therefore (Early) Neoproterozoic geological bodies constitute its major basement, and Early Precambrian rocks are rarely documented. Therefore, the SCC is

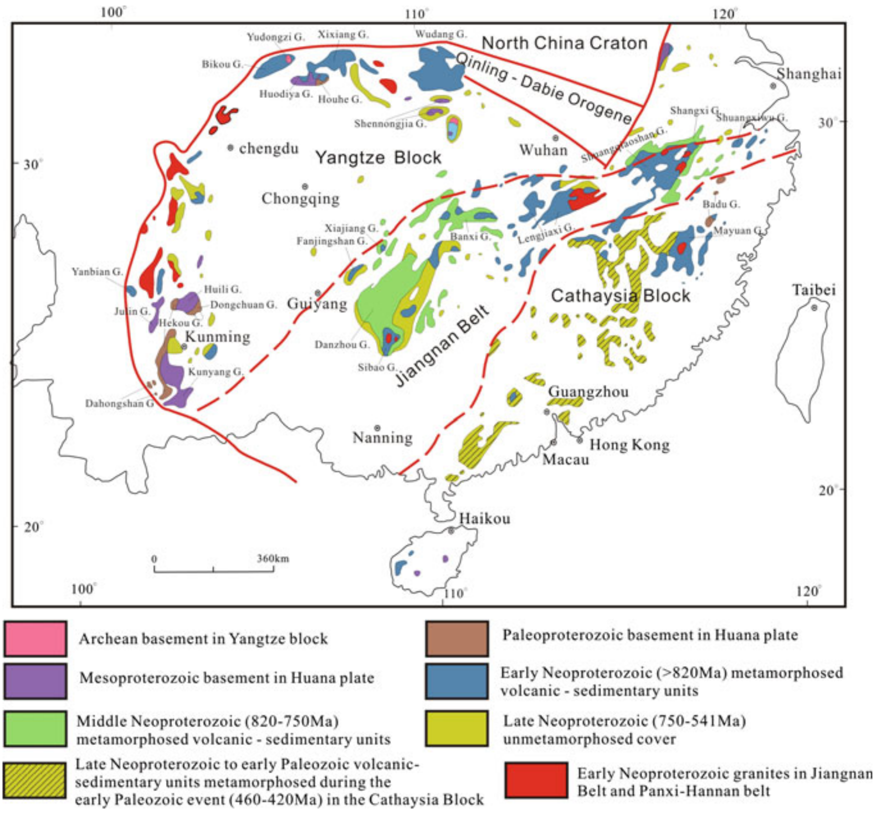

Fig. 1 Geological map showing the distribution of Precambrian geological bodies in the South China. (Revised after Zhao and Cawood 2012) Abbreviations: G = Group

apparently distinct from the North China Craton (NCC) because the NCC basement is dominantly made of Early Precambrian geological bodies. Paleoproterozoic geological bodies only were identified from the Huangling area in Hubei Province, the southwestern Zhejiang Province, and the northern Fujian Province (Fig. 1). In the Dongchuan area of the northeastern Yunnan Province, the Tangdan Group was also possibly formed during the Paleoproterozoic era. Moreover, the Kangding Group, located at the southwestern margin of the Yangtze Block, was previously considered to be formed during Archean to Paleoproterozoic (Li et al. 1988; Feng 1990; BGMRSC 1991; Cheng 1994). However, recent SHRIMP zircon U–Pb dating revealed that the Kangding Group is dominantly of Neoproterozoic magmatic complexes, with minor Meso- to Neoproterozoic metamorphosed strata (Zhou 2002a, b, 2006a; Geng et al. 2007a, 2008).

In this contribution, the Precambrian geological features of the Yangtze Block, the Jiangnan belt, and the Cathaysian Block are described in order. In convenience of work correlations in China, an age of 1.8 Ga is invoked as the lower limited age of Mesoproterozoic era.

2 Archean Geological Signatures of the SCC

Rare Archean terranes are exposed in South China, and minor outcrops are present in the northern Huangling, Huji town in Zhongxiang County, Hubei Province and Yudongzi locality in Lueyang, Shaanxi Province. Up to now, no substantial Archean materials have been observed in Jiangnan belt and Cathaysian block, but some detrital and inherited information of Archean can be disserved in the clastics and magmatic rocks in these Yangtze block, Jiangnan belt, and Cathaysian block.

2.1 Archean Geological Signatures of the Yangtze Block

In northern Yangtze block, some high-grade metamorphic terranes outcrop at the Zigui–Xingshan area in the Huangling region, Yichang city, Hubei Province. The rocks are mainly present at the core of the Huangling Dome or Anticline, and originally called as Kongling schist (Lee and Chao 1924). Geological survey has demonstrated that the Huangling dome is bounded at the northern margin by the Late Proterozoic–Paleozoic sequence, the core of medium- to high-grade metamorphics and granitic gneisses (Fig. 2). With the total area of some 300 km^2, the dome is actually an anticline along the NS strike. Further research has shown that the metamorphics of the southern dome are different from that of the northern part of the dome, and the former dominated by the granitoids of Neoproterozoic, with minor metamorphic sequence of Kongling Group, and the latter mainly consists of Archean TTG gneisses and supracrustal rocks, which were called as Dongchonghe complex (Li and Nie 1987; Shen et al. 1996) or Kongling complex (Zhang et al. 2006a). The complex

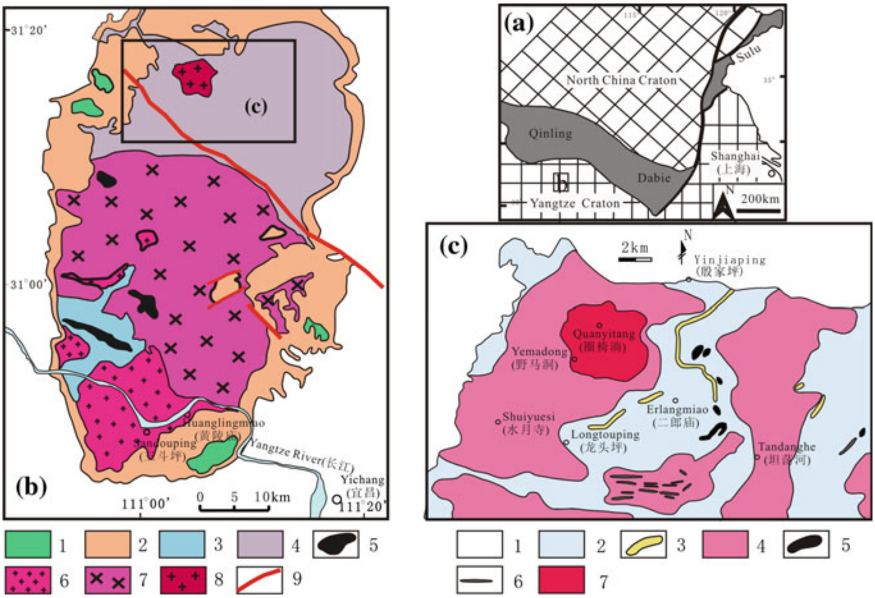

Fig. 2 Tectonic setting of the Kongling area (**a**), geological map of the Kongling anticline and Dongchonghe complex (**b**, **c**) (Modified from Qiu et al. (2000) and Zhang et al. (2006b)), **b** *1* Cambrian, *2* Neoproterozoic Sinian, *3* Meso-Neoproterozoic Kongling Group, *4* Archean Dongchonghe Complex, *5* Mafic-ultramafic complexes, *6* Neoproterozoic potassic granites, *7* Neoproterozoic Huangling granites, *8* Paleoproterozoic Quanyitang granites, *9* major faults; **c** *1* Neoproterozoic and later covers, *2* Archean metamorphosed supracrustal rocks, *3* Marble layers, *4* Archean TTG gneisses, *5* Mafic-ultramafic rocks, *6* mafic dykes, *7* Paleoproterzoic Quanyitang granites

has been intruded by the Paleoproterozoic Quanyitang potassic granite and Neoproterozoic Huangling granite (Fig. 2b, c).

The Dongchonghe complex is distributed at the Quchangsai, Yemadong, Dongchonghe, and Yanluoping area of Yichang, Hubei Province, in northern dome, and some places near Maoya in northern dome. The complex is composed of both the TTG and supracrustal rocks (Fig. 2c). The TTG is the dominant and includes the diorite, tonalite, trondhjemite, and granitic gneisses. The supracrustal rocks are graphite-bearing sillimanite-garnet biotite–plagioclase gneiss, (garnet) biotite-bio-plagioclase gneiss, migmatitic-bio-plagioclase gneiss, and minor bands of amphibolite, quartzite, graphite schist, biotite schist, siliceous rock, and marble. Some index minerals like andalusite, sillimanite, staurolite, and garnet can be found in the schists and gneisses, showing the feature of khondalite (Lu et al. 1996). Some diabase dykes intruded in the TTG and supracrustal rocks. The Dongchonghe complex has reached amphibolite facies in metamorphism, with the peak condition of 700 °C, 0.4 GPa, and then isothermal decompression process of dockwise *P-T* path (Lu et al. 1996). The complex has been intensively migmatized and undergone multiple phases of deformation.

