



Early Neoproterozoic accretionary assemblage in the Cathaysia Block: Geochronological, Lu–Hf isotopic and geochemical evidence from granitoid gneisses



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ABSTRACT

The South China Block (SCB) is composed of the Yangtze Block in the northwest and the Cathaysia Block in the southeast. The earliest Neoproterozoic granitic rocks in the SCB are important for our understanding of the tectonic regime and location of this ancient continent in relation to the Rodinia supercontinent. However, such rocks have rarely been reported for the Cathaysia Block so far. In this study, six granitic gneisses from the Wuyi-Yunkai domain gave zircon U–Pb ages of 985–913 Ma, indicating the presence of the early Neoproterozoic granitic magmatism in the Cathaysia interior. These granitic gneisses are peraluminous with high FeOt, MgO, TiO₂ and CaO/Na₂O but low SiO₂, Al₂O₃/TiO₂, Al₂O₃/(MgO + FeOt) and Rb/Sr ratios. They show steep REE chondrite-normalized patterns with δEu values of 0.35–0.70. These samples have strongly negative Ba, Sr, Nb–Ta, P and Ti anomalies in primitive mantle-normalized diagrams, and $\varepsilon\text{Nd}(t)$ values of -9.54 to -3.81 , similar to those of the Kwangian granitic rocks and Precambrian volcanosedimentary package in the Cathaysia Block. The zircon grains with the earliest Neoproterozoic age gave $\varepsilon\text{Hf}(t)$ values of -9.64 to $+2.78$ with the peak values at -2.5 and -7.5 , and Hf model ages of 1.35–2.00 Ga with the two-peaks of 1.57 Ga and 1.75 Ga, respectively. These data suggest that the granitic gneisses originated dominantly from a binary mixing of metapelitic and metaigneous components, with insignificant input of juvenile materials. We consider that these rocks are closely related to the closure of the earliest Neoproterozoic (~ 980 Ma) Wuyi-Yunkai back-arc basin in an accretionary continental margin setting. In combination with other data, it is proposed that the previously-defined Cathaysia block might consist of various sub-blocks separated by the arc-back-arc basin prior to the early Neoproterozoic period. The Wuyi-Yunkai arc-back-arc system was finally closed at ~ 920 Ma, significantly younger than the classical Grenvillian Orogenic event, and thus the SCB was located on the margin of the Rodinia supercontinent.

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1. Introduction

The amalgamation process of the Yangtze and Cathaysia Blocks to form the South China Block (SCB) and the location of the united SCB in the Rodinia supercontinent has been a hotly debated issue. Two major viewpoints have been proposed. One believed that the

SCB finally amalgamated at the end of the Mesoproterozoic along the Jiangnan orogen (inset in Fig. 1) and occupied an intra-cratonic position of the Rodinia (e.g., Li et al., 1995, 2008b,c, 2002, 2009; Ye et al., 2007). However, recent studies indicated that the formation of the Jiangnan orogen probably occurred at ~ 820 – 830 Ma, significantly later than the assembly time of the Rodinia (e.g., Zhou et al., 2009; Wang et al., 2006; Wang et al., 2007a,b; Wang et al., 2008a, 2011b; Wu et al., 2006; Zhao et al., 2011; Zhang et al., 2011a, 2012a,b, 2013). The other group of researchers suggested that the SCB was either located on the margin of Rodinia or external to the supercontinent (e.g., Torsvik et al., 2001; Yang et al., 2004; Wang et al., 2013a,b; Cawood et al., 2013 and reference therein). The

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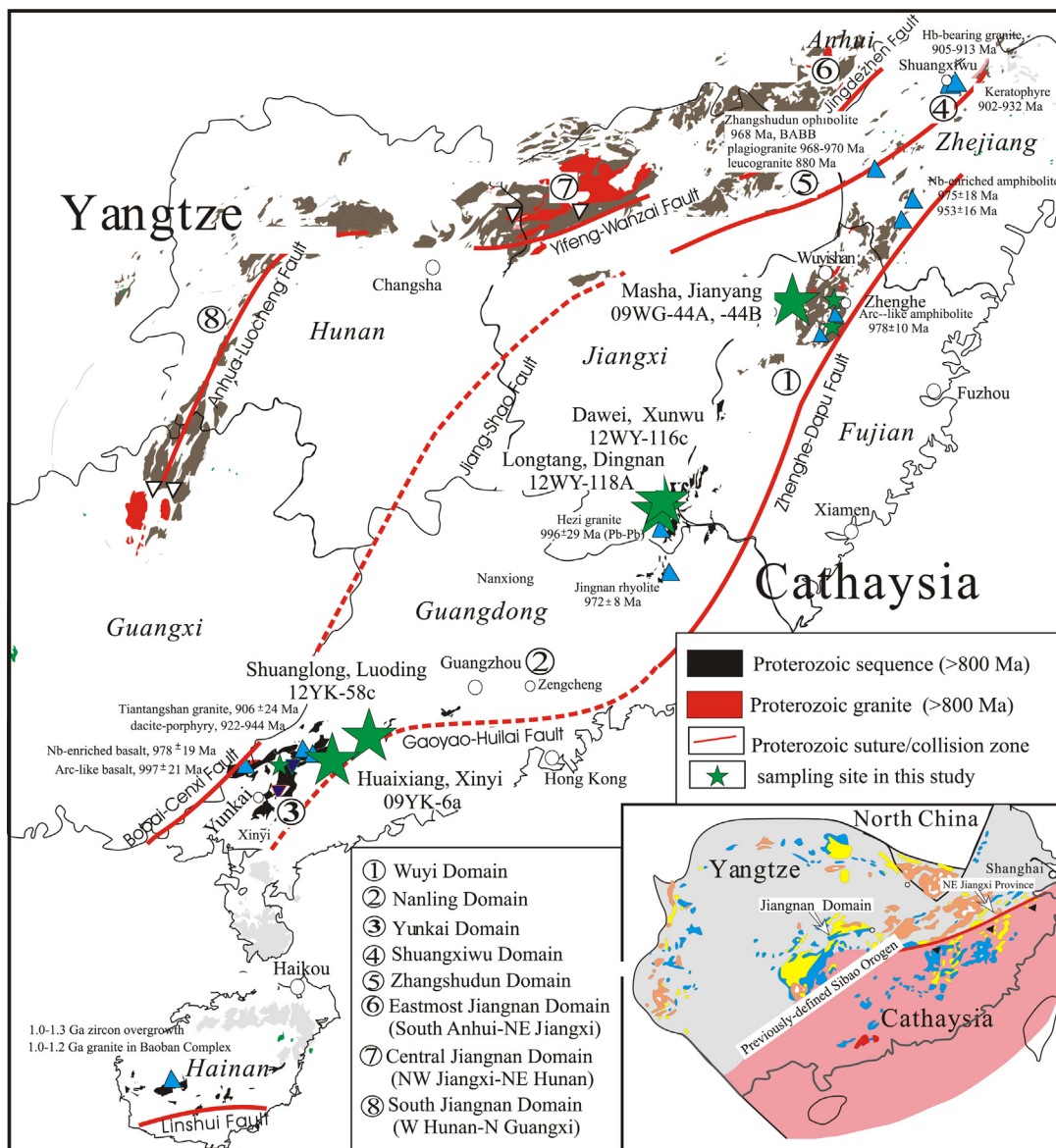


Fig. 1. A simplified geological map showing the location of the early Neoproterozoic granitic plutons in the eastern South China Block (revised from Wang et al., 2013a,b). Also shown are the reported early Neoproterozoic igneous rocks in the Cathaysia. Inset shows the previously-defined Sibaonian (~1.0 Ga) orogenic belt by the assemblage of the Yangtze and Cathaysia Blocks (after Zhang et al., 2012b).

main reason behind the debate is the lack of data and insufficient knowledge on the earliest Neoproterozoic geological history of the Cathaysia Block when the Rodinia was assembled.

Numerous studies have been carried out on the Neoproterozoic tectonic evolution of the Jiangnan orogen (e.g., Zhao and Cawood, 1999, 2012; Zhou et al., 2009; Wang et al., 2006, Wang et al., 2007a,b; Wang et al., 2008a, 2011a; Zhang et al., 2013 and references therein). However, the expected earliest Neoproterozoic (~0.95 Ga) rock associations were absent in the South Anhui, NW Jiangxi, NE and SW Hunan and NE Guangxi areas of the Jiangnan orogen (Fig. 1; e.g., Li and Li, 2003; Wu et al., 2006; Ye et al., 2007; Li et al., 2008a,b,c, 2009; Gao et al., 2009). This made many researchers question whether a tectonic event really took place in the earliest Neoproterozoic in the SCB. On the other hand, zircons inherited from the Cathaysia basement of the SCB and detrital grains from the metamorphic sedimentary rocks gave abundant U–Pb ages of ~0.90–1.00 Ga, distinct from those from the Jiangnan orogen (e.g., Yu et al., 2007; Wang et al., 2007c, 2010a,b; Wan et al., 2007, 2010; Li et al., 2011; Zhao et al., 2011; Zhou et al., 2009; Wang et al., 2012c,

2013a,b). In addition, Wang et al. (2013a,b) and Zhang et al. (2013) recently identified the ~985–970 Ma metabasites from the Wuyi-Yunkai area of the Cathaysia Block with a geochemical affinity to arc and back-arc basin volcanic rocks.

In this study, we document zircon U–Pb geochronological and Lu–Hf isotopic data and whole-rock elemental and Sr–Nd isotopic results for granitic gneiss and migmatite (described herein as granitic gneisses) from the Wuyi-Yunkai domain of the Cathaysia Block. Our data revealed the presence of 985–913 Ma granitic rocks, which were partial melting products of the metavolcanic-sedimentary rocks. These data place critical constraints on the tectonic history of the SCB in the earliest Neoproterozoic and define its location on the margin of the Rodinia.

2. Geological setting and petrography

The Yangtze basement is composed of an Archean-Paleoproterozoic crystalline nucleus (e.g., TTG rocks, felsic gneisses and amphibolites) in the northern Hubei Province and widespread

Neoproterozoic igneous and sedimentary rocks (e.g., Gao et al., 1999, 2011; Qiu et al., 2000; Zheng et al., 2007, 2008; Jiao et al., 2009). However, in the Cathaysia Block, the Neoproterozoic basement is poorly found and the Paleoproterozoic migmatite, granitoid gneisses and amphibolite only outcropped in NW Zhejiang and NE Fujian Provinces (e.g., Fujian BGMR, 1985; Zhejiang BGMR, 1989; Liu et al., 2008; Yu et al., 2009, 2010; Shu et al., 2008). The amalgamation of the Yangtze and Cathaysia Blocks finally formed the united SCB along the Jiangnan Orogen or Jiangshan–Shaoxing suture in the early Neoproterozoic period (e.g., Charvet et al., 1996; Wang et al., 2006; Wang et al., 2007a,b; Zhang et al., 2012a, 2013 and references therein). The coherent SCB is unconformably overlain in turn by an upper Neoproterozoic-lower Paleozoic, Devonian-lower Triassic and upper Triassic-lower Jurassic packages (e.g., Wang and Li, 2003; Shu et al., 2008, 2011; Yu et al., 2010; Wan et al., 2010; Wang et al., 2010a,b, 2013a,b).

The Cathaysia Block can be subdivided into the eastern and western Cathaysia separated by the Zhenghe–Dapu fault, which are extensively outcropped by Mesozoic volcanic rocks of SE Coastal Provinces and Precambrian metamorphic rocks of the Wuyi, Nanling and Yunkai domains, respectively (e.g., Fujian BGMR, 1985; Xu et al., 2005; Wang et al., 2012c, 2013a,b). In these metamorphic domains of the western Cathaysia, the main metamorphic rocks are exposed sparsely as tectonic inliers and contain the greenschist- to amphibolite-facies paragneiss, mica schist, paragneiss, quartzite, marble, granitoid gneiss, migmatite and amphibolite with a small amount of metavolcanic rocks. They are intruded by early Paleozoic to late Mesozoic granites and covered by Mesozoic volcanic and sedimentary rocks. According to the lithological and metamorphic

features, the metamorphic rocks were previously mapped as the lower and upper sequence of the Cathaysia basement. The lower sequence consists of biotite-plagioclase leptynite, sillimanite-mica schist, migmatite, gneiss and amphibolite, which is traditionally termed as the Mayuan Group in NW Fujian, Chencai and Badu Group in SW Zhejiang, Hezi/Xunwu Group in SE Jiangxi and Yunkai Group in SW Guangdong. The upper sequence is defined as the Mamiashan Group in Fujian, Longquan Group in Zhejiang and Taoxi Group in NE Guangdong (Fig. 1; e.g., Fujian BGMR, 1985; Zhejiang BGMR, 1989). The high-grade metamorphic rocks predominantly developed in the lower sequences including the previously-defined Badu, Chencai, Mayuan, Hezi/Xunwu and Yunkai Groups along the Wuyi, Nanling and Yunkai domains (e.g., Fujian BGMR, 1985; Zhejiang BGMR, 1989; Guangdong BGMR, 1988). However, new geochronological data show that, in the previously-defined Cathaysia basement, part of the migmatite, granitoid gneisses and amphibolite in northwestern Zhejiang and northern Fujian Provinces formed in the Paleoproterozoic era (e.g., Fujian BGMR, 1985; Zhejiang BGMR, 1989; Liu et al., 2008; Yu et al., 2009, 2010; Shu et al., 2008). In contrast, a large amount of the schist, granitoid gneiss, migmatite and volcanoclastics rocks were recently dated at the Neoproterozoic and even early Paleozoic period (e.g., Wan et al., 2007, 2010; Li et al., 2010; Zeng et al., 2008; Charvet et al., 2010; Yu et al., 2009, 2010a,b; Wang et al., 2007a,b, 2011a,b, 2012c, 2013a,b and references therein). In addition, a small amount of amphibolite, metagabbro and metadiabase occur as lens, pods and fragments, which might be the relicts of the earliest Neoproterozoic arc-back-arc system in the Cathaysia block (e.g., Wang et al., 2013a,b; Zhang et al., 2012a).

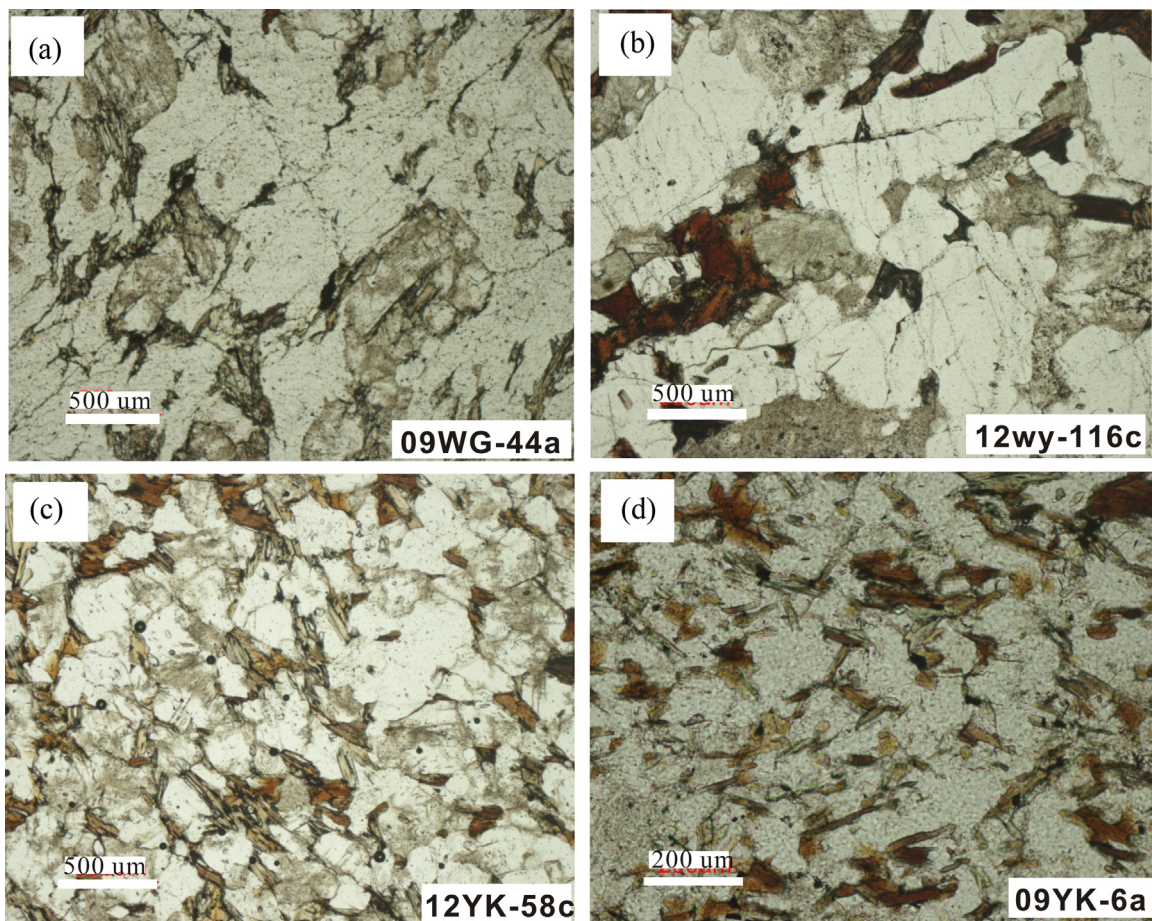


Fig. 2. Microscope photographs for representative granitic rocks: (a) 09WG-44a, (b) 12wy-116c, (c) 12YK-58c and (d) 09YK-6a.

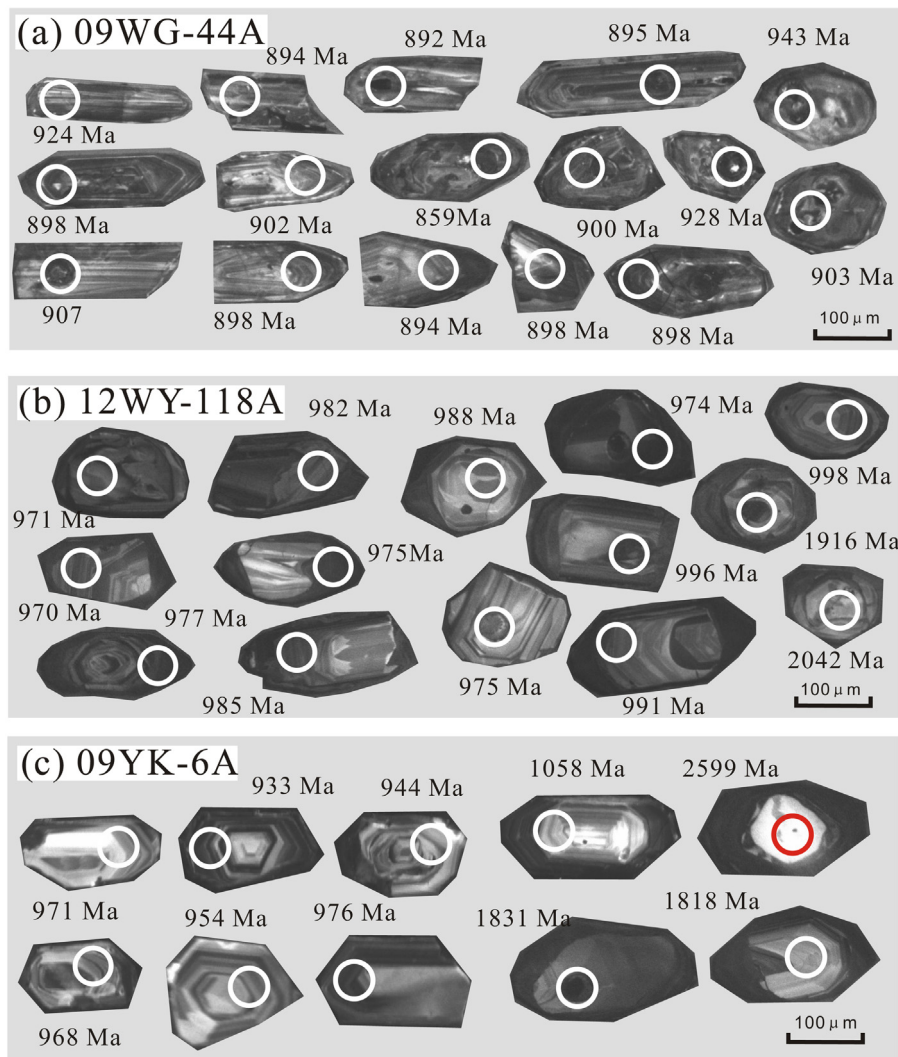


Fig. 3. CL images of representative zircons for granitic samples (a) 09WG-44A, (b) 12WY-118A and (c) 09YK-6A.

In this paper, we focus on the granitoid gneisses in the lower sequence of the Cathaysia basement, which were collected from Masha and Shibei (North Wuyi), Dawei (Xunwu in Nanling), Longtang (Dingnan), Shuanglong (Luoding) and Huaixiang (Xinyi) (Fig. 1). They appear either as leucosomes of migmatites and gneisses (e.g., Masha and Xinyi areas) with strong magmatic orientation or gneissic and mylonitic granite with post-magmatic ductile deformation (e.g., Longtang and Hezi areas). Their crystallization ages is poorly constrained so far. The principal mineral phases of the granitoid gneisses are plagioclase (~25–38%), K-feldspar (~26–34%), quartz (~15–35%) and biotite (~10–20%), with minor amounts of accessory minerals of apatite, zircon, monazite and Fe–Ti oxides (Fig. 2a–d). Among these rocks, several samples additionally contain muscovite (3–5%). The samples from the Nanling area commonly show a porphyritic texture with feldspar phenocrysts in a groundmass of fine-grained K-feldspar, plagioclase and quartz.

3. Analytical methods

Zircon grains for U–Pb dating and Lu–Hf isotopic compositions were separated using conventional heavy liquid and magnetic techniques. Their internal structure was examined by cathodoluminescence image at the Guangzhou Institute of Geochemistry (GIG),

the Chinese Academy of Sciences (CAS). U, Th and Pb isotopic measurements for 09WG-44B were undertaken using the Cameca IMS 1280 large-radius SIMS at the Institute of Geology and Geophysics (CAS) and other samples by Nu instruments MC-ICP-MS attached to the M-50-HR Excimer Laser Ablation System at the University of Hong Kong. The instrumental setting and detailed analytical procedures for two techniques were described in Li et al. (2009) and Xia et al. (2004), respectively. Common Pb correction was made using the observed ^{204}Pb peak. Data processing was carried out via the SQUID 1.03 and Isoplot/Ex 2.49 programs of Ludwig (2001). Zircon in situ Lu–Hf isotopic compositions were measured by Nu instruments MC-ICP-MS at the University of Hong Kong. External calibration was made by measuring zircon standard 91,500 with the unknowns during the analyses to evaluate the reliability of the analytical data, which yielded a weighted mean $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282307 ± 31 (2σ , Wu et al., 2006).

The representative samples were crushed to 200-mesh in a steel mortar and ground in a steel mill for the elemental and isotopic analyses. The whole-rock major oxides and trace element contents, along with Sr–Nd isotopic ratios for the samples were performed on X-ray fluorescence spectrometry, Elan6000 inductively coupled plasma mass spectrometer and MC-ICPMS at the GIG, CAS, respectively. The detailed sample preparation and chemical separation procedures were described by Wei et al. (2002) and

Liang et al. (2003). The mass fractionation corrections for isotopic ratios are based on $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$. The measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the SRM 987 standard and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of the La Jolla standard are 0.710265 ± 12 (2σ) and 0.511862 ± 10 (2σ), respectively. Within-run errors of precision for these analyses are estimated to be better than 0.000015 for $^{146}\text{Nd}/^{144}\text{Nd}$ in the 95% confidence level. $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios were calculated using the Rb, Sr, Sm and Nd contents measured by ICP-MS.

4. Zircon U–Pb and Lu–Hf isotopic results

Six samples (see Fig. 1 for the sampling locations) were selected for zircon U–Pb dating and in situ Lu–Hf isotopic measurement. The separated zircons from these samples are mostly transparent and euhedral in morphology. The internal texture is featured by oscillatory zonation in CL images, similar to those of acid igneous grains (Fig. 3a–c). The zircon U–Pb and in situ Lu–Hf isotopic analytical data are listed in Tables 1 and 2. The sampling location and dating results are summarized in Table 3.

09WG-44A and 09WY-44B samples from Masha (Jiayang) were selected for LA-ICPMS and SIMS zircon U–Pb dating, respectively. Twenty-five analyses for 09WG-44A form a discordia line with the upper intercept age of 907 ± 28 Ma and twenty concordant spots yield a weighted mean age of 909 ± 10 Ma (MSWD=0.5, Fig. 4a). Their $\epsilon\text{Hf}(t)$ values range from -5.2 to $+0.5$ and Hf two-stage model ages from 1.43 Ga to 1.65 Ga, respectively (Table 1). Twenty-four spots on 09WY-44B grains, which show the typical CL image of igneous grains (Fig. 2a), have variable Th/U ratios of 0.10–1.10. These analytical spots constitute a discordia line with the upper intercept age of 906 ± 18 Ma. Eighteen spots of them give a weighted mean age of 916 ± 6 Ma (MSWD = 1.0, Fig. 4b), with $\epsilon\text{Hf}(t)$ of $-5.7 \sim +2.8$ and T_{DM} of 1.35–1.69 Ga (Tables 2 and 3). The 38 concordant spots for the two samples together give a $^{206}\text{Pb}/^{238}\text{U}$ weighted mean age of 913 ± 5 Ma (MSWD=0.5) with the $\epsilon\text{Hf}(t)$ values peaking at -2.3 . This age can be interpreted as the crystallization age of the Masha granitic gneiss.

Two gneissoid samples (12WY-116C and -118A) were taken from Dawei (Xunwu) and Longtang (Dingnan), respectively (Fig. 1). Fourteen grains from 12WY-116C have $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages ranging from 1092 Ma to 2653 Ma, with variable $\epsilon\text{Hf}(t)$ values (-9.5 to 12.5) and Neoproterozoic–Proterozoic model ages (2.56 Ga to 2.82 Ga). Four spots (12WY-116C-01, -25, -29 and -30) show the apparent age of $^{207}\text{Pb}/^{206}\text{Pb} > ^{207}\text{Pb}/^{235}\text{U} > ^{206}\text{Pb}/^{238}\text{U}$, suggestive of Pb loss during later tectonothermal events. The remaining eight analyses have Th/U ratios = 0.14–1.60 and give a weighted mean age of 982 ± 27 Ma (MSWD = 0.5, Fig. 5a). The earliest Proterozoic grains show variable $\epsilon\text{Hf}(t)$ values with two clusters at -8.5 and -2.5 , respectively, and T_{DM} model ages from 1.48 Ga to 1.89 Ga (Table 3). For 12WY-118A, one cluster defined by 18 out of 27 grains yields a weighted mean age of 963 ± 11 Ma (Fig. 5b). Their Th/U ratios are 0.29–1.59 and $\epsilon\text{Hf}(t)$ values vary from -7.7 to -0.4 with two peaks of -6.8 and -1.9 . Their T_{DM} model ages range from 1.49 Ga to 2.00 Ga (Table 3). Four analyses from 12WY-118A have older $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages of 1265–2786 Ma, interpreted as inherited grains.

12YK-58C and 09YK-6A, the gneissic enclave and granitoid gneiss from Shuanglong (Luoding) and Huaixiang (Xinyi), respectively, were previously mapped as the Yunkai Group (Fig. 1). Seven grains from 12YK-58C give the older U–Pb apparent age (1475–1995 Ma) and yield upper intercept age of 2028 ± 48 Ma. The remaining 19 spots for 12YK-58C have Th/U ratios of 0.26–1.34 and constitute a well-defined discordant line with upper intercept age of 926 ± 28 Ma (Fig. 6a). These grains give $\epsilon\text{Hf}(t)$ values of -7.3 to -5.5 with peak at -6.8 and T_{DM} of 1.68–1.76 Ga (Tables 2 and 3).