The Dongconghe complex mainly consists of the Mesoarchean TTG gneisses and Neoproterozoic granitic (granodioritic) rocks. The Mesoarchean rocks are basically situated at the northern dome and the Neoproterozoic granite (granodiorite) at the eastern dome. Three stages of magmatism in the Archean can be discerned in the complex, the early phase of ~3.4–3.2 Ga, with a few exposures of TTG gneisses, such as the gray gneiss at Maoya (Wang et al. 2001), trondhjemitic gneiss at Yemadong (Zhang et al. 2006a), and granitic gneisses (Chen et al. 2013). The ~2.9 Ga phase of magmatism is the dominant part of the Dongchonghe complex and is widely distributed, including the trondhjemitic, tonalitic-dioritic, and migmatitc gneisses (Li and Nie 1987; Zheng et al. 1991; Ma et al. 1997; Ling et al. 1998; Qiu et al. 2000; Gao et al. 2001; Wang et al. 2001; Zhang et al. 2006a; Chen et al. 2013). The Neoarchean phase (~2.7–2.6 Ga) of magmatism is manifested in the eastern part of the northern dome, forming the magmatic complex dominated by the granitic and granodioritic schists (Chen et al. 2013). The magmatic rocks of the 3 phases are the skeleton of the Dongchonghe complex, but the setting and features of the magmatism are poorly understood and need further research. The metasediments of the Dongchonghe complex have shown plenty of 3.2–2.8 Ga detrital zircon records (Gao et al. 2001; Zhang et al. 2006b). One sample (KH21) has given the 2.75 Ga age of a metamorphic zircon, constraining the lowest deposition age of the complex (Gao et al. 2001). Recent study shows that the oldest rocks in the Kongling terrain were formed at ~3.4 Ga and metamorphosed after a few tens of million years (Guo et al. 2014).

All the geochronological data above suggest that there are three stages of magmatism in Archean in the Kongling region: the first 3.3–3.2 Ga, the second 3.0–2.9 Ga, and the third ~ 2.6 Ga. However, the 2.75 Ga of metamorphic zircon can give preliminary constraint on the deposition age older than 2.8 Ga and metamorphism reactivation at c. 2.75 Ga.

With the area of some 8 km^2, the Yangpo Group is located some 200 km NE of the Huangling dome and is present as a narrow NNW band of metamorphic sequence at Huji town, Zhongxiang city, Hubei Province (Fig. 3). The group is mainly composed of various schists, leptynites, meta-quartzite, meta-quartz-graywacke, intercalated with minor amphibolite, and intruded by beads of granites. The quartz schist produces many groups of zircon ages, the oldest one 3057 ± 4 Ma (n = 4, MSWD = 0.78), suggesting the presence of the Mesoarchean continental materials in the source. The youngest group is 2801 ± 24 Ma (n = 33, MSWD = 2.7) and can be used to limit the maximum deposition age (Wang et al. 2013a). However, the granite intruding the Yangpo Group is measured to have the zircon U–Pb age of 2655 ± 9 and 2652 ± 21 Ma (Wang et al. 2013a, 2013b). Thus, the Yangpo Group is deduced to have formed between ~2.8 and 2.65 Ga.

A suite of metamorphic strata sequence was exposed along the Gelaoling–Yudongzi area of the Lueyang County, Shaanxi Province (Fig. 4), and was traditionally named as the Bikou Group. Subsequently, the generalized Bikou Group was separated into three lithological units, from bottom to top in turn, of the Late Archean Yudongzi Group, the Mesoproterozoic Bikou Group (sensu stricto), and the upper Sinian to lower Cambrian strata units, respectively (Qin et al. 1990, 1992).

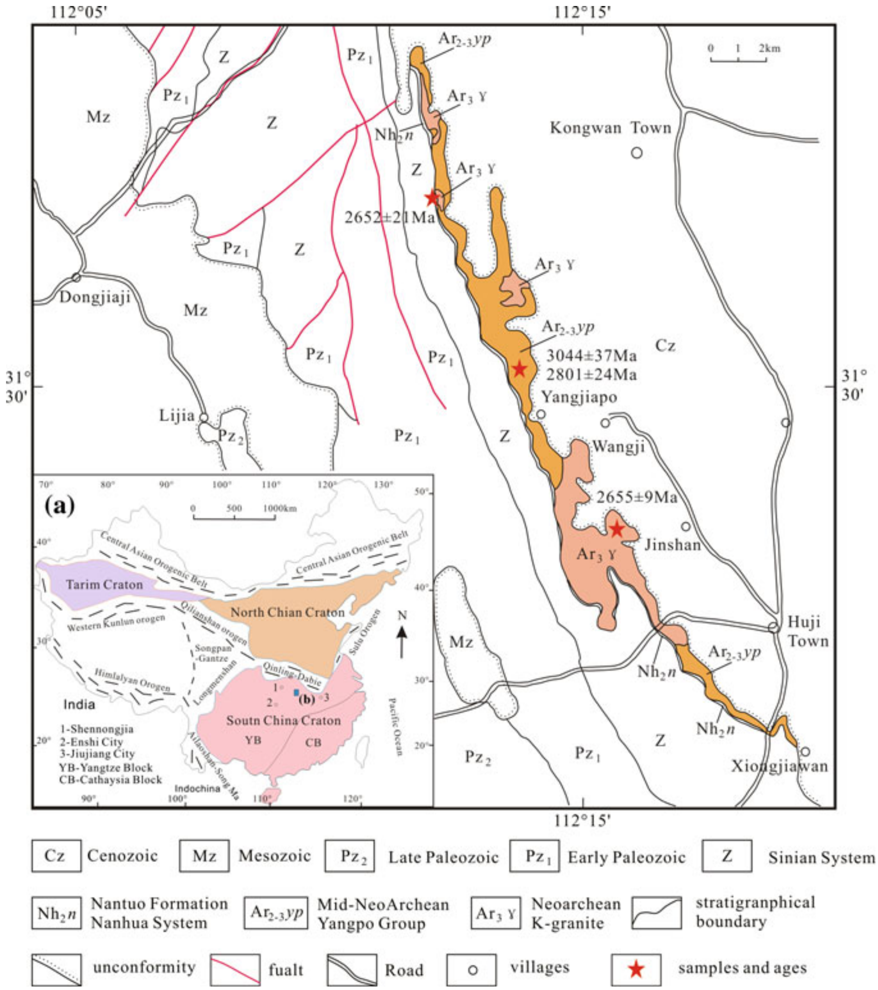

Fig. 3 (**a**) Schematic tectonic map of China showing the major Precambrian blocks connected by Phanerozoic fold belts (Zhao and Cawood 2012). **b** Geological map of the Huji region of Zhongxiang City. (after Wang et al. 2013a)

Although the Yudongzi Group is located in the southern Qinling Orogenic belt (Fig. 4a), the similar Nd isotopic features of its metamorphic rocks to those of the Archean rocks in the Kongling area imply that the Yudongzi Group should be attributed to the basement debris of the Yangtze Block (Zhang et al. 2001, 2002). Recent 1:50000 geological survey suggests that the original Late Archean Yudongzi Group can be further divided into the Yudongzi Group and the Archean TTG gneisses (Fig. 4b) (Huangniping gray gneisses and Longwanggou leuco-gneisses).

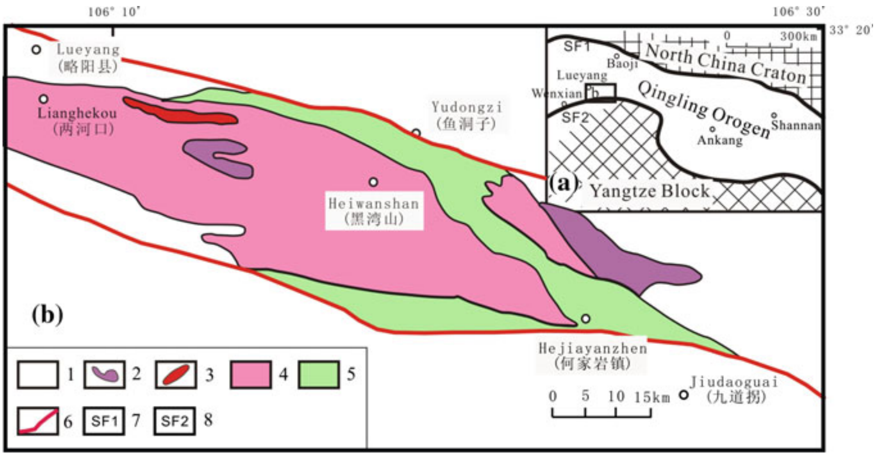

Fig. 4 Sketch geological map of the Yudongzi Complex in the Lueyang County, Shaanxi Province. *1* Neoproterozoic and later covers, *2* Altered mafic-ultramafic rocks, *3* Biotite monzogranites, *4* Archean TTG gneisses, *5* Archean Yudongzi Group, *6* Major faults, *7* Shangdan suture zone, *8* Mianlue suture zone

The newly defined Yudognzi Group is located in the northern and southern flanks of the TTG gneisses, and some occur as enclaves within the TTG gneisses, and they together constitute a granite–greenstone terrane (Wang et al. 1998). Narrow sense Yudongzi Group is mainly distributed in the Heishangou–Majiagou and Shuilinshu areas in the east of the Lueyang County, with a lithological assemblage of banded magnetite quartzites, amphibolites, felsic leptites, leptynites, magnetite actinolite schists, chlorite epidote actinolite schists, albite chlorite schists, and chlorite sericite schists. Moreover, metamorphosed volcano-sedimentary-type iron deposits and ductile shear-zone-type gold deposits locally occur within the Yudongzi Group (Wang et al. 1998). Conventional zircon U–Pb dating for a migmatic amphibolite yields an upper intercept age of 2657 ± 9 Ma, which was interpreted as a metamorphic age (Qin et al. 1992). In the Majiagou iron deposit field to the north of the Yudongzi–Gelaoling terrane, thirteen amphibolites and gneisses from the Yudongzi Group yield a comparable whole-rock Sm–Nd isochron age of 2688 ± 100 Ma (Zhang et al. 2002). A pinky fine-grained granite intruded into the Yudongzi Group gives an upper intercept age of 2693 ± 9 Ma, obtained by conventional zircon dating methods (Zhang et al. 2002). Recently, precise LA–ICPMS zircon U–Pb dating of a mylonitized fine-grained biotite granite and a strongly foliated biotite granite yields two ages of 2661 ± 17 Ma and 2703 ± 26 Ma, respectively (Zhang et al. 2010a, b). Albeit the lack of reliable ages for the Yudongzi Group, the accompanied deformed granites yield Neoarchean ages, implying that rocks of the Yudongzi Group should be formed in Neoarchean, and earlier than the deformed granites.