Table 1
Results of SIMS zircon U–Pb analyses for the 09WY-44B granitoid gneiss in the Wuyi Domain, Cathaysia Block.

spot	Th/U	Isotopic ratios		Apparent age (Ma)		Dis	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Yb}/^{177}\text{Hf}$	$\epsilon\text{Hf}(t)$	T_{DM}								
		$^{207}\text{Pb}/^{206}\text{Pb} \pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U} \pm 1\sigma$	$^{207}\text{Pb}/^{206}\text{Pb} \pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U} \pm 1\sigma$															
09WY-44B-1	0.21	0.06854	0.98	1.47419	1.79	0.15600	1.51	884.8	20.1	919.8	10.9	914.5	13.1	6.0	0.282235	0.000010	0.002054	0.080515	-0.1	1.48
09WY-44B-2	1.10	0.06277	0.63	0.80909	1.67	0.09348	1.55	700.6	13.4	601.9	7.6	576.1	8.5	-18.6	0.282243	0.000009	0.001448	0.058197	0.6	1.44
09WY-44B-3	0.19	0.06853	0.98	1.46712	1.80	0.15526	1.50	884.8	20.2	916.9	10.9	930.4	13.0	5.5	0.282128	0.000009	0.001653	0.065279	-3.6	1.61
09WY-44B-4	0.20	0.06856	1.70	1.31257	2.30	0.13886	1.56	885.5	34.7	851.3	13.4	838.2	12.2	-5.7	0.282157	0.000010	0.001205	0.049958	-2.3	1.55
09WY-44B-5	0.14	0.06972	0.52	1.47839	1.59	0.15378	1.50	920.2	10.7	921.6	9.7	922.1	12.9	0.2	0.282200	0.000009	0.001900	0.078051	-1.2	1.52
09WY-44B-6	0.18	0.06963	1.06	1.45583	1.84	0.15164	1.51	917.5	21.6	912.3	11.1	910.1	12.8	-0.9	0.282177	0.000009	0.001938	0.082936	-2.1	1.55
09WY-44B-7	0.13	0.06849	0.97	1.43758	1.78	0.15224	1.50	883.3	19.9	904.7	10.7	913.5	12.8	3.7	0.282236	0.000009	0.002460	0.104430	-0.3	1.49
09WY-44B-8	0.14	0.06853	0.98	1.24949	1.87	0.13224	1.59	884.5	20.1	823.2	10.6	800.6	12.0	-10.1	0.282138	0.000009	0.001665	0.065667	-3.3	1.60
09WY-44B-9	0.18	0.06948	1.27	1.47344	1.96	0.15381	1.50	912.9	25.9	919.5	11.9	922.3	12.9	1.1	0.282179	0.000009	0.001423	0.058977	-1.7	1.53
09WY-44B-10	0.23	0.06852	0.86	1.44807	1.74	0.15327	1.51	884.4	17.7	909.1	10.5	919.3	12.9	4.2	0.282209	0.000009	0.001374	0.057245	-0.6	1.49
09WY-44B-11	0.14	0.06994	1.08	1.43731	1.86	0.14905	1.51	926.6	22.1	904.6	11.2	895.6	12.7	-3.6	0.282129	0.000010	0.001421	0.059368	-3.4	1.60
09WY-44B-12	0.26	0.06996	1.36	1.46568	2.02	0.15195	1.50	927.1	27.6	916.3	12.3	911.9	12.8	-1.8	0.282160	0.000011	0.001335	0.052058	-2.3	1.55
09WY-44B-13	0.18	0.06837	1.74	1.41539	1.97	0.15015	1.50	879.7	26.3	895.4	11.8	901.8	12.6	2.7	0.282061	0.000010	0.001266	0.051038	-5.8	1.69
09WY-44B-14	0.29	0.06863	1.28	1.46501	2.29	0.15482	1.50	887.6	35.5	916.1	13.9	927.9	13.0	4.9	0.282161	0.000008	0.001410	0.053174	-2.3	1.56
09WY-44B-15	0.28	0.06884	0.91	1.44050	1.76	0.15176	1.50	894.1	18.8	905.9	10.6	910.8	12.8	2.0	0.282303	0.000012	0.001320	0.055779	2.8	1.35
09WY-44B-16	0.29	0.07007	1.14	1.49250	1.88	0.15447	1.50	930.5	23.2	927.3	11.5	926.0	13.0	-0.5	0.282151	0.000027	0.000512	0.018540	-2.1	1.53
09WY-44B-17	0.30	0.07029	1.36	1.48843	2.06	0.15357	1.55	937.0	27.6	925.7	12.6	920.9	13.3	-1.8	0.282128	0.000009	0.001722	0.069243	-3.7	1.62
09WY-44B-18	0.24	0.06836	1.17	1.45835	1.90	0.15472	1.50	879.5	24.0	913.3	11.5	927.4	13.0	5.8	0.282113	0.000009	0.002122	0.087635	-4.4	1.65
09WY-44B-19	0.10	0.07031	1.14	1.49050	2.02	0.15376	1.67	937.3	23.1	926.5	12.3	922.0	14.3	-1.7	0.282096	0.000009	0.001460	0.055030	-4.6	1.65
09WY-44B-20	0.18	0.06889	0.81	1.40771	1.71	0.14821	1.50	895.4	16.6	892.2	10.2	890.9	12.5	-0.5	0.282161	0.000009	0.001671	0.070216	-2.5	1.57
09WY-44B-22	0.29	0.06676	5.59	1.46062	5.79	0.15868	1.52	830.3	112.3	914.3	35.5	919.4	13.4	15.4						
09WY-44B-23	0.27	0.06881	1.50	1.32824	2.30	0.13999	1.75	893.1	30.7	858.1	13.4	844.6	13.8	-5.8						
09WY-44B-24	0.23	0.06795	1.69	1.46379	2.26	0.15623	1.50	867.1	34.6	915.6	13.7	935.8	13.1	8.5						
09WY-44B-25	0.24	0.06982	1.15	1.47442	1.89	0.15315	1.50	923.2	23.5	919.9	11.5	918.6	12.9	-0.5	0.282161	0.000009	0.001671	0.070216	-2.5	1.57

Table 2
LA-ICPMS zircon U–Pb and Lu–Hf analytical result of early Neoproterozoic granitic gneisses from Wuyi-Yunkai, Cathaysia Block.

spot	Th/U	Isotopic ratios				Apparent age (Ma)						¹⁷⁶ Hf/ ¹⁷⁷ Hf		¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Yb/ ¹⁷⁷ Hf	εHf(t)	T _{DM}		
		²⁰⁷ Pb/ ²⁰⁶ Pb ± 1σ		²⁰⁷ Pb/ ²³⁵ U ± 1σ		²⁰⁶ Pb/ ²³⁸ U ± 1σ		²⁰⁷ Pb/ ²⁰⁶ Pb ± 1σ		²⁰⁷ Pb/ ²³⁵ U ± 1σ		²⁰⁶ Pb/ ²³⁸ U ± 1σ							
09WG-44A granitic gneiss from Masha, Jiayang, Wuyi Mountain																			
09WG-44A-1	0.51	0.06983	0.00175	1.46546	0.03768	0.15221	0.00391	913	22	916	16	924	51	0.282208	0.000019	0.001592	0.050774	-0.8	1.50
09WG-44A-2	0.23	0.06776	0.0017	1.3844	0.03513	0.14815	0.00374	891	21	882	15	861	56	0.282235	0.000018	0.001297	0.040428	0.4	1.45
09WG-44A-3	0.17	0.06897	0.00173	1.43471	0.03708	0.15087	0.0039	906	22	904	15	898	47	0.282176	0.000022	0.002050	0.059871	-2.2	1.56
09WG-44A-4	0.58	0.06928	0.00173	1.45423	0.03724	0.15225	0.0039	914	22	912	15	907	56	0.282188	0.000021	0.001821	0.057239	-1.6	1.54
09WG-44A-5	0.35	0.06884	0.00172	1.44699	0.03668	0.15243	0.00386	915	22	909	15	894	52	0.282251	0.000020	0.002582	0.077587	0.2	1.48
09WG-44A-6	0.48	0.06906	0.00173	1.44458	0.03663	0.1517	0.00384	910	22	908	15	902	52	0.282147	0.000021	0.002079	0.062418	-3.2	1.60
09WG-44A-7	0.22	0.06899	0.00173	1.43776	0.03663	0.15113	0.00385	907	22	905	15	898	47	0.282082	0.000019	0.001563	0.044193	-5.2	1.67
09WG-44A-8	0.05	0.06826	0.00172	1.40404	0.0357	0.14914	0.00376	896	21	891	15	876	47	0.282150	0.000019	0.002082	0.062126	-3.1	1.60
09WG-44A-9	0.21	0.07045	0.00177	1.47734	0.03746	0.15207	0.00384	913	22	921	15	943	46	0.282177	0.000019	0.002799	0.083640	-2.6	1.59
09WG-44A-10	0.38	0.06879	0.00172	1.44164	0.03737	0.15195	0.00393	912	22	906	16	892	52	0.282163	0.000021	0.001904	0.057543	-2.5	1.57
09WG-44A-11	0.08	0.06562	0.00165	1.05805	0.02775	0.11669	0.00299	711	17	733	14	794	58	0.282172	0.000016	0.001313	0.039838	-1.9	1.54
09WG-44A-12	0.02	0.06768	0.0017	1.22489	0.03187	0.1311	0.00337	794	19	812	15	859	52	0.282259	0.000018	0.002537	0.076271	0.5	1.46
09WG-44A-13	0.11	0.06853	0.00172	1.43081	0.03705	0.15142	0.00392	909	22	902	15	885	84	0.282206	0.000024	0.001731	0.050468	-0.9	1.50
09WG-44A-14	0.07	0.06882	0.00172	1.43951	0.03676	0.15169	0.00387	910	22	906	15	894	52	0.282201	0.000017	0.001687	0.053879	-1.1	1.51
09WG-44A-15	0.13	0.0689	0.00173	1.43336	0.03687	0.15085	0.00388	906	22	903	15	895	52	0.282168	0.000017	0.000781	0.025221	-1.7	1.52
09WG-44A-16	0.44	0.06869	0.00172	1.26063	0.0342	0.13295	0.00354	805	20	828	15	900	52	0.282184	0.000024	0.002051	0.059437	-1.9	1.55
09WG-44A-17	0.05	0.06892	0.00173	1.43787	0.03652	0.15125	0.00382	908	21	905	15	898	52	0.282186	0.000019	0.002943	0.087153	-2.4	1.58
09WG-44A-18	0.07	0.06828	0.00171	1.27342	0.03318	0.13506	0.00347	817	20	834	15	876	47	0.282159	0.000020	0.001754	0.052975	-2.6	1.57
09WG-44A-19	0.38	0.06896	0.00173	1.43798	0.03685	0.15122	0.00387	908	22	905	15	898	47	0.282163	0.000018	0.002149	0.064733	-2.7	1.58
09WG-44A-20	0.16	0.06999	0.00176	1.46694	0.03713	0.15198	0.00383	912	21	917	15	928	56	0.282102	0.000019	0.001272	0.036847	-4.3	1.63
09WG-44A-21	0.18	0.06915	0.00173	1.4409	0.03677	0.15111	0.00385	907	22	906	15	903	52	0.282107	0.000022	0.001735	0.047255	-4.4	1.65
09WG-44A-22	0.56	0.06793	0.0017	1.23222	0.03126	0.13152	0.00332	797	19	815	14	866	52	0.282284	0.000023	0.002592	0.081424	1.3	1.43
09WG-44A-23	0.2	0.06888	0.00173	1.4479	0.03787	0.15245	0.00399	915	22	909	16	894	52	0.282166	0.000018	0.001347	0.040311	-2.1	1.55
09WG-44A-24	0.15	0.06884	0.00173	1.44632	0.0395	0.15223	0.00413	913	23	908	16	894	52	0.282087	0.000017	0.001285	0.038856	-4.9	1.65
09WG-44A-25	0.72	0.06887	0.00172	1.43082	0.03685	0.15066	0.00388	905	22	902	15	894	52	0.282227	0.000023	0.002424	0.077467	-0.6	1.50
12WY-116C granitic gneiss from Hezi, Anyuan, Nanling Mountain																			
12WY-116C-01	0.54	0.069933	0.002068	1.287489	0.046393	0.132096	0.003460	928	61	840	21	800	20	0.281900	0.000049	0.000677	0.016021	-9.6	1.89
12WY-116C-02	0.40	0.114766	0.002876	5.458031	0.138518	0.344795	0.008742	1876	45	1894	22	1910	42	0.281594	0.000028	0.001550	0.036625	-1.1	2.36
12WY-116C-03	1.05	0.163449	0.004094	9.977553	0.252126	0.442584	0.011178	2492	42	2433	23	2362	50	0.281216	0.000017	0.000466	0.010931	-2.9	2.80
12WY-116C-04	0.56	0.076874	0.001953	1.741020	0.044347	0.164267	0.004246	1118	51	1024	16	980	24	0.281918	0.000027	0.000623	0.015351	-9.0	1.86
12WY-116C-05	0.39	0.070899	0.001777	1.615065	0.041317	0.165169	0.004223	954	52	976	16	985	23	0.282165	0.000027	0.000518	0.012629	0.0	1.51
12WY-116C-06	0.70	0.165521	0.004147	11.02025	0.280495	0.482665	0.012265	2513	42	2525	24	2539	53	0.281210	0.000028	0.000494	0.011299	0.9	2.81
12WY-116C-07	0.54	0.090386	0.002272	3.112952	0.079227	0.249672	0.006322	1435	48	1436	20	1437	33	0.281614	0.000025	0.000376	0.009303	-9.5	2.26
12WY-116C-10	0.18	0.070895	0.001776	1.604322	0.040636	0.164056	0.004150	954	52	972	16	979	23	0.282073	0.000024	0.000297	0.007902	-3.3	1.63
12WY-116C-11	0.57	0.071760	0.001799	1.630321	0.041866	0.164776	0.004236	989	51	982	16	983	23	0.281927	0.000019	0.000517	0.013000	-8.5	1.84
12WY-116C-12	0.37	0.070437	0.001767	1.590317	0.041239	0.163631	0.004219	943	51	966	16	977	23	0.282201	0.000026	0.000861	0.019470	0.8	1.48
12WY-116C-13	0.22	0.103587	0.002602	4.303276	0.109601	0.301454	0.007714	1700	79	1694	21	1699	38	0.281714	0.000020	0.001126	0.026966	-0.9	2.17
12WY-116C-14	0.18	0.179993	0.004514	12.53618	0.335357	0.504212	0.013320	2653	41	2645	25	2632	57	0.281361	0.000022	0.000674	0.016763	8.0	2.62
12WY-116C-15	0.31	0.178526	0.004477	12.48813	0.337850	0.507011	0.013676	2639	41	2642	25	2644	59	0.281210	0.000027	0.000671	0.015633	2.9	2.82
12WY-116C-16	0.56	0.075904	0.001910	1.732341	0.044780	0.165474	0.004274	1092	50	1021	17	987	24	0.281919	0.000026	0.000640	0.014922	-8.8	1.86
12WY-116C-17	0.48	0.088644	0.002225	2.997010	0.076070	0.245142	0.006211	1398	48	1407	19	1413	32	0.282128	0.000031	0.001089	0.025998	7.6	1.59
12WY-116C-18	0.63	0.135501	0.003402	7.339980	0.188746	0.392621	0.010013	2172	43	2154	23	2135	46	0.281804	0.000031	0.000722	0.015956	12.5	2.02
12WY-116C-19	0.20	0.072610	0.001821	1.645784	0.042068	0.164409	0.004217	1003	51	988	16	981	23	0.281988	0.000031	0.000645	0.016361	-6.5	1.76
12WY-116C-20	0.41	0.099812	0.002503	3.891745	0.098597	0.282663	0.007148	1621	47	1612	20	1605	36	0.281738	0.000028	0.000352	0.007719	-1.3	2.09
12WY-116C-21	0.68	0.072116	0.001808	1.629254	0.041810	0.163779	0.004197	991	50	982	16	978	23	0.282147	0.000029	0.000755	0.020330	-1.0	1.55
12WY-116C-22	1.60	0.072883	0.001838	1.656724	0.042901	0.164818	0.004247	1011	51	992	16	983	24	0.282114	0.000029	0.000714	0.019969	-2.0	1.59
12WY-116C-23	0.55	0.091082	0.002282	3.163404	0.084007	0.251766	0.006678	1450	48	1448	20	1448	34	0.282072	0.000028	0.000412	0.010441	7.0	1.64
12WY-116C-25	0.48	0.065461	0.001737	0.917715	0.024018	0.101860	0.002632	791	56	661	13	625	15	0.282054	0.000031	0.000378	0.010404	-4.0	1.66
12WY-116C-26	0.17	0.092182	0.002311	3.008877	0.076406	0.236595	0.005992	1472	42	1410	19	1369	31	0.282158	0.000033	0.001519	0.042537	7.3	1.56
12WY-116C-27	0.14	0.072216	0.001810	1.634480	0.042112	0.164076	0.004222	992	51	984	16	979	23	0.282111	0.000040	0.000560	0.014462		