2.2 Age Information from the South China Craton

Except for the minor Archean geological bodied exposed in the Kongling area, Huji area of Hubei Province and the Yudongzi area of Shaanxi Province, no other reliable Neoarchean rocks, have been documented from the South China Craton. However, detrital zircons from Mesoproterozoic to Late Paleozoic (even modern rivers) sediments and zircon xenocrysts from some Mesozoic to Cenozoic magmatic rocks contain amounts of Archean age information, which are listed in Table 1. From these in situ zircon dating results, the following three features are observed. Firstly, Archean detrital zircons were identified not only in the Neoproterozoic Liantuo Formation near the Kongling Complex and in the Bikou Group around the Yudongzi Group, but also from the Yunnan Province, Western Sichuan, the Jiangnan belt and the Cathaysian Block, which are far away from the exposure regions of Archean rocks or even without exposed Archean rocks. Therefore, Archean terranes may have been widely distributed in the South China Craton. Secondly, host rocks with the Archean age information show a large age range, suggesting that certain amounts of Archean rocks outcropped in the source region of both Meso- to Neoproterozoic and recent sediments. Moreover, large amounts of Archean zircons captured by the Mesozoic to Cenozoic magmatic rocks reveal the existence of Archean basement in the lower or middle continental crust. Thirdly, hidden Archean basement may be existed widely in some areas, as indicated by ~3856 Ma zircon xenocrysts from the Meso- to Cenozoic volcanic rocks in the southeastern Guangxi Province (Zheng et al. 2008, 2011), ~3802 Ma detrital zircon grains from the Neoproterozoic Liantuo Formation in Hubei Province (Zhang et al. 2006b), ~3778, 3732 and 3775 Ma detrital zircons from Proterozoic sedimentary rocks in Dongchuang area of Yunnan Province (Zhu et al. 2011a, b; Zhao et al. 2010; Li et al. 2013), ~3817 and ~3959 Ma detrital zircons from the Ordovician sandstones in Jiangxi Province (Yao et al. 2011), and the ~3755 Ma inherited zircons from Tanxi gneisses in the Nanxiong area of Guangdong Province (Yu et al. 2007). These ancient zircons provide important clues to trace the early formation and evolution history of the South China Craton. Until now, 2.5 Ga rocks have not been identified from the South China Craton, and the large amounts of 2.5 Ga detrital or inherited zircons in the sedimentary or magmatic rocks led to the conclusion that intense ~2.5 Ga tectonothermal events may also occur in the South China Craton, similar to the North China Craton.

Although minor Archean geological bodies exposed in the South China Craton, the numerous Archean detrital zircons in sedimentary rocks indicate that large Archean terranes may have served as a major source region. Meanwhile, the large amounts of Archean inherited zircons imply the possible presence of Archean basement during Meso- to Cenozoic in the lower continental crust of the South China Craton. It is noteworthy that the South China Craton experienced crustal evolution in the early earth history and was significantly modified during the terminal Archean, as suggested by the 3.7 and 2.5 Ga ancient zircons.

Table 1 Archean age information of the South China Craton

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
Formation ages of Archean rocks					
Yangtze Block	Kongling, Yichang of Hubei	Granitic gneiss	SIMS concordia age (6)	3437 ± 12	Guo et al. 2014
	Kongling, Yichang	Granitic gneiss	SIMS concordia age (2)	3426 ± 69	Guo et al. 2014
	Kongling, Yichang	Granitic gneiss	LA-ICPMS concordia age (7)	3329 ± 42	Chen et al. 2013
	Kongling, Yichang	Biotite–plagioclase gneiss	LA-ICPMS concordia age (24)	3218 ± 13	Jiao et al. (2009)
	Kongling, Yichang	Trondhjemitic gneiss	SHRIMP concordia age (13)	2947 ± 75	Qiu et al. (2000)
	Kongling, Yichang	Trondhjemitic gneiss	SHRIMP concordia age (6)	2903 ± 10	Qiu et al. (2000)
	Kongling, Yichang	Migmatite	SHRIMP upper intercept age	2916 ± 31	Zhang et al. (2006a)
	Kongling, Yichang	Migmatite	LA-ICPMS upper intercept age	2936 ± 28	Zhang et al. (2006a)
	Kongling, Yichang	Migmatite	LA-ICPMS upper intercept age	2930 ± 44	Zhang et al. (2006a)
	Kongling, Yichang	Migmatite	LA-ICPMS upper intercept age	2947 ± 28	Zhang et al. (2006a)
	Kongling, Yichang	Migmatite	LA-ICPMS upper intercept age	2947 ± 28	Zhang et al. (2006a)
	Kongling, Yichang	Trondhjemitic gneiss	LA-ICPMS concordia age (9)	2909 ± 30	Chen et al. 2013
	Kongling, Yichang	Trondhjemitic gneiss	LA-ICPMS concordia age (16)	2937 ± 16	Chen et al. 2013
	Kongling, Yichang	Trondhjemitic gneiss	LA-ICPMS concordia age (20)	2907 ± 15	Chen et al. 2013
	Kongling, Yichang	Granitic gneiss	LA-ICPMS concordia age (9)	2691 ± 32	Chen et al. 2013
	Kongling, Yichang	Granitic gneiss	LA-ICPMS concordia age (15)	2707 ± 24	Chen et al. 2013

(continued)

Table 1 (continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
	Kongling, Yichang	A-type granitic gneiss	LA-ICPMS concordia age (9)	2645 ± 15	Chen et al. 2013
	Kongling, Yichang	A-type granitic gneiss	LA-ICPMS concordia age (15)	2622 ± 14	Chen et al. 2013
	Kongling, Yichang	A-type granitic gneiss	LA-ICPMS concordia age (14)	2640 ± 18	Chen et al. 2013
	Kongling, Yichang	A-type granitic gneiss	LA-ICPMS concordia age (17)	2671 ± 17	Chen et al. 2013
	Huji, Zhongxiang	K-granitic gneiss	LA-ICPMS concordia age (15)	2652 ± 21	Wang et al. 2013a
	Huji, Zhongxiang	K-granitic gneiss	SHRIMP concordia age (12)	2655 ± 9	Wang et al. 2013b
	Lueyang, Shaanxi	Granite of Yudongzi Complex	LA-ICPMS upper intercept age	2703 ± 26	Zhang et al. (2010)
	Lueyang, Shaanxi	Granite of Yudongzi Complex	LA-ICPMS upper intercept age	2661 ± 17	Zhang et al. (2010)
Archean age information from detrital zircons					
Yangtze Block	Kongling, Yichang	Inherited zircons from trondhjemitic gneiss	SHRIMP concordia spot age	3051 ± 12	Qiu et al. (2000)
	Kongling, Yichang	Inherited zircons from trondhjemitic gneiss	SHRIMP concordia spot age	2738 ± 18, 2727 ± 8	Qiu et al. (2000)
	Kongling, Yichang	Meta-pelite	SHRIMP single-grain 7/6 age	3275 ± 11, 3213 ± 16, 3169 ± 6, 3133 ± 14	Qiu et al. (2000)
	Kongling, Yichang	Meta-pelite	SHRIMP concordia spot age	3234 ± 6, 2949 ± 4	Qiu et al. (2000)
	Kongling, Yichang	Meta-pelite	SHRIMP upper intercept age	2974 ± 49	Qiu et al. (2000)
	Kongling, Yichang	Inherited zircons from migmatite	LA-ICPMS concordia age (2)	3182 ± 175	Zhang et al. (2006a)
	Kongling, Yichang	Inherited zircons from migmatite	LA-ICPMS concordia age (2)	3242 ± 40	Zhang et al. (2006a)
	Kongling, Yichang	Inherited zircons from migmatite	LA-ICPMS concordia age (5)	3123 ± 36	Zhang et al. (2006a)
	Kongling, Yichang	Biotite–plagioclase gneiss	LA-ICPMS concordia age (24)	3218 ± 13	Jiao et al. (2009)

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Table 1 (Continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
	Kongling, Yichang	Metamorphic zircons from biotite–plagioclase gneiss	LA-ICPMS concordia age (5)	2732 ± 16	Jiao et al. (2009)
	Huji, Zhongxiang	Detritao zircons from Quartze schist, Yangpo Group	LA-ICPMS concordia age (4) and Concordia age (33)	3057 ± 41 and 2801 ± 24	Wang et al. (2013a, b)
	Liantuo, Yichang	Red sandstone, Liantuo Formation	LA-ICPMS 7/6 age	3508 ± 20, 3369 ± 21, 3321 ± 26, 3319 ± 18, 3267 ± 21, 3235 ± 17	Liu et al. (2006)
	Gaojiayan, Changyang	Tillite, Nantuo Formation	LA-ICPMS 7/6 age	3502 ± 16, 3437 ± 15, 3086 ± 18	Liu et al. (2006)
	Liantuo, Yichang	Sandstone, Liantuo Formation	SHRIMP concordia spot age	3802 ± 8, 3445 ± 10	Zhang et al. (2006b)
	Liantuo, Yichang	Sandstone, Liantuo Formation	SHRIMP concordia age (5)	2942 ± 42	Zhang et al. (2006b)
	Liantuo, Yichang	Sandstone, Liantuo Formation	SHRIMP concordia age (3)	3306 ± 15	Zhang et al. (2006b)
	Liantuo, Yichang	Sandstone, Liantuo Formation	SHRIMP concordia age (10)	2951 ± 18	Zhang et al. (2006b)
	Yanbian, Sichuan	Sandstone, Neoproterozoic Zhagu Formation	LA-ICPMS 7/6 age	2649 ± 22, 2517 ± 24, 2943 ± 23	Sun et al. (2008)
	Yanbian, Sichuan	Arkose, Neoproterozoic Xiaoping Formation	LA-ICPMS 7/6 age	2669 ± 20, 2594 ± 20, 2680 ± 22, 2728 ± 24	Sun et al. (2008)
	Hekou, Sichuan	Quartzite, Mesoproterozoic Hekou Group	LA-ICPMS concordia spot age	2668 ± 8	Greentree et al. (2006)
	Hekou, Sichuan	Quartzite, Mesoproterozoic Hekou Group	SHRIMP concordia spot age	2798 ± 5, 3051 ± 9	Greentree et al. (2006)
	Dongchuan, Yunnan	Shale, Yinmin Formation of Mesoproterozoic Dongchuan Group	SHRIMP concordia age (12)	2736 ± 5	Greentree et al. (2006)
	Dongchuan, Yunnan	Shale, Mesoproterozoic Meidang Formation	SHRIMP concordia age (2)	3575 ± 9	Greentree et al. (2006)
	Dongchuan, Yunnan	Shale, Mesoproterozoic Meidang Formation	SHRIMP concordia spot age	3364 ± 8, 3034 ± 8	Greentree et al. (2006)

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Table 1 (Continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
	Kunyang, Yunnan	Fine-grained sandstone, Mesoproterozoic Laowushan Formation	SHRIMP concordia age (2)	2707 ± 4	Greentree et al. (2006)
	Xide, Sichuan	Quatz schist, Mesoproterozoic Dengxiangying Group	SHRIMP 7/6 age	3308 ± 8, 2563 ± 41, 2551 ± 11	Geng et al. (2008)
	Dongchuan, Yunnan	Conglomerate, Proterozoic Wangchang Formation	LA-ICPMS 7/6 age	3778 ± 14	Zhu et al. (2011a)
	Dongchuan, Yunnan	Conglomerate, Proterozoic Wangchang Formation	LA-ICPMS concordia age (8)	2855 ± 14	Zhu et al. (2011a)
	Dongchuan, Yunnan	Phyllite, Yinmin Formation of Mesoproterozoic Dongchuan Group	LA-ICPMS 7/6 age	3755 ± 12, 3405 ± 13, 3409 ± 14	Li et al. (2013)
	Kunyang, Yunnan	Sandstone, Heishantou Formation of Mesoproterozoic Kunyang Group	LA-ICPMS 7/6 age	2690 ± 27, 2446 ± 29	Sun et al. (2009)
	Huili, Sichuan	Sandstone, Mesoproterozoic Tongan Formation	LA-ICPMS 7/6 age	2521 ± 26, 2488 ± 27, 2485 ± 27	Sun et al. (2009)
	Mianxian, Shaanxi	Turbidite, Proterozoic Bikou Group	LA-ICPMS 7/6 age	2529 ± 29, 2492 ± 26, 2592 ± 32	Sun et al. (2009)
	Kunyang, Yunnan	Siltstone Mesoproterozoic Heishantou Formation	LA-ICPMS 7/6 age	2526 ± 37	Wang et al. (2012)
	Kunyang, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS 7/6 age	2734 ± 23, 2855 ± 21	Wang et al. (2012)
	Kunyang, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS upper intercept age	2766	Wang et al. (2012)
	Kunyang, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS 7/6 age	2783 ± 23, 2888 ± 23	Wang et al. (2012)
	Kunyang, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS upper intercept age	2800	Wang et al. (2012)
	Kunyang, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS 7/6 age	2642 ± 24, 3030 ± 26, 2943 ± 24, 2830 ± 26	Wang et al. (2012)

(continued)

Table 1 (Continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
	Kunyang, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS upper intercept age	2800	Wang et al. (2012)
	Kunyang, Yunnan	Sandstone, Neoproterozoic Chengjiang Formation	LA-ICPMS 7/6 age	2849 ± 29, 2702 ± 37, 2988 ± 27	Wang et al. (2012)
	Dongchuan, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS upper intercept age (6)	2849 ± 21	Zhao et al. (2010)
	Dongchuan, Yunnan	Sandstone, Mesoproterozoic Yinmin Formation	LA-ICPMS 7/6 age	2596 ± 33, 2574 ± 23	Zhao et al. (2010)
	Dongchuan, Yunnan	Breccia, Mesoproterozoic Yinmin Formation	LA-ICPMS 7/6 age	3732 ± 26, 3511 ± 26	Zhao et al. (2010)
Jiangnan Belt	Sibao, Guangxi	Sandstone, Neoproterzoic Sibao Group	LA-ICPMS concordia spot age	2547 ± 8, 2536 ± 9, 2631 ± 13, 2528 ± 8, 2508 ± 9, 2513 ± 13, 2512 ± 12, 2883 ± 40, 2624 ± 10, 2512 ± 10, 2509 ± 11	Wang et al. (2007)
	Sibao, Guangxi	Siltstone, Neoproterzoic Sibao Group	LA-ICPMS concordia spot age	2521 ± 7	Wang et al. (2007)
	Sibao, Guangxi	Quartz schist, Neoproterozoic Sibao Group	LA-ICPMS concordia spot age	2707 ± 29, 2710 ± 24, 2622 ± 7	Wang et al. (2007)
	Wenjiashi, Hunan	Sandy pelite, Neoproterozoic Lengjiaxi Group	LA-ICPMS concordia spot age	2543 ± 7, 2520 ± 7	Wang et al. (2007)
	Tianli, Jiangxi	Quartz mica schist, Mesoproterozoic Tianli Formation	SHRIMP 7/6 age	3505 ± 3	Li et al. (2007)
	Tianli, Jiangxi	Quartz mica schist, Mesoproterozoic Tianli Formation	SHRIMP peak age	3300	Li et al. (2007)
	Tianli, Jiangxi	Quartz mica schist, Mesoproterozoic Tianli Formation	SHRIMP peak age	2800	Li et al. (2007)
	Tianli, Jiangxi	Quartz mica schist, Mesoproterozoic Tianli Formation	SHRIMP peak age	2750	Li et al. (2007)
	Wuyuan, Jiangxi	Sandy slate, Neoproterozoic Xikou Group	LA-ICPMS concordia spot age	2535 ± 35, 2545 ± 38, 2530 ± 34	Zhang et al. (2010)

(continued)

Table 1 (continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
Cathaysian Block	Taoxi, Fujian	Proterozoic pelitic granulite	LA-ICPMS upper intercept age	2523 ± 26	Yu et al. (2005)
	Longchuan, Guangdong	Late Neoproterozoic paragneiss	LA-ICPMS 7/6 age	3012 ± 15, 2915 ± 116	Yu et al. (2006)
	Longchuan, Guangdong	Late Neoproterozoic paragneiss	LA-ICPMS upper intercept age	2577 ± 48	Yu et al. (2006)
	Tanxi, northern Guangdong	Neoproterozoic paragneiss	LA-ICPMS 7/6 age	3755 ± 15	Yu et al. (2007)
	Tanxi, northern Guangdong	Neoproterozoic paragneiss	LA-ICPMS upper intercept age	3284 ± 86	Yu et al. (2007)
	Tanxi, northern Guangdong	Neoproterozoic paragneiss	LA-ICPMS 7/6 age	2650 ± 16	Yu et al. (2007)
	Tanxi, northern Guangdong	Neoproterozoic paragneiss	LA-ICPMS upper intercept age	2518 ± 38	Yu et al. (2007)
	Zengcheng, Guangdong	Neoproterozoic migmatite	LA-ICPMS 7/6 age	3315 ± 9, 3294 ± 8, 2838 ± 8	Yu et al. (2008)
	Zengcheng, Guangdong	Neoproterozoic migmatite	LA-ICPMS upper intercept age	2517 ± 30	Yu et al. (2008)
	Chongyi, Jiangxi	Ordovician feldspathic quartz sandstone	LA-ICPMS concordia spot age	3817 ± 17, 3959 ± 21, 3232 ± 13, 3257 ± 20, 3327 ± 21, 3379 ± 11, 3353 ± 13	Yao et al. (2011)
	Ji'an, Jiangxi	Permian medium-grained sandstone	Cameca SIMS 7/6 age	3278	Li et al. (2012a)
	Ji'an, Jiangxi	Permian medium-grained sandstone	Cameca SIMS peak age	2520	Li et al. (2012a)
	Leiyang, Hunan	Permian fine-grained sandstone	Cameca SIMS 7/6 age	2962	Li et al. (2012a)
	Leiyang, Hunan	Permian fine-grained sandstone	Cameca SIMS peak age	2500	Li et al. (2012a)
	Yongding, Fujian	Permian medium-grained sandstone	Cameca SIMS 7/6 age	2865	Li et al. (2012a)
	Yongding, Fujian	Permian medium-grained sandstone	Cameca SIMS peak age	2510	Li et al. (2012a)
	Jiangle, Fujian	Permian coarse-grained sandstone	Cameca SIMS 7/6 age	3248	Li et al. (2012a)
	Jiangle, Fujian	Permian coarse-grained sandstone	Cameca SIMS peak age	2540	Li et al. (2012a)
	Zhoutan, Jiangxi	Garnet mica schist, Zhoutan Group	LA-ICPMS concordia spot age	2501 ± 38	Li et al. (2012a)
	Lanhe river, Guangdong	Mesoproterozoic Lanhe gneiss	LA-ICPMS 7/6 age	2607 ± 29, 2517 ± 9, 2691 ± 9, 2659 ± 9	Xu et al. (2005)

(continued)