Table 2 (Continued)

spot	Th/U	Isotopic ratios		Apparent age (Ma)				¹⁷⁶ Hf/ ¹⁷⁷ Hf		¹⁷⁶ Lu/ ¹⁷⁷ Hf	¹⁷⁶ Yb/ ¹⁷⁷ Hf	εHf(t)	T _{DM}						
		²⁰⁷ Pb/ ²⁰⁶ Pb ± 1σ	²⁰⁷ Pb/ ²³⁵ U ± 1σ	²⁰⁶ Pb/ ²³⁸ U ± 1σ	²⁰⁷ Pb/ ²⁰⁶ Pb ± 1σ	²⁰⁷ Pb/ ²³⁵ U ± 1σ	²⁰⁶ Pb/ ²³⁸ U ± 1σ												
12WY-118A granitic gneiss from Hezi, Anyuan, Nanling Mountain																			
12WY-118A-01	0.50	0.082741	0.002333	2.265658	0.064757	0.198591	0.005641	1265	55	1202	20	1168	30	0.282176	0.000014	0.001129	0.032194	3.9	1.52
12WY-118A-03	1.02	0.084498	0.002370	2.577412	0.073763	0.221228	0.006327	1306	58	1294	21	1288	33	0.282127	0.000023	0.001201	0.030235	4.7	1.59
12WY-118A-04	0.29	0.069736	0.001968	1.564159	0.044560	0.162650	0.004598	920	58	956	18	971	25	0.282137	0.000025	0.000505	0.014163	-1.3	1.55
12WY-118A-06	0.47	0.071032	0.002002	1.591090	0.045708	0.162446	0.004642	967	58	967	18	970	26	0.281974	0.000025	0.000535	0.014672	-7.1	1.78
12WY-118A-07	0.45	0.070995	0.001994	1.602940	0.046804	0.163724	0.004772	967	57	971	18	977	26	0.281976	0.000025	0.000570	0.014667	-6.9	1.78
12WY-118A-08	0.56	0.072434	0.002035	1.643495	0.047243	0.164534	0.004718	998	57	987	18	982	26	0.282149	0.000020	0.000436	0.011382	-0.6	1.53
12WY-118A-09	0.41	0.072807	0.002056	1.665107	0.051557	0.165093	0.004979	1009	57	995	20	985	28	0.281988	0.000024	0.000734	0.020842	-6.5	1.77
12WY-118A-10	0.57	0.073661	0.002072	1.673708	0.047513	0.164754	0.004663	1031	56	999	18	983	26	0.281970	0.000024	0.001669	0.046639	-7.7	1.84
12WY-118A-11	0.40	0.073320	0.002060	1.669010	0.047475	0.165167	0.004708	1033	57	997	18	985	26	0.282125	0.000027	0.001129	0.029834	-1.9	1.59
12WY-118A-12	0.12	0.121065	0.003396	5.778777	0.163137	0.346202	0.009782	1972	50	1943	24	1916	47	0.281821	0.000023	0.000738	0.017346	8.2	2.00
12WY-118A-13	0.32	0.076362	0.002183	1.732794	0.061283	0.163241	0.005398	1106	53	1021	23	975	30	0.282125	0.000016	0.001998	0.052978	-2.6	1.63
12WY-118A-14	0.37	0.065227	0.001880	0.933234	0.027483	0.103733	0.002975	783	61	669	14	636	17	0.282088	0.000031	0.001080	0.025805	-3.4	1.64
12WY-118A-15	0.42	0.075211	0.002114	1.690981	0.048400	0.163074	0.004666	1076	56	1005	18	974	26	0.282128	0.000027	0.000974	0.026479	-1.9	1.58
12WY-118A-16	0.61	0.077653	0.002229	1.788852	0.051562	0.167137	0.004748	1139	57	1041	19	996	26	0.282088	0.000025	0.000590	0.016050	-2.6	1.62
12WY-118A-18	0.24	0.066523	0.001874	0.983955	0.029079	0.107135	0.003102	833	58	696	15	656	18	0.282182	0.000030	0.000391	0.010526	0.4	1.49
12WY-118A-19	0.40	0.070131	0.001973	1.565155	0.044628	0.161817	0.004595	931	58	957	18	967	25	0.282069	0.000045	0.001947	0.048728	-4.8	1.71
12WY-118A-20	0.60	0.072229	0.002052	1.654980	0.047945	0.166261	0.004777	992	25	991	18	991	26	0.282163	0.000032	0.001045	0.028798	-0.3	1.54
12WY-118A-21	1.59	0.076004	0.002137	1.754912	0.049935	0.167483	0.004772	1094	56	1029	18	998	26	0.282153	0.000024	0.000573	0.015154	-0.2	1.53
12WY-118A-22	0.90	0.067074	0.001912	1.117679	0.034928	0.120139	0.003568	839	55	762	17	731	21	0.282122	0.000021	0.000756	0.020294	-1.9	1.58
12WY-118A-23	0.63	0.074107	0.002090	1.707550	0.048871	0.167157	0.004788	1044	57	1011	18	996	26						
12WY-118A-24	0.51	0.128231	0.003599	6.592510	0.190614	0.372702	0.010746	2074	45	2058	25	2042	50						
12WY-118A-25	0.42	0.074794	0.002098	1.717778	0.050814	0.166523	0.004916	1065	56	1015	19	993	27						
12WY-118A-26	0.63	0.069271	0.001945	1.558507	0.044096	0.163134	0.004603	907	58	954	18	974	26						
12WY-118A-27	0.52	0.073639	0.002086	1.679154	0.048064	0.165668	0.004766	1031	57	1001	18	988	26						
12WY-118A-28	0.42	0.073401	0.002061	1.649340	0.046895	0.162957	0.004624	1025	56	989	18	973	26						
12WY-118A-29	0.13	0.066317	0.001865	1.036571	0.032897	0.113216	0.003537	817	55	722	16	691	20						
12WY-118A-30	0.50	0.065075	0.002373	0.922263	0.040580	0.101863	0.002999	776	77	664	21	625	18						
12YK-58C gneissic granite from Longxin, Luoding, Yunkai Mountain																			
12YK-58C-02	0.74	0.065374	0.001641	1.025407	0.028170	0.113659	0.003098	787	54	717	14	694	18						
12YK-58C-03	0.67	0.066567	0.001670	0.901702	0.022865	0.098195	0.002483	833	52	653	12	604	15						
12YK-58C-04	0.60	0.064791	0.001630	0.902353	0.022994	0.100960	0.002559	769	49	653	12	620	15						
12YK-58C-06	0.75	0.069962	0.001771	1.387316	0.035674	0.143738	0.003650	928	56	884	15	866	21						
12YK-58C-07	0.54	0.067784	0.001703	1.142847	0.029708	0.122188	0.003147	861	56	774	14	743	18						
12YK-58C-08	1.21	0.124310	0.003118	5.615209	0.142301	0.327466	0.008287	2020	44	1918	22	1826	40						
12YK-58C-09	1.05	0.065665	0.001661	1.118304	0.030498	0.123475	0.003342	794	53	762	15	751	19	0.282020	0.000026	0.000963	0.026049	-6.8	1.73
12YK-58C-10	0.93	0.122158	0.003067	4.985237	0.131315	0.295770	0.007744	1988	44	1817	22	1670	39	0.281855	0.000042	0.001697	0.037428	2.8	2.00
12YK-58C-11	0.85	0.066380	0.001685	0.934800	0.024128	0.102074	0.002585	818	54	670	13	627	15	0.282012	0.000027	0.001057	0.025826	-7.1	1.75
12YK-58C-12	1.31	0.123859	0.003117	6.192258	0.158907	0.362501	0.009275	2013	44	2003	22	1994	44	0.281806	0.000053	0.00075	0.018512	9.4	2.02
12YK-58C-13	0.75	0.069980	0.001757	1.334190	0.034428	0.138215	0.003552	928	56	861	15	835	20						
12YK-58C-16	0.61	0.122625	0.003080	4.657135	0.129422	0.274903	0.007461	1995	44	1760	23	1566	38	0.282063	0.000057	0.001251	0.03091	8.4	1.69
12YK-58C-17	0.26	0.066711	0.001675	1.032656	0.026328	0.112233	0.002852	828	52	720	13	686	17	0.282055	0.000060	0.00095	0.022426	-5.5	1.68
12YK-58C-18	1.26	0.068965	0.001749	1.355514	0.035162	0.142477	0.003629	898	47	870	15	859	20	0.282019	0.000069	0.000902	0.022805	-6.7	1.73
12YK-58C-19	0.58	0.064320	0.001638	0.898181	0.024432	0.101285	0.002743	754	54	651	13	622	16	0.282020	0.000075	0.000941	0.022745	-6.7	1.73
12YK-58C-20	1.18	0.065335	0.001648	1.032482	0.026362	0.114583	0.002905	785	54	720	13	699	17	0.282018	0.000040	0.001123	0.027609	-6.9	1.74
12YK-58C-21	0.43	0.067311	0.001690	1.272043	0.032857	0.137017	0.003526	856	52	833	15	828	20	0.281998	0.000061	0.000546	0.014048	-7.3	1.74
12YK-58C-22	0.86	0.067727	0.001720	1.173315	0.030124	0.125629	0.003196	861	58	788	14	763	18	0.282020	0.000036	0.001005	0.024028	-6.8	1.74
12YK-58C-23	0.68	0.064234	0.001611	0.892774	0.022650	0.100765	0.002549	750	253	648	12	619	15						
12YK-58C-25	0.87	0.068070	0.001732	1.115323	0.029239	0.118868	0.003121	872	54	761	14	724	18	0.282019	0.000047	0.001569	0.037984	-7.2	1.76
12YK-58C-26	1.00	0.124130	0.003112	6.210428	0.157723	0.362729	0.009197	2016	44	2006	22	1995	44	0.281817	0.000021	0.001091	0.028395	9.3	2.02
12YK-58C-27	1.24	0.125445	0.003146	6.256098	0.159873	0.361551	0.009216	2035	44	2012	22	1990	44	0.281866	0.000039	0.001051	0.025383	11.0	1.95
12YK-58C-28	0.14	0.119681	0.003011	4.251242	0.117369	0.257160	0.006952	1952	45	1684	23	1475	36						
12YK-58C-29	0.57	0.068810	0.001730	1.398938	0.035629	0.147405	0.003746	894	52	888	15	886	21						
12YK-58C-30	1.34	0.064972	0.001635																

09YK-6A gneissic granite from Huaixiang, Xinyi, Yunkai Mountain	0.53	0.112505	0.002210	5.095362	0.098789	0.328474	0.006284	1840	35	1835	16	1831	30
09YK-6A-1	0.53	0.112505	0.002210	5.095362	0.098789	0.328474	0.006284	1840	35	1835	16	1831	30
09YK-6A-2	0.91	0.072225	0.001520	1.621069	0.034408	0.162785	0.003484	992	42	978	13	972	19
09YK-6A-3	0.49	0.168358	0.003541	10.75271	0.233001	0.463217	0.010323	2541	35	2502	20	2454	45
09YK-6A-4	0.99	0.070566	0.001487	1.575549	0.033535	0.161933	0.003481	945	43	961	13	968	19
09YK-6A-5	0.62	0.070858	0.001493	1.520673	0.032524	0.155650	0.003377	953	43	939	13	933	19
09YK-6A-6	0.19	0.070682	0.001990	1.553859	0.037889	0.159441	0.003173	948	57	952	15	954	18
09YK-6A-7	1.26	0.074989	0.001717	1.842116	0.041780	0.178164	0.004002	1068	45	1061	15	1057	22
09YK-6A-8	0.17	0.068243	0.001437	1.483121	0.032003	0.157622	0.003480	876	43	924	13	944	19
09YK-6A-10	0.96	0.072900	0.001679	1.555002	0.035753	0.154705	0.003552	1011	46	952	14	927	20
09YK-6A-11	0.68	0.171590	0.003613	11.74902	0.252926	0.496603	0.010921	2573	35	2585	20	2599	47
09YK-6A-12	0.61	0.157678	0.003353	9.928543	0.218571	0.456681	0.010386	2431	36	2428	20	2425	46
09YK-6A-13	0.40	0.070742	0.001495	1.594628	0.034013	0.163487	0.003518	950	43	968	13	976	19
09YK-6A-14	0.51	0.113491	0.002395	5.099724	0.108075	0.325900	0.006935	1856	38	1836	18	1818	34
09YK-6A-15	0.52	0.115273	0.002423	5.121257	0.108292	0.322216	0.006853	1884	37	1840	18	1801	33

Notes: $\epsilon\text{Hf}(t)$ values and T_{DM} for grains with the UPb age of younger than 1000 Ma from 09WG-44A, 12WY-116C, 12WY-118A and 12YK-58C are back-calculated to the formation ages of 913 Ma, 982 Ma, 963 Ma and 926 Ma, respectively.