Table 1 (continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
	Lanhe river, Guangdong	Devonian sedimentary rock	LA-ICPMS 7/6 age	2669 ± 9	Xu et al. (2005)
	Shunchang, Fujian	Quartz mica schist, Proterozoic Wanquan Group	LA-ICPMS 7/6 age	2686 ± 16, 2653 ± 11, 2642 ± 12, 2562 ± 14	Xu et al. (2010)
	Jian'ou Fujian	Biotite gneiss, Proterozoic Mamianshan Group	LA-ICPMS 7/6 age	2595 ± 14, 2591 ± 14, 2532 ± 12	Xu et al. (2010)
	Jian'ou Fujian	Fine-grained gneiss, Proterozoic Mayuan Group	LA-ICPMS 7/6 age	2802 ± 12	Xu et al. (2010)
	Qujiang River, Fujian	Modern river sediments	LA-ICPMS 7/6 age	3054 ± 23	Xu et al. (2007)
	Beijiang river, Guangdong	Modern river sediments	LA-ICPMS 7/6 age	2696 ± 7, 2625 ± 7, 2730 ± 8, 2556 ± 30, 2566 ± 27, 3550 ± 15, 2752 ± 16	Xu et al. (2007)
Archean age information from zircon xenocrysts or inherited zircons from magmatic rocks					
Yangtze Block	Huili, Sichuan	Triassic patassic felspar syenite	SHRIMP 7/6 age	2818 ± 14, 2692 ± 12	Liu et al. (2004)
	Ningxiang, Hunan	Xenocrysts from lamprophyre	LA-ICPMS concordia spot age	2980 ± 7, 2835 ± 10, 2751 ± 8, 2740 ± 9, 2525 ± 7	Zheng et al. (2006)
	Ma'anshan, Anhui	Xenocrysts from Cretaceous trachyandesite	SHRIMP 7/6 age	3098 ± 1, 2592 ± 10	Zhang et al. (2003)
	Tongling, Anhui	Mesozoic quartz diorite	SHRIMP 7/6 age	2670, 2598	Wang et al. (2004)
	Kunming, Yunnan	Cambrian bentonite	SHRIMP 7/6 age	2955 ± 24, 2914 ± 6	Compston et al. (1997)
	Yiyang, Hunan	Proterozoic basaltic komatiite	SHRIMP 7/6 age	2636 ± 12, 3122 ± 47, 2925 ± 45, 2640 ± 13	Shen et al. (2005)
Jiangnan Belt	Pingnan, Guangxi	Xenocryst from Cenozoic olivine basalts	LA-ICPMS concordia spot age	3178 ± 20	Zheng et al. (2011)
	Pingnan, Guangxi	Xenocrysts from Cenozoic olivine basalts	LA-ICPMS 7/6 age	3856 ± 18, 3313 ± 20	Zheng et al. (2011)
	Pingnan, Guangxi	Xenocrysts from Cenozoic olivine basalts	LA-ICPMS concordia spot age	2879 ± 20, 2716 ± 19	Zheng et al. (2011)
	Pingnan, Guangxi	Xenocrysts from Cenozoic olivine basalts	LA-ICPMS concordia age (20)	2716 ± 19	Zheng et al. (2011)

(continued)

Table 1 (continued)

Geological unit	Location	Lithology or zircon types	Analytical method	Age/Ma	Citation
	Pingnan, Guangxi	Xenocrysts from Cenozoic olivine basalts	LA-ICPMS concordia spot age	2500 ± 50, 2890 ± 17, 2798 ± 17	Zheng et al. (2011)
	Pingnan, Guangxi	Xenocrysts from Cenozoic olivine basalts	LA-ICPMS concordia age (4)	2530 ± 30	Zheng et al. (2011)
	Pingle, Guangxi	Xenocryst from Jurassic minette	LA-ICPMS concordia spot age	2525 ± 21	Zheng et al. (2011)
	Zhenyuan, Guizhou	Xenocrysts from lamprophyre	LA-ICPMS concordia spot age	2676 ± 9, 2632 ± 10	Zheng et al. (2006)
Cathaysian Block	Jianning, Fujian	Inherited zircons from Proterozoic amphibolite of Tianjingping Formation	SHRIMP 7/6 age	2770 ± 27, 2818 ± 18, 2696 ± 41	Li et al. (1998)
	Guzhai, Guangdong	Inherited zircon from Caledonian granodiorite	LA-ICPMS 7/6 age	3102 ± 20	Ding et al. (2005)
	Guzhai, Guangdong	Inherited zircon from Caledonian granodiorite	LA-ICPMS upper intercept age	2708 ± 100	Ding et al. (2005)

Note Concordia age—weighted average age of a set of data along the concordia curve
Digits in ()—the number of data for weighted mean age calculation
Concordia spot age—a single concordia age on the concordia curve from one analysis
7/6 age—$^{207}Pb/^{206}Pb$ age of one analysis with certain Pb loss

3 Paleoproterozoic Era of South China Craton

In South China, Paleoproterozoic geologic body is distributed sporadically in the southwestern Zhejiang and northern Fujian. In addition, Paleoproterozoic geologic bodies in Yangtze Block also spread scatteredly in Kongling of Hubei, Dahongshan of Yunnan, and Dongchuan of Yunnan. Mayuan Group in Fujian, Xingzi Group in Jiangxi, Ailaoshan Group in Yunnan, Susong Group in Anhui, and Kangding complex were previously considered to be Paleoproterozoic (Cheng et al. 1994; Jin et al. 1996; Li et al. 1988). However, recently geochronologic data suggest these groups might be formed in Meso-Neoproterozoic (Wan et al. 2007; Dong et al. 2010; Gao et al. 2012a; Jiang et al. 2003; Geng et al. 2008).

3.1 Paleoproterozoic Era of the Yangtze Block

Houhe complex, as a metamorphic rock series in the northwestern Yangtze Block, consists of Houhe Group and Bajiaoshu Gneiss. Houhe Group is mainly made up of banded garnet-bearing biotite-plagioclase gneiss, two-mica plagioclase gneiss, amphiolite, and few diopside-bearing amphiolite and marble and is metamorphosed in amphibolite facies. Bajiaoshu Gneiss consists of biotite-plagioclase gneiss, amphibole plagioclase gneiss, and a few gray gneisses which are made up from granitic gneiss. All of these rock series construct the Houhe complex, as the crystalline basement of this area (He et al. 1997), which is uncomfortably covered by low-grade metamorphic Huodiya Group (Ling et al. 2003). Using LA–ICPMS zircon U–Pb method, investigators have obtained a $^{207}Pb/^{206}Pb$ weighted average age of 2081 ± 9 Ma from the gray gneiss in Houhe complex, which represented the emplacement age of the parent rock of the gray gneiss (Wu et al. 2012). These gray gneisses are characteristic of high Fe (Fe_2O_3 = 2.86–6.69 %), high Al (Al_2O_3 = 16.01–18.88 %), high Y (12.9–32.7 ppm), high Yb (0.95–2.25 ppm), Low Sr (149–390 ppm), Cr (9.07–45.1 ppm), and Ni (4.97–21.3 ppm), similar to the arc-related calc-alkaline granite, suggesting these rocks might formed in the arc-subduction environment (Wu et al. 2012).

Although there is no Paleoproterozoic metamorphic strata outcrop in Kongling area, Hubei Province, Paleoproterozoic magmatic rocks have been founded, including the 1.85 Ga Quanyitang granites that intruded into Archean gneisses (Xiong et al. 2009; Peng et al. 2012) and the 1.85 Ga mafic dikes that emplaced into Archean gneisses and metamorphic strata sequence (Peng et al. 2009). The Quanyitang granites show geochemistry characteristics of A2-type granites (Xiong et al. 2009; Peng et al. 2009, 2012). 1851 ± 18 Ma (zircon LA–ICPMS U–Pb) Rapakivi granites have been found in Huashanguan area of Zhongxiang, Hubei Province, in south to the Kongling area (Zhang et al. 2011). The A-type granites, Rapakivi granites, and mafic dikes in the northern margin of the Yangtze Block show similar forming ages of ~1.85 Ga, suggesting at least partial South China Craton had stabilized into the rigid block before 1.85 Ga because of the existence of the ~1.85 Ga A-type granites, Rapakivi granites, and mafic dikes that formed in rigid block under extensional environment (Whalen et al. 1987; Eby 1992; Bonin 2007; Halls et al. 2000; Halls and Zhang 2003; Hou et al. 2006; Peng et al. 2009, 2012). However, whether the whole South China Block had already finished the cratonization before 1.85 Ga similar to the North China Craton is still a question and needs more lines of evidence.

Paleoproterozoic geological bodies might also exist in Dongchuan area, Yunnan Province, the southwest part of Yangtze Block. The metamorphic strata sequence in Dongchuan area is usually attributed to Mesoproterozoic Kunyang Group; however, these strata sequence is made up of Tangdan Group (including Shaihaigou Formation, Wangchang Formation, Caiyuanwan Formation, and Pingdingshan Formation) in the lower part and Dongchuan Group (including Yinmin Formation, Luoxue Formation, Heishan Formation, and Qinglongshan Formation) in the upper part, and the former are uncomfortably overlain by the latter (Yin et al. 2011a, b). Zircon grains of the volcanic tuff from Yinmin Formation of Dongchuan Group yield a U–Pb age of 1740 ± 15 Ma, which represents the forming age of the tuff (Zhao et al. 2010). Thus, the Tangdan Group that lies below the Dongchuan Group must be older than 1740 Ma. Two groups of zircon ages were obtained from the welded tuff in the Shaihaigou Formation of Tangdan Group. One group of zircons shows Pb loss, yielding an upper intercept age of 2742 ± 48 Ma. The other group contains 12 analyses plotted close to concordia curve and yielded $^{207}Pb/^{206}Pb$ weighted mean age of 2285 ± 12 Ma. The former was interpreted as inherited zircon age, and the later suggested as a forming age of the tuff (Zhu et al. 2011b). The zircon grains from the tuff in Wangchang Formation gave SHRIMP U–Pb age of 2299 ± 14 Ma (Zhou et al. 2012). Additionally, two ages of 2855 ± 14 Ma and 1838 ± 10 Ma were obtained from detrital zircon of the metamorphic sedimentary rocks (Zhu et al. 2011a). In spite of some paradoxes in the chronological data, the Tangdan Group may be deduced as Paleoproterozoic due to its tuff ages of 2285–2299 Ma and the constraints of uncomfortably overlying Dongchuan Group.

3.2 *Paleoproterozoic Era of the Cathaysian Block*

The Proterozoic metamorphic geological bodies in Southwestern Zhejiang can be divided into Chencai Group in Zhuji, Badu Group, and Longquan Group in Suichang-Longquan (Fig. 5). The believable Paleoproterozoic geological bodies in

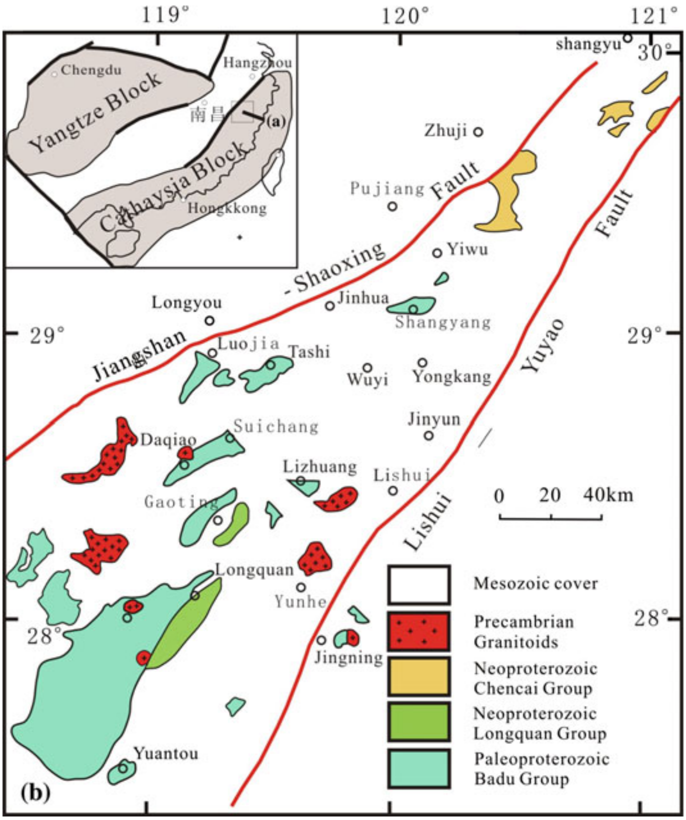

Fig. 5 Geological map of the South China Block (**a**) and the southwestern Zhejiang Province (**b**)

this area mainly comprise medium-grade metamorphic Badu Group and the granitoid plutons that emplaced into the Badu Group (Yu et al. 2009, 2010, 2012; Ding et al. 2005; Kong et al. 1995; Gan et al. 1995; Li et al. 1996; Li et al. 1998). However, Chencai Group and Longquan Group were controversially considered to be Paleoproterozoic (Hu et al. 1991, 1992) or Meso-Neoproterozoic (Kong et al. 1995; Jin et al. 1997). A zircon SHRIMP U–Pb dating of the Metamorphic gabbro from Chencai Group yielded an emplacement age of 1781 ± 21 Ma (Li et al. 2009), but this is the only sample so it is hard to confirm their distribution range. Moreover, new zircon SHRIMP and LA–ICPMS dating indicated that the major lithological assemblages of Chencai Group and Longquan Group belong to Neoproterozoic, and these results will be discussed later.

Badu Group was divided into Tangyuan Formation, Qiantou Formation, Zhangyan Formation, Siyuan Formation, and Dayanshan Formation from the bottom to top. Tangyuan Formation consists of meta-mafic rocks and leptynites, mainly comprising the lithological assemblage of amphibolite, amphibole anorthosite, sahlite-bearing amphibole anorthosite, garnet-bearing biotite–plagioclase leptynite, etc., and their protoliths are mafic igneous rocks and volcanic graywacke. Qiantou Formation is mainly composed of biotite–plagioclase leptynite, partial amphibole plagioclase leptynite, pyroxene-bearing amphibolites, etc., and their protoliths are graywackes and intermediate-acid volcanic rocks. The major lithological assemblage of Zhangyan Group is biotite quartz schist, biotite schist, and biotite leptynite, undergoing strong migmatization, and their protoliths are argillaceous-half argillaceous clastic rocks. Siyuan Formation contains biotite leptynite, arkose quartzite, tint leptite, biotite quartz schist, etc., generally undergoing migmatization, and their protoliths are sandstones and argillaceous-half argillaceous clastic rocks. Dayanshan Formation consists chiefly of biotite schist, biotite quartz schist, locally changing into biotite–plagioclase gneiss, and their protoliths are mainly terrigenous clay, with less granitoid rocks that were derived from migmatization (Jin et al. 1997; Zhao 2012).

The metamorphic rock series in Badu Group generally contain garnet, sillimanite, biotite, K-feldspar, and crystalline graphite. These rocks were metamorphosed under granulite facies condition (Zhao 2012), showing complicatedly superimposed fold deformation, and developing abundant migmatization genetic granitoid rocks.

Previous investigators reported some whole-rock Sm–Nd method and Sm–Nd internal isochron ages of 1735 ± 55 to 2199 ± 95 Ma from the metamorphic rocks of the Badu Group (Wang et al. 1992; BGMRZJ 1989; Li et al. 1996). Recently, Zhao et al. (2014a) obtained a metamorphic age of 1869 ± 19 Ma (zircon Th/U = 0.009–0.093) and a forming age of 1923 ± 8 Ma from the garnet-bearing felsic gneiss in Badu Group. Two groups of detrital zircon ages, 2451 ± 63 Ma and 2002 ± 29 Ma, were obtained from sillimanite amphibole plagioclase gneiss. Garnet amphibole plagioclase gneiss, garnet two-pyroxene granulite, and marble revealed their metamorphic ages of 1884 ± 18 to 1852 ± 12 Ma. Yu et al. (2012) obtained metamorphic ages of 1887 ± 26 and 1885 ± 9 Ma from the migmatitic biotite gneiss and quartz-enriched gneiss revealed, respectively, and the two dated samples have abundant Archean detrital zircons and suggest the Badu Group had deposited since

2.5 Ga. However, in these samples, there were also some ~2.1 Ga detrital zircons that plotted on or close to the concordia, indicating the Badu Group actually started deposition after 2.2 Ga. Integrated all the information above, forming time of the Badu Group may be determined from 2.2 to 1.9 Ga, following the granulite facies-amphibolite facies metamorphism in 1880–1850 Ma.

Paleoproterozoic granitoids intruded Badu Group are extensive in southwest Zhejiang Province and always exhibit gneissic structure with the same structural orientation as the Badu Group. Most of these granitoids were regarded as S-type granites, but some of them might be A-type granites (Hu et al. 1991; Yu et al. 2009; Liu et al. 2009; Xia et al. 2012; Zhao et al. 2014a; Liu et al. 2014). The representative granitoids include the Xiaji, Danzhu Quankeng and Huaqiao plutons in Longquan County, Lizhuang (Jinluohou) and Jingju plutons in Songyang County, Tianhou (Dazhe) pluton in Suichang County, and Chimushan (Sanzhishu) and Wengkeng plutons in Jingning County (Fig. 6). On the basis of previous geochronological data through conventional multi-grain or single-grain zircon U–Pb (TIMS), Rb–Sr and Sm–Nd methods, these granitoids were thought to have a wide age span of 2080–1755 Ma (Hu et al. 1991, 1992; Wang et al. 1992; Gan et al. 1993, 1995). Recent precise zircon U–Pb ages (SHRIMP and LA–ICP–MS) have revealed the most of the granitoids formed on 1832 and 1888 Ma, and the two samples of granite yield the age results of the 1912 and 1925 Ma (Fig. 6).

Except for the Badu Group and the concomitant granites in the southwestern Zhejiang, Paleoproterozoic geological bodies also outcrop sporadically in other regions of the Cathaysian Block. For example, Mayuan Group in Wuyishan area, Fujian. A SHRIMP zircon U–Pb age of 1766 ± 19 Ma was obtained from an amphibolite sample of Tianjingping Formation in Mayuan Group (Li et al. 1998). Similarly, another SHRIMP U–Pb age of 1790 ± 19 Ma from a gneiss sample of Tianjingping Formation was documented by Wan et al. (2007). The gneissic granites that intruded into the Mayuan Group show their forming ages of 1851–1857 Ma (Li et al. 2011). Although some Neoproterozoic or even younger strata were involved locally (Wan et al. 2007), major geological bodies may be determined as Paleoproterozoic, but their distribution and scale are still unclear and need to be further investigated.

In the southwestern Cathaysian Block, a suit of metamorphic series was reported in western Guangdong–southeastern Guangxi and is divided into Paleoproterozoic Tiantangshan Group, Meso-Neoproterozoic Yunkai Group, and Neoproterozoic plutons (Qin et al. 2006). Of which the Tiantangshan Group is mainly composed of garnet sillimanite feldspar biotite (quartz) schists, garnet sillimanite biotite gneisses, biotite leptynites, pyroxene (amphibole) plagioclase leptynites, feldspar quartzites, garnet pyroxenites, and diopsidites, etc. These rocks generally underwent amphibolite facies metamorphism (partial granulite facies), with a certain degree of migmatization. Zircon SHRIMP U–Pb dating reveals that the garnet pyroxenite emplaced at 1817 ± 36 Ma (Qin et al. 2006), indicating the Tiantangshan Group is Paleoproterozoic.