Seven out of 13 grains from 09YK-6A show Th/U ratios of 0.17–0.99 and give weighted mean age of 954 ± 14 Ma with MSWD = 1.0 (Fig. 6b). The $^{206}\text{Pb}/^{207}\text{Pb}$ apparent ages of the remaining six grains for 09YK-6A cluster at 1840–1884 Ma ($n=3$) and 2431–2573 Ma ($n=3$), respectively.

5. Whole-rock geochemical results

The elemental and Sr–Nd isotopic analytical results for the representative samples are presented in Table 4. These samples exhibit $\text{SiO}_2 = 65.6\text{--}77.2$ wt%, $\text{Al}_2\text{O}_3 = 11.3\text{--}16.6$ wt%, $\text{FeOt} = 4.3\text{--}6.6$ wt%, $\text{MgO} = 0.89\text{--}3.39$ wt%, $\text{CaO} = 1.33\text{--}2.88$ wt % and $\text{K}_2\text{O} + \text{Na}_2\text{O} = 4.0\text{--}7.2$ wt %. TiO_2 contents range from 0.44 wt% to 0.91 wt % and P_2O_5 from 0.05 wt% to 0.18 wt%. They show high $\text{TiO}_2 + \text{FeOt} + \text{MgO}$ (5.8–10.2 wt%) and $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{CaO})$ ratios (2.36–4.28). In the QAF diagram (Fig. 7a), they plot predominantly into the fields of monzogranite and quartz-rich granite. CIPW-normative calculations show the constitutes of 25–53 vol.% Qz, 8–19 vol.% Or, 13–29 vol.% Ab and 6–16 vol.% An. They are strongly peraluminous with the A/CNK value ranging from 1.15 to 1.48 and contain 1.8–5.0 vol.% corundum (Fig. 7b). Such signatures are similar to those of typical S-type granites, falling into the S-type range in the triangle diagram of $\text{Al}_2\text{O}_3\text{--}(\text{K}_2\text{O} + \text{Na}_2\text{O})\text{--}(\text{CaO} - (\text{FeOt} + \text{MgO}))$ (Fig. 7c).

Our samples give total REE contents from 150 ppm to 361 ppm and δEu values from 0.35 to 0.70. They show steep REE chondrite-normalized patterns with $(\text{La}/\text{Yb})_n = 7.1\text{--}14.0$ and $(\text{Gd}/\text{Yb})_n = 1.30\text{--}2.04$ (Fig. 8a). On the primitive mantle-normalized spidergram (Fig. 8b), these samples are characterized by markedly negative Nb-Ta, P, Sr and Ti anomalies, similar to those of the Jingningian (~820 Ma) and Kwangsian (400–460 Ma) peraluminous granites and Precambrian metamorphic volcanosedimentary rocks in the Jiangnan Fold Belt and Cathaysia Block (e.g., Chen and Jahn, 1998; Wan et al., 2007, 2010; Wang et al., 2007a,b, 2012c, Zhang et al., 2013; Zhao et al., 2013). Their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.7068 to 0.7233 and $\epsilon_{\text{Nd}}(t)$ values from -3.81 to -9.54 (Fig. 9). The corresponding Nd model ages are in the range of 1.91–2.49 Ga.

6. Discussion

6.1. Petrogenetic constraints

Our samples show Zr correlating with Rb and Ba, suggesting that their mobility of LILE (e.g., Rb, Sr and Ba) after intrusion of the granitic rocks does not seriously change their contents. Their ratios can be used to constrain the source nature. These samples are strongly peraluminous and K-rich, with the majority having $\text{K}_2\text{O}/\text{Na}_2\text{O} > 1$. They have low SiO_2 , low $\text{Al}_2\text{O}_3/\text{TiO}_2$ and Rb/Sr ratios as well as high $\text{CaO}/\text{Na}_2\text{O}$ ratios (>0.6) relative to the partial melting product of typical meta-pelitic sources, such as leucogranite in Himalaya Orogen (Harris and Inger, 1992; Altherr et al., 2000). In contrast, they are similar to the peraluminous granites in the Lachlan Fold Belt, which were probably derived from meta-greywacke source. Their $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values fall into the fields of the global lower crust and global sedimentary rocks (Fig. 9b). In the $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeOt})$ vs $\text{CaO}/(\text{MgO} + \text{FeOt})$ diagram (Fig. 10a), these samples plot into the jointed field of the meta-greywacke and metaigneous sources. In the plot of Rb/Sr and Rb/Ba, they fall into the field of the plagioclase-rich and clay-poor crustal source (Fig. 10b). High FeOt, MgO and TiO_2 contents, and low $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeOt})$ and Rb/Sr ratios suggest the involvement of the metaigneous component in the source (Table 4, e.g., Chappell and White, 1992; Sylvester, 1998; Altherr et al., 2000; Anthony, 2005; Wang et al., 2007a,b, 2011a,b).

Table 3
Summary of lithology, sampling locations, zircon U–Pb dating and Lu–Hf isotopic results of the representative samples from Cathaysia.

Sample	Lithology	Sampling location	Inherited zircon age	Crystallization age	$\varepsilon_{\text{Hf}}(t)$	T_{DM} model age
09WG-44A	Granitic gneiss previously mapped as Mayuan Group	North of Masha, Shaowu, SW Fujian E117°49.911', N27°24.138'		909 ± 10 Ma, n = 20, MSWD = 0.6	–5.2 to +1.3 with peak of –2.3	1.43–1.67 Ga with peak of 1.56 Ga
09WG-44B	Granitic gneiss previously mapped as Mayuan Group	North of Masha, Shaowu, SW Fujian E117°49.911', N27°24.138'		916 ± 6 Ma, n = 20, MSWD = 1.0	–5.8 to +0.6 with peak of –2.2	1.35–1.69 Ga with peak of 1.57 Ga
12WY-116C	Granitic gneiss previously mapped as Xuwu Group	Dawei village, Xunwu, SE Jiangxi E 115°19.438', N 24°57.838'	1435 Ma, 1450 Ma, 1472 Ma, 1407 Ma, 1612 Ma, 1700 Ma, 1876 Ma, 2154 Ma, 2492 Ma 2513 Ma, 2653 Ma, 2642 Ma,	982 ± 27 Ma, n = 8, MSWD = 0.5	–9.6 to +0.8 with peaks of –2.5 and –8.6	1.51–1.89 Ga with peaks of 1.57 Ga and 1.85 Ga
12WY-118A	Granitoid gneiss previously mapped as Xuwu Group	North Longtang, Dingnan, SE Jiangxi E 115°11.360', N 24°51.920'	1265 Ma, 1306 Ma, 1972 Ma, 2074 Ma	963 ± 11 Ma, n = 17, MSWD = 0.2	–5.8 to +0.6 with peaks of –2.1 and –7.0	1.35–1.69 Ga with peaks of 1.57 Ga and 1.72 Ga
12YK-58C	Granitoid gneiss mapped as Yunkai Group	Shuanglong, Luoding, SW Guangdong E 111°20.082', N 22°43.093'	2028 ± 48 Ma	Upper intercept age of 926 ± 28 Ma	–5.5 to –7.3 with peak of –6.8	1.68–1.75 Ga with peak of 1.72 Ga
09YK-6A	Metagranite previously mapped as Yunkai Group	Huaixiang, Xinyi, SW Guangdong E 111°03.286', N 22°25.818'	1068 Ma, 1840 Ma, 1856 Ma, 1856 Ma, 2431 Ma, 2541 Ma, 2573 Ma	954 ± 14 Ma, n = 7, MSWD = 1.0		

Our samples exhibit similar REE and incompatible elemental pattern and variation of major oxides with the Kwangsi granitic rocks in South China (Fig. 8a and b), which are commonly believed to originate from a Proterozoic metapelitic and meta-igneous source with little addition of newly mantle-derived components (e.g., Wang et al., 2007a,b, 2011a,b; Zhang et al., 2012a). Their $\varepsilon_{\text{Nd}}(t)$ values and Nd model ages are also identical to those of the Kwangsi granite in South China when age is back-calculated to 920 Ma (Fig. 11a and b). Such geochemical signatures are also similar to the metamorphic basement in the Wuyi-Yunkai Domains of the Cathaysia consisting of mainly the meta-sedimentary rocks with proportional meta-igneous rocks (e.g., Yu et al., 2005, 2007). The diverse components of the Cathaysia basement provide an ideal source for our earliest Neoproterozoic granite. In the plots of Zr/Nb and Zr/Hf and Nb/La (Fig. 11c and d), they fall into the fields of the Kwangsi granites and show a linear correlation. In addition, our zircon grains with the earliest Neoproterozoic age share the

$\varepsilon_{\text{Hf}}(t)$ values of $-9.64 \sim +2.78$ with the peak values at ca. -2.5 and ca. -7.5 , respectively (Table 3 and Fig. 9b). The corresponding Hf model ages range from 1.35 Ga to 2.00 Ga with the peaks of ~ 1.57 Ga and ~ 1.75 Ga, respectively (Table 3). These observations all suggest a binary mixing of the metapelitic and metaigneous components in the source. The metaigneous component is characterized by low SiO_2 and Rb/Sr but high $\text{FeO} + \text{MgO} + \text{TiO}_2$, $\varepsilon_{\text{Nd}}(t)$ and $\varepsilon_{\text{Hf}}(t)$ values, along with younger Nd and Hf model ages (Fig. 11a–d).

6.2. Tectonic implications

Our zircon U–Pb geochronological results for the Masha (NW Fujian) granitic gneiss (09WG-44A and 09WG-44B) yield the weighted mean age of 913 ± 5 Ma ($n = 38$, MSWD = 0.5). Two gneissoid samples (12WY-116C and 09WG-118A) from Dawei and Longtang (SE Jiangxi) have zircon U–Pb age of 982 ± 27 Ma and

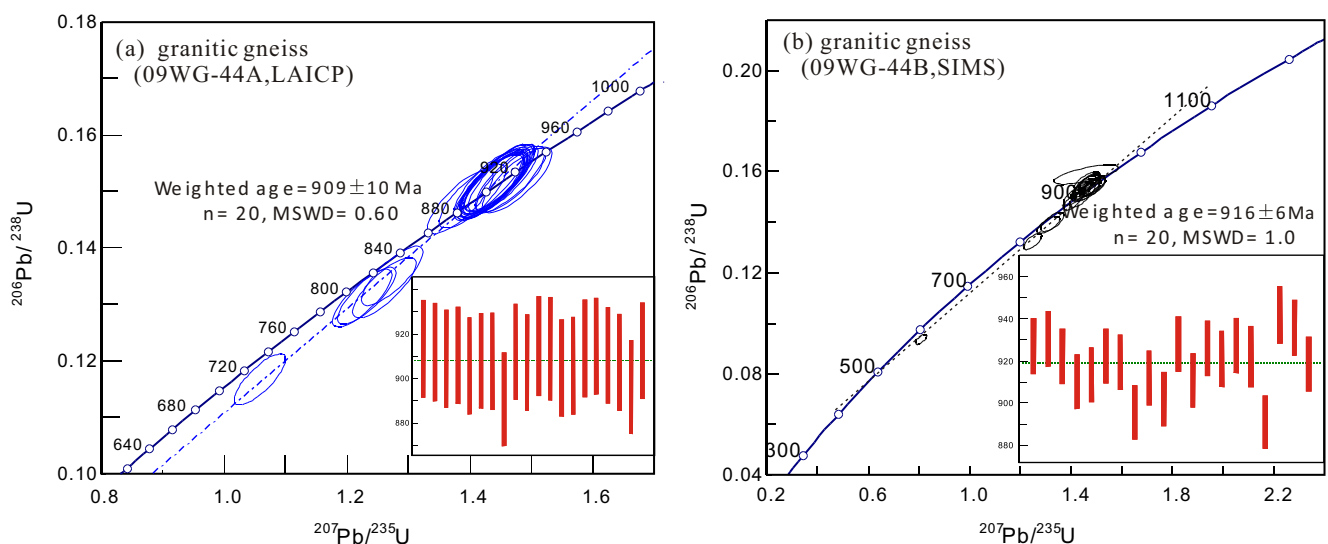


Fig. 4. Concordia diagrams of zircon U–Pb data for the granitic gneisses from Masha (Jianyang), the Wuyi Domain, (a) 09WG-44A, (b) 09WG-44B. The locations for these samples are shown in Fig. 1.

Table 4
Major oxides, elemental and Sr–Nd isotopic analytical results for the early Neoproterozoic granitic rocks in the Cathaysia Block.

Sample	09WG-44A	09WG-44B	12WG-44D1	12WG-44D2	09WG-48A	09WG-60A	09WG-60G	09WG-60H	09WG-60I	12WY-116C	12WY-118A	Hezi*	12YK-58C	09YK-6A	09YK-6B	09YK-6E	09YK-6G	09YK-14B
SiO ₂	66.53	65.07	67.48	67.94	69.39	67.58	66.17	67.42	70.58	71.61	66.17	66.32	64.45	72.61	73.80	75.77	73.02	70.67
TiO ₂	0.88	0.89	0.87	0.75	0.87	0.75	0.73	0.73	0.72	0.43	0.73	0.60	0.86	0.65	0.69	0.66	0.62	0.56
Al ₂ O ₃	14.33	14.94	14.38	14.91	12.34	13.71	13.82	13.83	11.82	13.25	14.86	15.03	15.77	12.19	11.92	11.08	11.92	14.24
FeO _t	5.93	5.68	5.84	4.77	6.08	6.41	6.10	5.94	5.42	4.74	6.08	4.55	5.01	5.32	4.77	4.17	5.06	4.60
MgO	1.59	1.65	1.53	1.31	2.67	2.70	2.67	2.59	2.70	1.54	1.54	0.88	2.83	1.81	1.65	1.53	1.91	1.77
CaO	2.25	1.96	2.20	1.95	2.05	1.65	3.14	2.59	2.40	1.60	3.12	2.11	3.33	1.28	1.27	0.87	1.33	1.53
K ₂ O	3.75	4.76	3.63	4.61	1.33	2.72	2.31	2.18	2.70	1.81	4.08	4.63	3.98	2.42	2.44	2.40	2.10	2.09
Na ₂ O	2.24	2.26	2.27	2.14	2.55	1.78	2.55	2.82	1.48	2.54	1.92	2.18	1.86	2.00	1.84	1.51	2.17	2.83
MnO	0.06	0.05	0.06	0.04	0.07	0.07	0.06	0.06	0.07	0.08	0.05	0.06	0.08	0.06	0.05	0.04	0.05	0.04
P ₂ O ₅	0.05	0.13	0.05	0.16	0.09	0.09	0.12	0.12	0.12	0.06	0.17	0.24	0.11	0.15	0.15	0.15	0.13	0.12
LOI	1.77	1.98	1.58	1.31	1.95	1.94	1.77	1.19	1.37	1.87	1.14	1.12	1.30	1.28	1.29	1.54	1.38	
Total	99.38	99.38	99.88	99.88	99.38	99.42	99.46	99.47	99.38	99.51	99.87	96.60	99.40	99.79	99.85	99.48	99.86	99.84
A/NK	1.85	1.68	1.87	1.75	2.19	2.33	2.06	1.97	2.20	2.16	1.96	1.75	1.90	2.06	2.10	2.18	2.04	2.06
A/CNK	1.35	1.26	1.37	1.37	1.18	1.27	1.19	1.18	1.15	1.48	1.43	1.47	1.19	1.32	1.37	1.41	1.28	1.40
Cr						76.4	73.2	73.0	68.8	54.4	64.7		42.8	69.0	62.0	38.5	68.9	69.6
Co						17.4	15.7	15.6	11.4	11.6	13.1		12.7	11.8	9.1	7.9	11.2	9.6
Ni						36.1	34.5	33.6	29.8	22.5	46.2		27.6	27.3	23.4	18.9	26.3	25.6
Ga	22.00	21.49	20.56	21.12	17.42	17.97	17.15	17.62	14.50	22.20	12.58		21.37	16.47	15.08	13.26	15.59	18.37
Rb	156	178	81	84	83	84	97	86	120	138	79		87	114	105	86	104	113
Sr	122	126	321	333	245	112	290	158	119	125	84		299	108	108	84	121	125
Y	52.62	44.86	27.61	27.96	24.42	24.87	27.42	27.25	22.53	33.46	11.43		42.60	27.20	26.35	21.53	26.57	32.15
Zr	311	305	167	171	225	210	190	221	230	198	197		282	274	300	209	244	288
Nb	15.18	14.01	10.59	10.94	16.78	15.05	14.14	14.92	13.50	20.80	8.96		14.32	18.06	18.25	12.81	12.38	12.97
Ba	733	974	463	477	475	721	459	573	470	96	558		655	528	624	661	572	455
La	72.82	66.60	28.58	28.69	45.91	45.74	44.64	49.58	36.31	41.11	33.61		49.74	45.64	46.87	53.37	42.42	39.82
Ce	146.7	136.3	58.49	58.36	95.39	87.50	89.48	94.31	72.91	81.57	66.23		105.3	93.20	98.49	102.5	83.35	77.76
Pr	18.56	16.93	7.17	7.22	10.88	10.43	10.39	11.25	8.79	9.34	7.75		13.56	11.13	11.80	12.25	10.01	9.52
Nd	68.98	63.42	28.70	28.58	39.56	37.55	38.36	41.16	32.70	33.37	28.33		54.01	39.73	41.45	43.62	35.64	34.53
Sm	13.64	12.03	5.89	5.86	7.20	6.61	7.01	7.49	6.14	6.89	5.58		10.75	7.06	7.36	7.67	6.55	6.80
Eu	1.49	1.58	1.51	1.51	1.31	1.30	1.40	1.43	1.13	0.65	1.04		1.70	1.35	1.44	1.17	1.31	1.44
Gd	11.83	10.73	5.79	5.75	5.98	5.66	6.04	6.31	5.21	6.27	4.52		9.40	6.22	6.33	6.51	6.22	6.32
Tb	1.88	1.68	0.94	0.96	0.92	0.87	0.89	0.96	0.80	1.06	0.62		1.55	0.90	0.91	0.87	0.87	0.97
Dy	10.05	9.03	5.63	5.54	5.00	5.01	5.08	5.48	4.56	6.20	2.92		8.50	5.01	4.85	4.33	4.80	5.53
Ho	2.14	1.79	1.14	1.16	0.96	1.03	1.05	1.08	0.88	1.24	0.49		1.73	0.97	0.96	0.76	0.93	1.10
Er	5.84	4.94	3.16	3.18	2.69	2.88	2.90	2.98	2.32	3.22	1.14		4.74	2.73	2.62	1.99	2.63	3.37
Tm	0.85	0.68	0.45	0.45	0.38	0.43	0.44	0.44	0.34	0.46	0.15		0.71	0.40	0.40	0.29	0.38	0.58
Yb	5.13	4.30	2.89	2.91	2.43	2.75	2.77	2.82	2.17	2.78	0.95		4.84	2.69	2.57	1.79	2.62	4.42
Lu	0.73	0.64	0.44	0.45	0.37	0.43	0.43	0.43	0.34	0.41	0.14		0.73	0.40	0.39	0.27	0.38	0.71
Hf	9.18	8.45	4.80	4.81	6.40	6.07	5.48	6.12	6.68	5.62	5.70		7.83	7.49	8.17	2.44	6.48	7.81
Ta	0.84	0.71	0.75	0.76	0.70	0.92	0.88	0.93	1.06	1.93	0.89		0.90	1.17	1.19	1.18	1.09	1.49
Pb	27.83	29.70	10.24	10.89	19.88	15.03	24.17	22.27	14.21	16.33	20.21		10.47	33.10	24.91	22.02	24.19	19.72
Th	32.41	26.15	8.75	8.59	21.09	18.76	19.06	21.35	15.22	22.83	15.31		14.20	19.34	21.05	23.09	19.09	17.17
U	3.61	2.60	1.74	1.70	1.36	2.01	1.97	2.65	2.36	9.26	2.21		2.51	3.59	3.83	3.69	3.46	4.20
T (°C)	862	854	808	817	789	791	778	795	788	828	824		817	843	860	771	827	858
⁸⁷ Rb/ ⁸⁶ Sr	3.69	4.09	0.73	0.73	0.99					3.20	2.72		0.85	3.07	2.83			
⁸⁷ Sr/ ⁸⁶ Sr	0.771810	0.769135	0.721042	0.720915	0.724136					0.761410	0.745140		0.717902	0.753147	0.751831			
2σ	6	6	5	5	6					13	12		6	12	10			
(⁸⁷ Sr/ ⁸⁶ Sr) _i	0.72331	0.71533	0.71148	0.71133	0.71114					0.716560	0.707022		0.70679	0.71184	0.71459			
¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.120	0.115	0.124	0.124	0.110					0.125	0.119		0.120	0.107	0.107			
¹⁴³ Nd/ ¹⁴⁴ Nd	0.511935	0.511913	0.511992	0.511999	0.511628					0.511704	0.511896		0.511982	0.511630	0.511666			
2σ	3	4	3	5	3					7	6		3	7	6			
εNd (t)	-4.64	-4.51	-4.08	-3.92	-9.54					-9.23	-4.77		-3.81	-8.95	-8.47			
T _{DM} (Ga)	1.97	1.91	1.98	1.96	2.25					2.49	2.03		1.91	2.19	2.13			

T(°C): zircon saturation temperature. εNd (t): εNd values when time back-calculated to 950 Ma. T_{DM}(Ga): Nd model age.

* Sample cited from Liu et al. (2001).

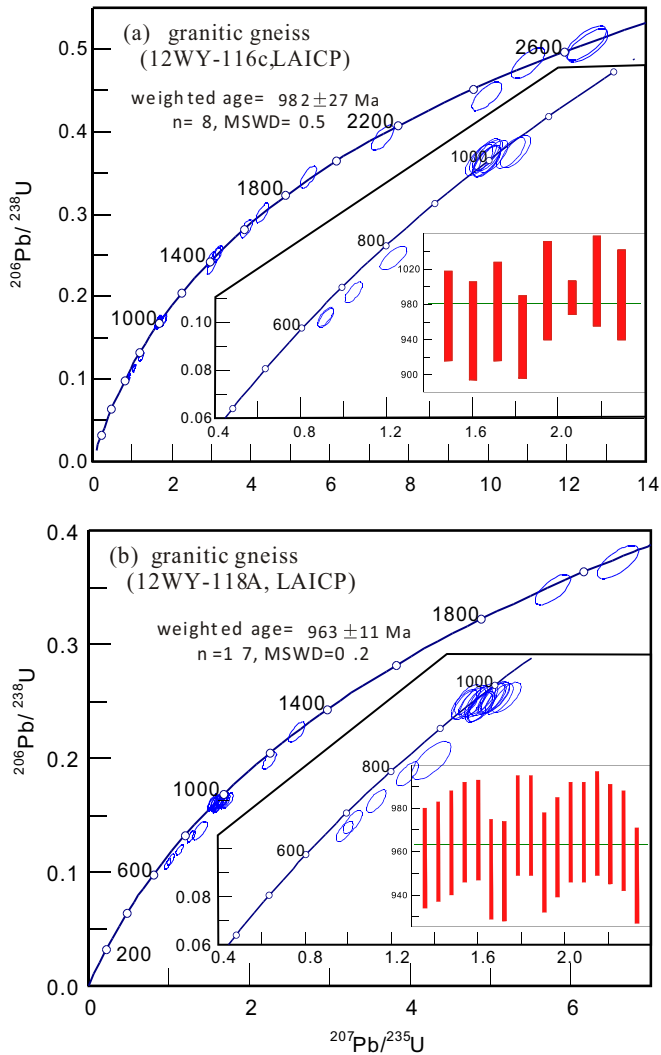


Fig. 5. Concordia diagrams of zircon U–Pb data for the granitic gneisses from Dawei (Xunwu) and Longtang (Dingnan), SE Jiangxi, the Nanling Domain. (a) 12WY-116c from Dawei (Xunwu), (b) 12WY-118A from Longtang (Dingnan). Sample locations are shown in Fig. 1.

963 ± 11 Ma, respectively. The granitic gneisses from SW Guangdong give the zircon U–Pb ages of 926 ± 28 Ma (12YK-58C) and 954 ± 14 Ma (09YK-6A), respectively. These ages can be interpreted as the crystallization time of these granitic rocks. Shu et al. (2008, 2011) and Liu et al. (2001) reported the SHRIMP zircon U–Pb age of 972 ± 8 Ma and the Pb–Pb age of 996 ± 29 Ma for the rhyolite and granodiorite from Jingnan (NE Guangdong) and Hezi (SE Jiangxi), respectively. The dacite-porphyry in the Yunkai complex has the zircon evaporate age of ~1000 Ma (Zhang et al., 1997). In addition, the late Neoproterozoic and Paleozoic sedimentary rocks in the Jianyang, Zengcheng, Nanxiang and Xinyi areas of the Cathaysia Block contain abundant detritus zircons with the U–Pb ages of ~0.92–1.0 Ga with the peak age of ~940 Ma (e.g., Yu et al., 2007; Wang et al., 2007c, 2008c, 2010a,b; Wan et al., 2007, 2010; Li et al., 2011). The inherited grains with the U–Pb age of ~0.90–1.0 Ga were also observed in the Kwangsi gneiss and massive granites in the Cathaysia Block (e.g., Ding et al., 2005; Wang et al., 2011a,b; Zhang et al., 2012b). These data evidenced the development of the earliest Neoproterozoic (~913–982 Ma) magmatism along the Wuyi-Yunkai domain in the Cathaysia interior (e.g., Shu et al., 2008, 2011).

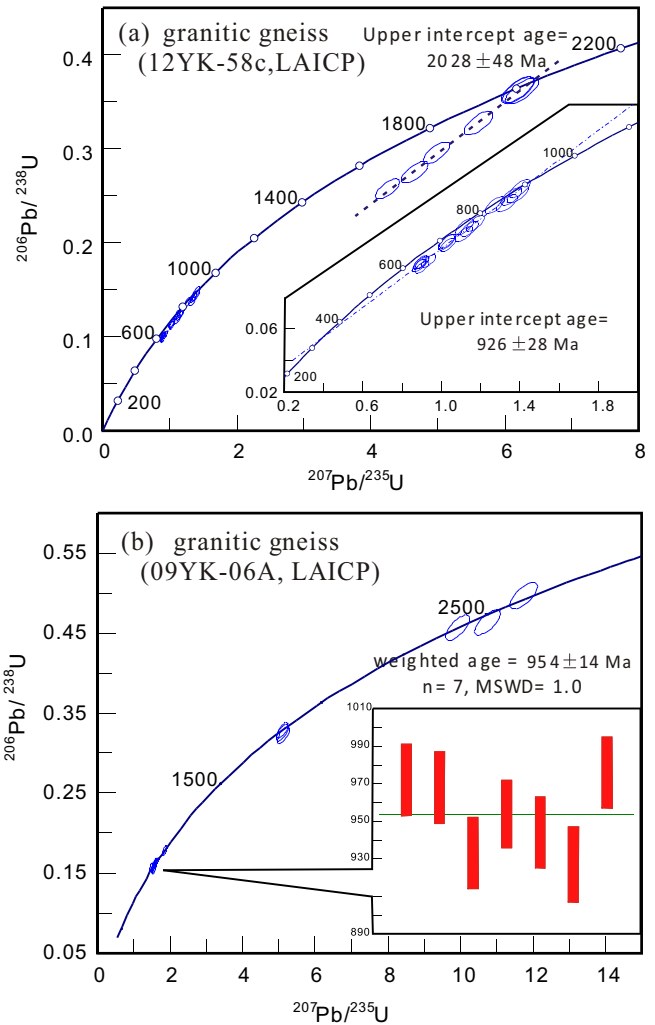


Fig. 6. Concordia diagrams of zircon U–Pb data for the granitic gneisses from Shuanglong (Luoding) and Huaixiang (Xinyi), SW Guangdong, the Yunkai Domain. (a) 12YK-58c from Shuanglong (Luoding), (b) 09YK-06A from Huaixiang (Xinyi). Sample locations are shown in Fig. 1.