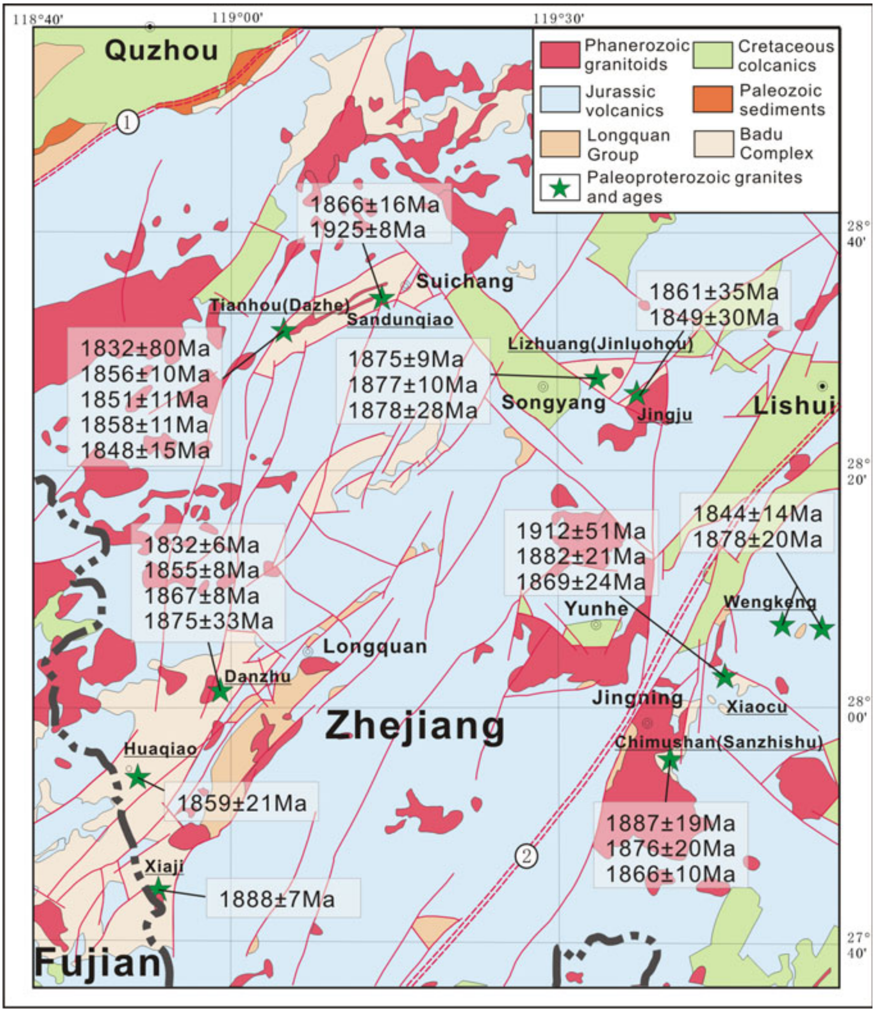

Fig. 6 Geological map of southwestern Zhejiang Province (after Liu et al. 2014). Zircon SHRIMP and LA–ICP–MS U–Pb ages are from Li and Li (2007), Wang et al. (2008), Yu et al. (2009), Liu et al. (2009), Xia et al. (2012), Zhao et al. (2014b), Liu et al. (2014). ① Jiangshan-Shaoxing Fault, ②-Zhenghe-Dabu Fault

3.3 Information of Paleoproterozoic Ages in the South China Craton

Except for these identified Paleoproterozoic geological bodies, detrital zircons from post-Mesoproterozoic sedimentary rocks and inherited zircons from magmatic rocks contain a large number of Paleoproterozoic age information (Li et al. 2012b;

Yao et al. 2011; Zheng et al. 2008, 2011; Yu et al. 2007), revealing Paleoproterozoic geological bodies have wider distribution in the South China Craton. In Mesozoic–Cenozoic, Paleoproterozoic geological bodies still spread widely in the deep crust. In the histogram of detrital and inherited zircon ages (Fig. 7), two Paleoproterozoic peaks can be obviously recognized in the Yangtze Block (2.3 and 1.85 Ga), suggesting the two events had strongly influence to the Yangtze Block. In the Jiangnan Belt, the age peaks of 1.8–1.9 Ga and 2.0–2.1 Ga are relatively small, revealing this region was also influenced by the two events, but was different from the Yangtze Block. In the Cathaysian Block, the peak of 1.8–1.9 Ga is very obvious and a relatively smaller peak of 2.3 Ga, indicating that the Cathaysian Block was reformed by a tectonic thermal event at ~2.3 Ga. According to the statistics by Li et al. (2012b), the western Yangtze Block appears relatively obvious peaks of 1.85 and 2.32 Ga; the eastern Yangtze Block shows relatively obvious peaks of 2.0 and 2.48 Ga; and the Cathaysian Block displays relatively obvious peaks at 1.85 and 2.48 Ga. Considering the whole South China Craton, the three tectonic thermal events (at 2.48, 2.3, and 1.8–1.9 Ga, respectively) had important significance to the formation and evolution of the basement of South China Craton, especially the 1.8–1.9 Ga tectonic thermal events play a crucial role to the formation of the South China basement.

4 The Major Precambrian Geological Events and Evolution of South China Craton

The exposed Precambrian geological bodies are infrequent in the South China Craton. In order to discuss the Precambrian geological events and the evolution of South China Craton, we have collected 3297 in situ U–Pb dating analyses of detrital and inherited zircons. Some low harmonious degree analyses have been rejected (<80 % for zircons >1.0 Ga; <90 % for zircons <1.0 Ga) from these analyses. Using the remaining 2711 analyses, the histograms are produced in order to discuss some important Precambrian events. Combined with some exposed geological bodies, we discussed the Precambrian geological events and the evolution of South China Craton as below.

As shown in Fig. 7, South China Craton, whether the Yangtze Block, the Jiangnan Belt, or the Cathaysian Block, has some detrital and inherited zircon grains showing >3.5 Ga ages, indicating the existence of some ancient geological bodies with older than 3.5 Ga in South China Craton. These zircons are characterized by oscillation zonings and high Th/U ratios, suggesting they came from intermediate to acid magmatic rocks (Pidgen 1992; Hanchar and Miller 1993; Hoskin and Schaltegger 2003; Wu and Zheng 2004). Therefore, the Geological events before 3.5 Ga dominated intermediate to acid volcanic magmatic events. The $\varepsilon_{Hf}(t)$ values of the old zircon grains are around 0 instead of getting close to the depleted mantle evolution curve (Fig. 8), suggesting these zircons came from the

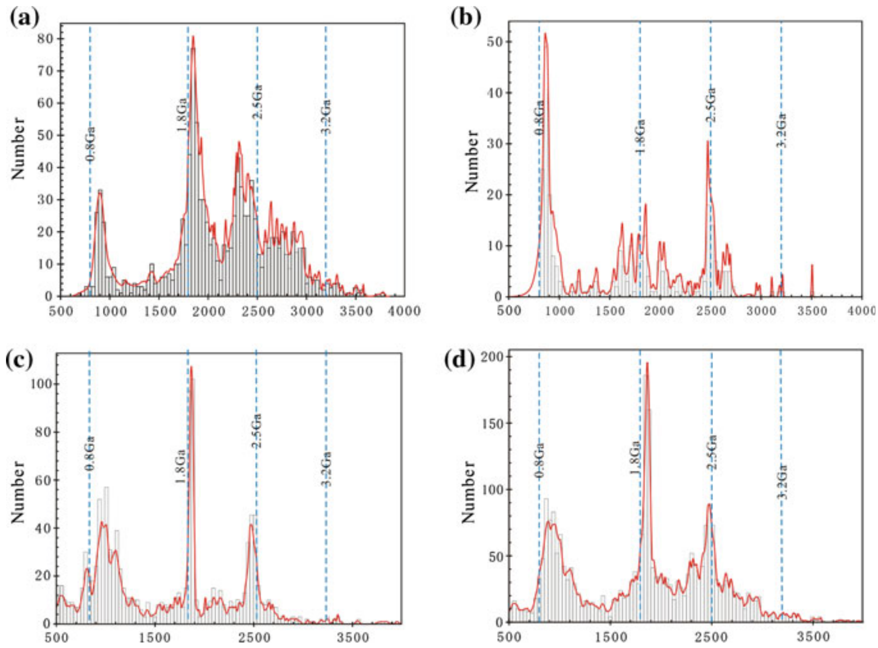

Fig. 7 Histogram of detrital zircon ages in the South China Block (**a**-Yangtze Block, **b**-Jiangnan Belt, **c**-Cathaysian Block, **d**-the whole South China). These data come from Zhao et al. (2010), Greetree et al. (2006), Greetree and Li (2008), Zhu et al. (2011a), Geng et al. (2008), Sun et al. (2008, 2009), Wang et al. (2012), Zhang et al. (2006b), Zhang et al. (2010), Liu et al. (2006), Gao et al. (2001), Wang et al. (2007), Xu et al. (2005, 2007), Yu et al. (2007, 2008, 2009), Zheng et al. (2006, 2011), Liu et al. (2009), Li et al. (2007), Yao et al. (2011), Li et al. (2012a), Xu et al. (2010), Zhao (2012), and unpublished data of the author

magma undergoing crustal contamination, suggesting South China Craton have thicker crust during >3.5 Ga. The zircon grains from the 2.9–3.3 Ga old metamorphic migmatites display Hf-isotopic model ages from 3.6–3.4 Ga, up to 4.0 Ga in the Kongling area (Gao et al. 2001; Zhang et al. 2006b; Jiao et al. 2009; Zhang and Zheng 2013). The crustal residual ages of zircon Hf isotope also shows the existence of the reconstructive 4.0 Ga crustal materials (Li et al. 2012b). These data reveal that South China Craton indeed preserves Paleoarchean, even Hadean, crustal materials.