The generation of S-type granites is usually related to continental-collisional and intraplate orogenic regimes or the closure of back-arc basins (e.g., Pearce, 1996; Sylvester, 1998; Brown, 2001; Atherton and Ghani, 2002; Clemens, 2003; Healy et al., 2004; Wang et al., 2007a,b, 2013a,b). Along the Wuyi-Yunkai domain of the Cathaysia Block, small amounts of the earliest Neoproterozoic (~969–997 Ma) mafic and ultramafic rocks were recently identified (e.g., Zhang et al., 2012a; Wang et al., 2013a,b). These metabasic rocks occur as lens, pods and fragment in the high-grade metamorphic basement and geochemically signify the development of a ~970–1000 Ma arc-back-arc system (e.g., Zhang et al., 2012a; Wang et al., 2013a,b). Shu et al. (2008, 2011) and Zhang et al. (1997) also proposed that the 972 Ma rhyolitic rocks in Nanling (NE Guangdong) and synchronous dacite porphyry in SW Guangdong (Yunkai) formed in a volcanic arc setting. In the Shuangxiwu-Zhangshudun area, there preserved arc-type volcanic series and dismembered ophiolitic association that were dated at ~905–980 Ma. These data indicate an earliest Neoproterozoic (~970 Ma) active continental margin rather than intraplate tectonic regime along the Wuyi-Yunkai belt of the Cathaysia Block. Our samples have zircon saturation temperature of 790–862 °C with the peak temperature at ~820 °C (Table 4). Their Al₂O₃/TiO₂ ratios range from 16.3 to

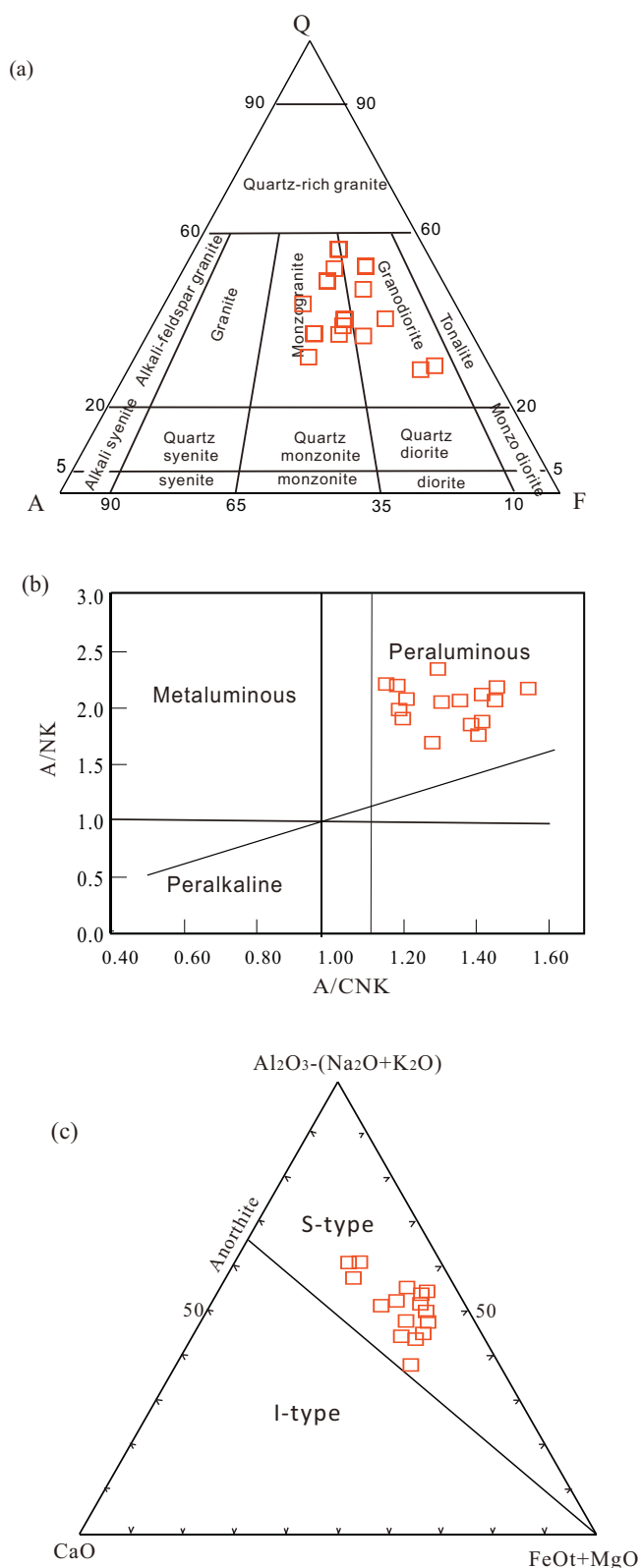


Fig. 7. (a) QAF diagram, (b) A/CNK vs A/NK (a), and (c) CaO–FeO+MgO–Al₂O₃–(Na₂O+K₂O) for the early Neoproterozoic granitic gneisses from the Cathaysia interior. Symbols in (b) and (c) are the same as those in Fig. 5a.

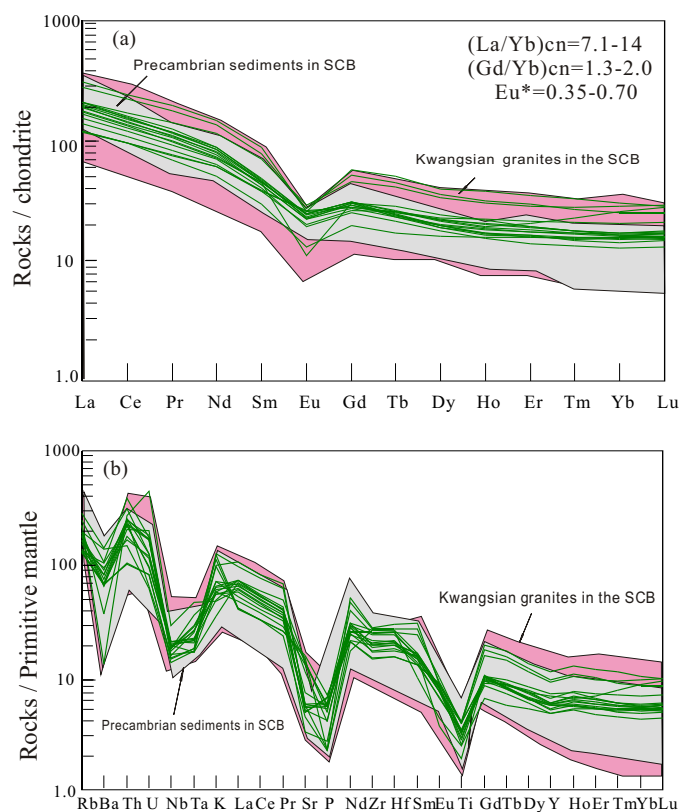


Fig. 8. (a) Chondrite-normalized rare earth element and (b) primitive mantle-normalized incompatible elemental patterns for the early Neoproterozoic granitic gneisses within the Cathaysia Block. Normalized values for chondrite and primitive mantle are from Taylor and McLennan (1985) and Sun and McDonough (1989), respectively. Also shown are the patterns for Kwanghsian granitic rocks (e.g., Wang et al., 2007a,b; Wan et al., 2007; Zeng et al., 2008; Wang et al., 2012c; Zhang et al., 2013) and Precambrian sedimentary rocks in the SCB (Wan et al., 2007, 2010; Wang et al., 2012c).

30.8 (Table 4), further indicating the high-temperature petrogenesis of the granites (e.g., Sylvester, 1998). It is general that the high-temperature granites are preponderantly generated in rifting- or subduction-related regimes (e.g., Sylvester, 1998). However, the granitic magma in a rift setting usually shows I- and A-type geochemical affinity and has a significant input of juvenile materials. However, our samples are characterized by S-type granites and were derived from the mixing source of metapelitic and metaigneous components with little input from juvenile components. This dismisses any possibility of these granites generating in a rifting setting. On the discrimination diagrams of Rb–Y+ Nb and Nb–Y (e.g., Harris et al., 1986; Pearce et al., 1984; Pearce, 1996), these samples plot into the field of volcanic arc granites or overlapping fields of the arc- and syncollisional granites (Fig. 12a and b). Therefore, the synthesis of these data indicates that the S-type granites might be petrogenetically linked to the closure of a back-arc tectonic setting. In fact, along the Phanerozoic circum-Pacific orogenic belts, the majority of “postcollisional” S-type granites formed in an early arc/back-arc regime, as illustrated by the Lachlan and New England fold belts of the Terra Australis accretionary orogenic system (e.g., Clemens, 2003; Collins and Richards, 2008; Kemp et al., 2009; Cawood et al., 2009, 2011). Wang et al. (2013a,b) also considered that the formation of early Paleozoic S-type granites in Sibumasu of SW Yunnan was geodynamically related to the closure of the back-arc basin in an accretionary continental margin setting.

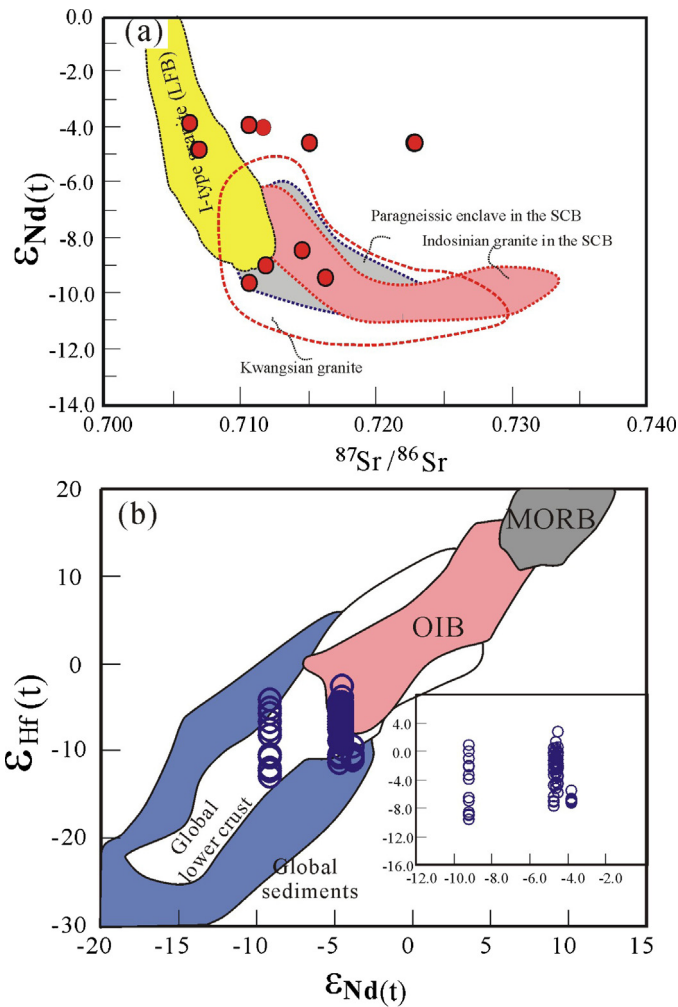


Fig. 9. (a) Initial Sr–Nd isotopic composition and (b) $\epsilon_{\text{Nd}}(t)$ versus $\epsilon_{\text{Hf}}(t)$ of the early Neoproterozoic granitic gneisses in the Cathaysia Block. Also shown in (a) are those for the Ordovician sedimentary rocks, S- and I-type granites from the Lachlan Fold Belt are from Healy et al. (2004). The data for the Indosinian and Kwanghsian granitic rocks and paragneissic enclave in the SCB are from Huang and Depaolo (1989), Wan et al. (2007, 2010); Zeng et al. (2008); Wang et al. (2007a,b, 2012c) and Zhang et al. (2013).

A question remains as to what time for the closure of the back-arc basin? Wang et al. (2013a,b) and Zhang et al. (2012) proposed that the Wuyi-Yunkai arc-back-arc system developed at ~969–997 Ma. Greentree et al. (2006) proposed the earliest Neoproterozoic (~960 Ma) sedimentary succession deposited in a foreland basin, indicative of the back-arc basin being inverted to be a compressive basin. The detrital zircons in the late Neoproterozoic sedimentary rocks commonly show an igneous origin and give U–Pb ages of ~0.90–1.0 Ga (peak age being ~940 Ma) along the Wuyi-Yunkai area (e.g., Yu et al., 2007, 2010; Wan et al., 2007, 2010; Wang et al., 2007c, 2008c, 2010b, 2008b). These data, together with the formation age of 913–926 Ma for Masha and Longtang S-type granitic rocks, indicate that the Wuyi-Yunkai arc-back-arc system might be finally closed at ~920 Ma (e.g., Yu et al., 2010; Zhang et al., 2012a; Wang et al., 2013a and reference therein). During the process, the accumulated sedimentary rocks in the earliest Neoproterozoic back-arc basin were significantly thickened to induce the crustal anatexis for producing the S-type granites. This process is also evidenced by the 1.0 Ga zircon overgrowths in sample 97HN93 from the Baobang Group in the Hainan domain of the Cathaysia Block. The Mamianshan bimodal volcanic rocks and OIB-type mafic rocks at Wuyi formed in a continental rift or intra-plate setting,

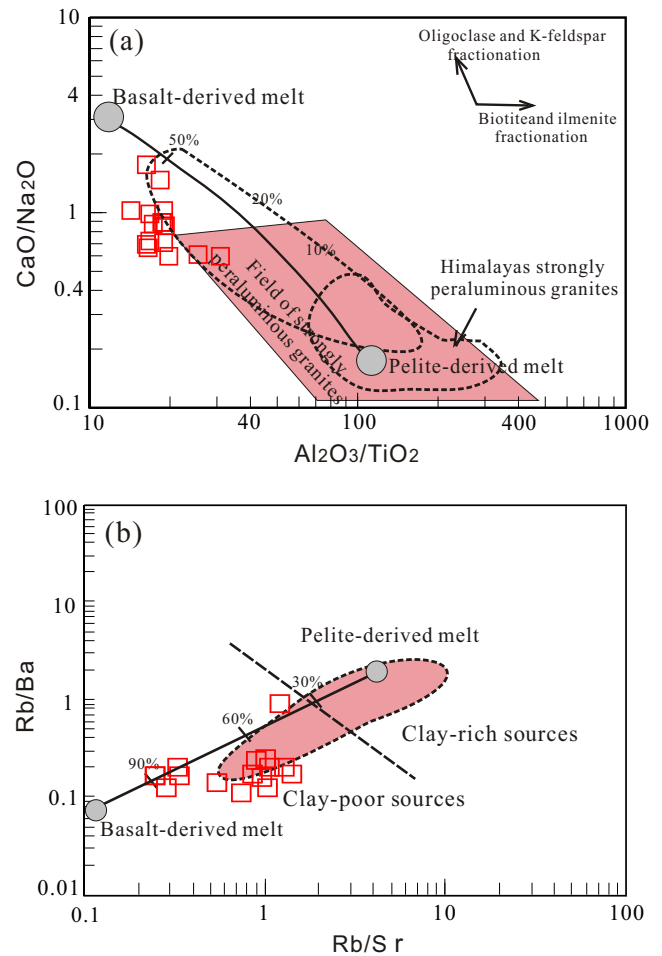


Fig. 10. $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus $\text{CaO}/\text{Na}_2\text{O}$ (a) and Rb/Sr versus Rb/Ba (b) for the early Neoproterozoic granitic gneisses in Cathaysia. The mixing curve between the basalt- and pelite-derived melts in (a and b) is from Patiño-Douce and Harris (1998) and Sylvester (1998).

and were dated at ~890–790 Ma (e.g., Li et al., 2005, 2010b; Shu et al., 2006, 2008, 2011), further constraining the closure time of the Wuyi-Yunkai arc-basin system being closed before 890 Ma.

Numerous data show that the Shuangxiwu arc or back-arc system developed at 970–910 Ma and terminated at around 880–890 Ma (e.g., Li et al., 2005, 2010b), younger than those of the Wuyi-Yunkai arc-back-arc system (e.g., Wang et al., 2013a,b). The back-arc basin or “Huanan ocean” along the Jiangnan orogen developed since ~890 Ma and its final closure occurred at ~830–820 Ma (e.g., Zhao et al., 2011; Wang et al., 2007b, 2011a; Zhou et al., 2009; Ma et al., 2009; Zhang et al., 2012a, 2013; Zhao and Cawood, 2012 and reference therein). This indicates that the previously-defined Cathaysia block might not be a united block but the aggregation of various fragments (e.g., eastern and western Cathaysia) separated by the arc-back-arc systems (e.g., Wuyi-Yunkai, Shuangxiwu and Jiangnan) prior to the early Neoproterozoic period (see Fig. 13a). The Wuyi-Yunkai arc-back-arc system might be the part of the Neoproterozoic arc-basin system of the SCB.

A series of events can be inferred based on available data. A long-lived early Neoproterozoic (950–735 Ma) oceanic subduction and related arc-basin system (e.g., Panxi-Hannan and Ailaoshan) developed along the western and northern, even southern, margins of the Yangtze Block (e.g., Zhao et al., 2011, 2013; Zhao and Cawood, 2012; Cai et al., 2014 and references therein). At ~1000 Ma the subduction of oceanic lithosphere beneath the western/northern Yangtze Block most likely led to the development of various

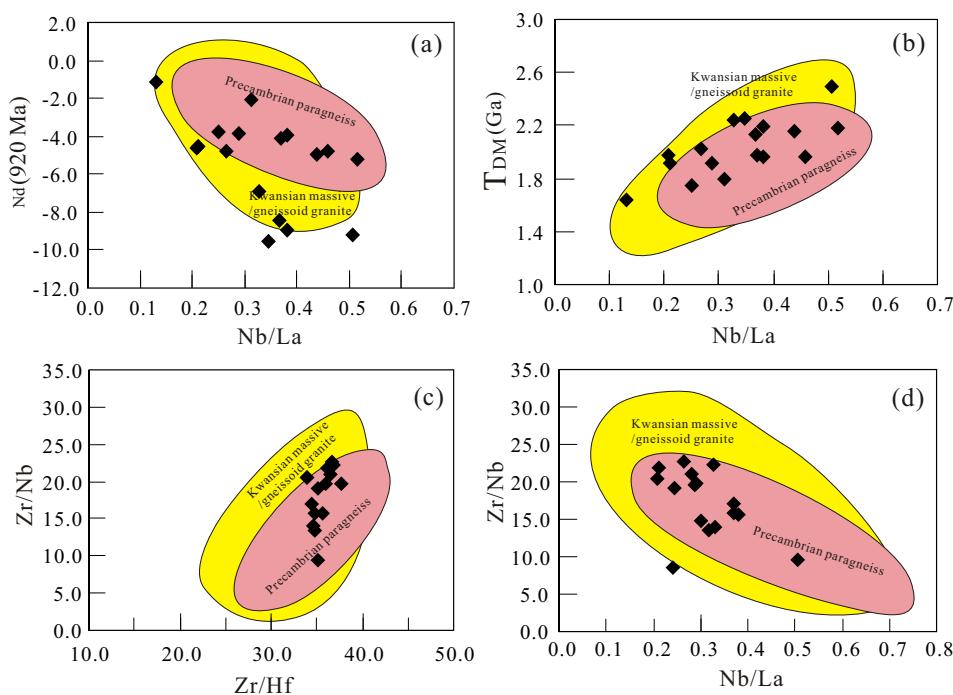


Fig. 11. (a and b) Nb/La versus ϵNd (920 Ma) and T_{DM} (Ga), (c and d) Zr/Nb versus Zr/Hf and Nb/La for the early Neoproterozoic granitic gneisses in the Cathaysia Block. Also shown is the range of the Kwansian massive/gneissoid granitic rocks and Precambrian paragneisses in the SCB (e.g., Huang and Depaolo, 1989; Wan et al., 2007, 2010; Zeng et al., 2008; Wang et al., 2007a,b, 2012c, 2013a,b; Zhang et al., 2013).

arc-back-arc systems in the SCB, including Wuyi-Yunkai (Fig. 13b). At ~ 920 – 970 Ma (Fig. 13c), the Wuyi-Yunkai arc-back-arc system was finally closed and led to the formation of the Shuangxiwu back-arc system in response to the assembly of Rodinia. The closure of the Shuangxiwu arc-back-arc system and associated orogenesis further resulted in the accretion of the East Cathaysia northward to West Cathaysia till ~ 890 Ma (Fig. 13d). The continued subduction along the western margin of the Yangtze Block then initiated the development of the Jiangnan arc-back-arc system and the associated magmatism in the eastern SCB (Fig. 5e). At ~ 800 – 830 Ma, the closure of the Jiangnan BABB ended the amalgamation of the Yangtze with Cathaysia Blocks and finally formed the united SCB (Fig. 13f).

In summary, the SCB is finally formed by the amalgamation of the various fragments due to the northwesterly episodic closure of

a series of arc-back arc systems along Wuyi-Yunkai, Shuangxiwu and Jiangnan at ~ 920 Ma, ~ 890 Ma and ~ 820 Ma, respectively (Fig. 13b–f), significantly younger than the global Grenvillian (~ 1.0 – 1.3 Ga) orogenic event along Laurentia, Australia and east Antarctica (e.g., Boger et al., 2000; Jayananda et al., 2000). It would be impossible for such a continuing and long-lived amalgamation to develop within the central Rodinia supercontinent. Our data suggest that the SCB was most likely located on the margin of Rodinia (e.g., Zhang et al., 1997; Yang et al., 2004; Cawood et al., 2010; Cawood et al., 2013; Wang et al., 2013a,b). The early Neoproterozoic progressive amalgamation process of the SCB might be part of an exterior accretionary orogen between Western Australia and East Antarctica around the periphery of Rodinia (e.g., Cawood et al., 2013; Cawood et al., 2007, 2010; Wang et al., 2010a,b, 2013a,b).

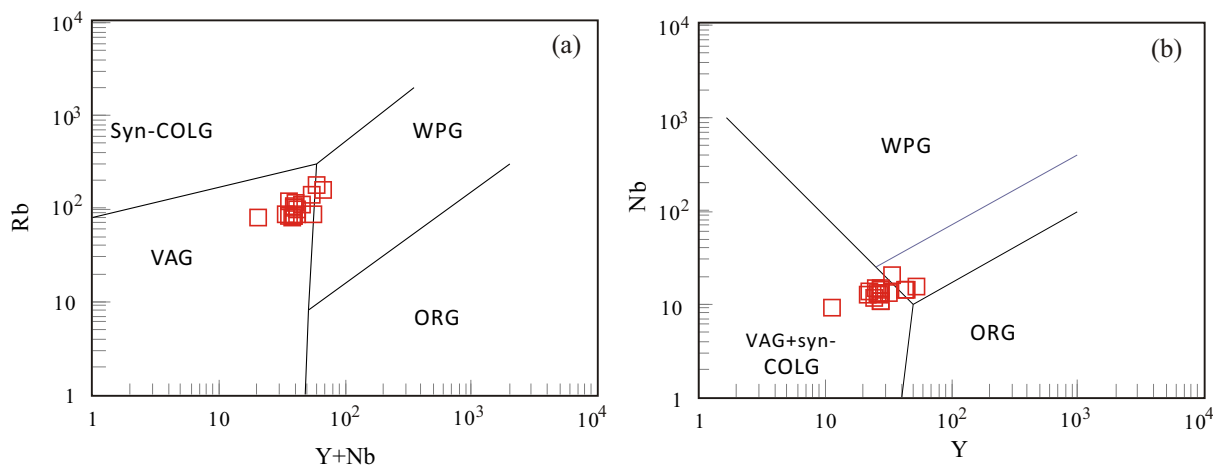


Fig. 12. (a) Y + Nb vs Rb and (b) Y vs. Nb for the early Neoproterozoic granitic gneisses in the Cathaysia interior. Syn-COLG, VAG, WPG and ORG note syn-collisional granite, volcanic arc granite, within-plate granite and ocean ridge granite, respectively.

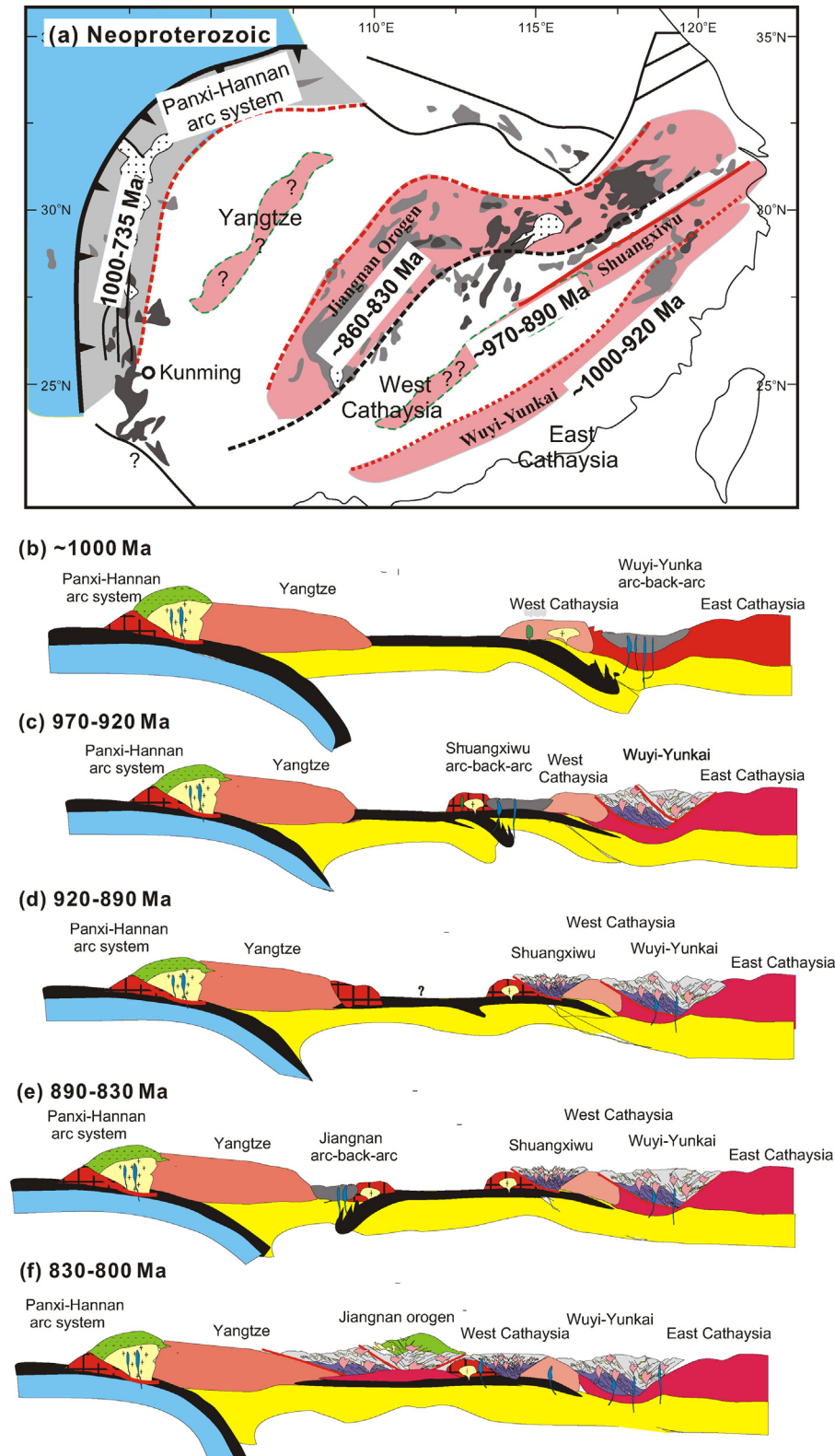


Fig. 13. (a) Simplified geological sketch of the South China Block showing the early Neoproterozoic (950–735 Ma) tectonic pattern, and (b–f) Schematic cartoon showing the early Neoproterozoic tectonic evolution of the South China Block. (b) At ~1.0 Ga, the development of the Wuyi-Yunkai arc-back-arc system in response to the subduction of oceanic lithosphere beneath the western/northern Yangtze Block. (c) At ~970–920 Ma, the closure of the Wuyi-Yunkai arc-back-arc system and the formation of the Shuangxiwu back-arc system. (d) At ~920–890 Ma, the accretion of East Cathaysia northward on West Cathaysia due to the closure of the Shuangxiwu arc-back-arc system; (e) the development of the Jiangnan arc-back-arc system and the associated magmatism at ~890–830 Ma in response to the assembly of Rodinia. (f) At ~800–830 Ma, the final amalgamation of the Yangtze with the merged Cathaysia Block along the Jiangnan Orogen. The long-lived subduction along the periphery of Rodinia resulted in the episodic amalgamation of the various fragments of the SCB by the closure of the Wuyi-Yunkai, Shuangxiwu and Jiangnan arc-back arc systems.

7. Conclusions

A comprehensive geochemical, zircon U–Pb geochronological and Lu–Hf isotopic study on the granitic gneisses along the Wuyi–Yunkai Domains of the Cathaysia allows us to derive the following conclusions.

- (1) Six granitic gneisses from the Wuyi–Yunkai domain yield zircon U–Pb age of 913–982 Ma, indicating the development of the earliest Neoproterozoic magmatism in the Cathaysia interior.
- (2) The granitic rocks are characterized by K-rich, strongly peraluminous S-type rocks and originated from the metapelitic coeval with metaigneous source with little addition of juvenile materials.
- (3) The S-type granites might be petrogenetically related to the closure of the earliest Neoproterozoic Wuyi–Yunkai back-arc basin at ~980–910 Ma and the SCB most likely located on the margin of Rodinia.

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