Present older rocks with 3.2–3.3 Ga U–Pb ages only have been found in Kongling area (Jiao et al. 2009; Gao et al. 2011). Integrated with the geological facts, the 2.9 Ga TTG gneisses intruded into the Dongchonghe supracrustal rock series, and the Dongchonghe supracrustal rocks were metamorphosed at ~2.75 Ga; therefore, the Dongchonghe supracrust rocks are most likely to be formed during 3.3–2.9 Ga. This supracrust rock series dominate migmatic biotite–plagioclase gneisses, intercalated Al-enriched gneisses, garnet sillimanite quartzites, calcium and magnesium silicate rocks and marbles, and all of these rocks have graphite

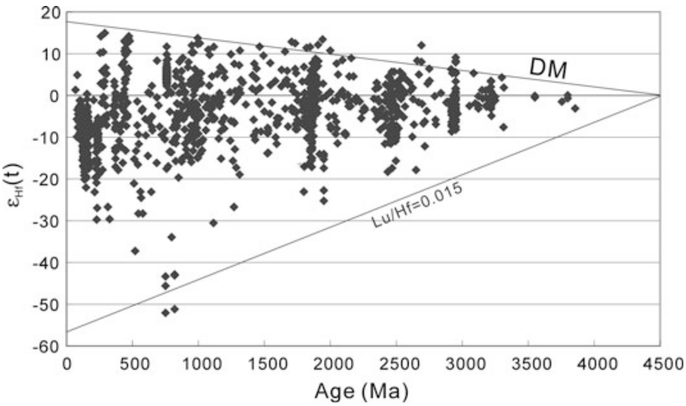

Fig. 8 εHf(t)-Age diagram of detrital zircons from South China. Data resource: Peng et al. (2009), Zhang et al. (2006a, 2006b, 2006c), Wang et al. (2011), Xu et al. (2005, 2007), Yu et al. (2007, 2008, 2009), Zheng et al. (2011), Liu et al. (2009), Li et al. (2012a), Yao et al. (2011), Xiang et al. (2008), Zhao et al. (2008)

mineral, indicating that this association has the features of Khondalite series, which is a suit of organic terrigenous sedimentary formation under the depression-rift zones located in neritic region of ancient continental margin (Jiang 1986; Lu et al. 1996). These features suggest that the basement of the South China Craton had already larger scale, where can provide stable material sources for the deposition of Khondalites. From the age histogram, we can see only a very small peak around 3.2 Ga, suggesting the crust at that time was seldom preserved because of the strong denudation before Mesoproterozoic.

During 2.9–3.0 Ga, large-scale TTG magmatism occurred in Hubei Kongling area (Qiu et al. 2000; Zhang et al. 2006a). In the age histogram, detrital zircons from the Yangtze block and the Jiangnan Belt have the signatures of this event, while zircons from the Cathaysian Block do not have (Fig. 7), suggesting this event affected mainly the Yangtze block and the Jiangnan Belt. The zircon $\varepsilon_{Hf}(t)$ values of 2.9 Ga TTG gneisses in Kongling area range from −8.7 to −0.1, with an average valve of −4.03, weighted average values (T_{DM1}) of 3.35 Ga, and weighted T_{DM2} average values of 3.46 Ga (Zhang et al. 2006a), suggesting these TTG gneisses are the productions of the partial melting of ancient crust, suggesting the crust-mantle differentiation ages were Paleoarchean or Hadean. Detrital zircons formed at 2.9 Ga show $\varepsilon_{Hf}(t)$ from −10 to +10. Some spots plot around the depleted mantle evolutionary line, while most analyses are actually far from the line (Fig. 8), suggesting that 2.9 Ga magmatic event was mainly produced by of the partial melting of the pre-existent crust, with little involvement of the mantle materials.

An important magmatic tectonothermal event occurred around 2.7–2.6 Ga, mainly displaying the emplacement of magmatic rocks in the northern margin of the Yangtze Block (Zhang et al. 2010a, b; Wang et al. 2013a, b; Chen et al. 2013), and the magmatic zircon rims display 2.7 Ga metamorphic growth rims from the 3.2 Ga biotite–plagioclase gneisses in Kongling area, Hubei. A smaller age peak of 2.7–2.6 Ga is shown in the zircon age histogram (Fig. 7) from the Yangtze Block, the Cathaysian Block, and the Jiangnan Belt (see Table 1), suggesting that this tectonothermal event has affected a certain range of the South China Craton.

No 2.5 Ga geological body has been found in South China Craton, but detrital and inherited zircons reveal that this event affect extensively on the Yangtze Block, the Cathaysian Block, and the Jiangnan Belt. The xenolith from the Cenozoic lamprophyre contains ~2.5 Ga inherited zircons (Zheng et al. 2006, 2011). The fluviatile sands in Beijiang also discovered ~2.5 Ga zircons (Xu et al. 2007), suggesting preserving 2.5 Ga geological bodies in the Cenezoic (even present) deep crust. Based on the analyses of the detrital zircons from Badu Group metamorphic sedimentary rocks in the Cathaysian Block, Yu et al. (2012) suggested that Badu Group might deposit in a sedimentary basin that was connected with arc around 2.5 Ga. Based on zircon Hf isotopes, they suggest that the 2.5 Ga magmatic event led a mass of the juvenile crust growth and the reworking of the ancient crust (Yu et al. 2012). In Figs. 6, 7, and 8, these zircons show $\varepsilon_{Hf}(t)$ from −10 to +8, inferring that the partial melting of pre-existent crust was the main part of this event, coupled with the involvement of mantle material. However, the scale and evolution process of this event still need to be more investigated.

The 1.8–1.9 Ga geological events were recorded in the Yangtze Block and the Cathaysian Block. In Kongling area, the Yangtze Block, only records of the Late Paleoproterozoic breakup event are preserved; however, a full orogenic process was retained in southwestern Zhejiang region of the Cathaysian Block. Some 1.85 Ga geological bodies, for example, simultaneously Quanyitang A-type granite, Huashanguan rapakivi granite, and mafic dikes in the northern margin of the Yangtze Block, suggest a Paleoproterozoic extensional environment (Whalen et al. 1987; Eby 1992; Bonin 2007; Halls et al. 2000; Halls and Zhang 2003; Hou et al. 2006; Peng et al. 2009, 2012). There are no believable >1.85 Ga geological bodies in the northern margin of the Yangtze Block to be reported, so we can only discuss from the related zircon dating information. Qiu et al (2000) obtained SHRIMP ages of 1.99 and 1.93 Ga from TTG gneisses and metamorphic pelites, respectively. Zhang et al. (2006a, b) documented metamorphic ages of 1.94–1.98 Ga from metamorphic pelites and amphibolites and metamorphic ages of 1.98–2.01 Ga from migmatites. Based on the summarization of the Paleoproterozoic magmatic and metamorphic events, Zheng and Zhang (2007) provided that the Paleoproterozoic continental substances are widely distributed in different regions of the Yangtze Block and the Cathaysian Block. In addition, Hf-isotopic data of the Paleoproterozoic zircons suggest that the reworking of the ancient crust is the main Paleoproterozoic event of South China Craton. Combining all of these data, we can be inferred that the northern margin of the Yangtze Block occurred widely regional metamorphism during 2.0–1.9 Ga in the northern margin of the Yangtze Block, and the magmatism under extensional environment occurred around 1.85 Ga.

In the southwestern Zhejiang region of the Cathaysian Block, there are Badu Group and many Late Paleoproterozoic granitoid rock outcrops (Gan et al. 1995), for example, 1866 Ma Sanzhishu granite (Liu et al. 2009),1832–1867 Ma Danzhu granite (Li and Li 2007; Liu et al. 2009; Yu et al. 2009), 1856 Ma Tianhou granodiorite (Yu JH et al., 2009), 1875 Ma Lizhuang biotite granite (Yu et al. 2009), 1887 Ma Xiaji two-mica monzonitic granite (Yu et al. 2009), which were attributed to S-type granites under the collisional orogenic environment (Hu et al. 1991).The current researches show that earlier (1875–1887 Ma) Xiaji two-mica monzonitic granites and the Lizhuang biotite granites show high SiO_2, K_2O, and Rb, low Sr, REE and mafic compositions, high A/CNK value (1.09–1.40), and high Rb/Sr ratios, which are similar to those of S-type granites in geochemistry (Yu et al. 2009). However, the later (1832–1867 Ma) Danzhu, Houtian, and Sanzhishu plutons have relatively low-SiO_2 content, metaluminous to peraluminous (A/CNK = 0.80–1.07) features, high Ga/Al and FeO/(FeO + MgO) ratios, and these magmatic rocks have formation temperature of 885–920 °C, belonging to the high-temperature A2-type granite (Liu et al. 2009; Yu et al. 2009). S-type granites are usually thought to be mainly formed in the syn-collision tectonic environment (Pearce et al. 1984; Harris et al. 1986), while the A-type granites form in anorogenic environment or the extensional environment after orogenic period (Anderson and Thomas 1985; Whalen et al. 1987; Eby 1992; Bonin 2007), so the granites in this area suggest the evolution from the syn-collision S-type granites to the high-temperature A-type granites in the extensional environment after orogenic period. Moreover, Badu Group Al-rich gneiss peak metamorphic temperature and pressure are 800–850 °C, 0.60–0.70 GPa, respectively, and the retrograde metamorphic peak temperature and confining pressure are 560–590 °C, 0.25–0.33 GPa, respectively; Badu Group garnet two-pyroxene granulite shows its peak metamorphic temperature and pressure of 850–900 °C, 0.92–1.10 GPa, and the retrograde metamorphic peak temperature and confining pressure of 650–700 °C, 0.58–0.65 GPa, reflecting a clockwise P–T path (Zhao and Zhou 2012). Nearly, isothermal decompression clockwise PT path is usually associated with rapid uplift after the collision (Bohlen and Mezger 1989; Harley 1989). The peak metamorphism occurred during 1858–1884 Ma in this region (Zhao 2012; Yu et al. 2009), being consistent with the formation age of S-type granites. Both the transition from S-type granites to A-type granites, and metamorphism from the >1.1 GPa granulites to the clockwise P–T path reflect a more complete collision orogenic process. It can be said that the 1.9–1.8 Ga event was a collision orogenic event. Due to limited field outcrops, it is still difficult to determine the scale and direction of the collision orogenic event.

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