

Age and origin of middle Neoproterozoic mafic magmatism in southern Yangtze Block and relevance to the break-up of Rodinia

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Abstract

SHRIMP U–Pb zircon age, geochemical and Sm–Nd isotopic data are reported for mid-Neoproterozoic volcanic rocks and mafic intrusions in northern Guangxi (Guibei) and western Hunan (Xiangxi) Provinces along the southern margin of the Yangtze Block. The mafic igneous rocks studied are generally synchronous, dated at ~765 Ma. The least-contaminated dolerite samples from Xiangxi are characterized by high $\epsilon_{\text{Nd}}(T)$ value of 3.3 to 5.3 and OIB-type geochemical features, indicating that they were derived from an OIB-like mantle source in a continental rift setting. The spilites and gabbros in Guibei show basaltic compositions transitional between the tholeiitic and calc-alkaline series. Despite depletion in Nb and Ta relative to La and Th, they have $\text{Zr}/\text{Sm}=27\text{--}35$ and $\text{Ti}/\text{V}=30\text{--}40$, affinitive to intraplate basalts. Their $\epsilon_{\text{Nd}}(T)$ values are variable, ranging from -1.2 to 3.2 for the spilites and from -1.7 to 2.9 for the gabbros, suggesting that these spilites and gabbros crystallized from crustal-contaminated mafic magmas derived from a metasomatised subcontinental lithospheric mantle source. We conclude that the ~765 Ma mafic magmatic rocks in Guibei and Xiangxi were formed in a single continental rift setting as part of the broadly concurrent ~780–750 Ma rift magmatism over much of South China, which may be related to the plume activities during the breakup of Rodinia.

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Keywords: Neoproterozoic; Mafic magmatism; U–Pb zircon age; Geochemistry; South China

1. Introduction

Neoproterozoic igneous rocks are widespread around the Yangtze Block, South China (Fig. 1a). Among them, felsic intrusive and volcanic rocks are volumetrically dominant, with subordinate mafic and rare intermediate rocks. The mafic rocks, including basalts, mafic dykes/sills and gabbroic intrusions, are closely associated in time and space with the felsic rocks. The significance of these igneous rocks in understanding the Neoproterozoic tectonic evolution of South China has been widely recognized, but the petrogenesis and tectonomagmatic affiliations of the rocks are still controversial (e.g., Li et al., 2004a; Wang et al., 2004a). Li et al. (1999, 2002a, 2003b) considered the 830–740 Ma Neoproterozoic rocks as intraplate magmatism, which were concurrent with rapid continental-scale

crustal doming and unroofing and the development of the Nahua and Kangdian Rifts (Wang and Li, 2003) and were likely caused by a mantle plume or superplume beneath Rodinia. The extensive ~820 Ma granites in northern Guangxi (or “Guibei” in Chinese) were regarded as results of crustal melting by conductive heating from mafic intrusions and underplating related to the plume activities (e.g., Ge et al., 2001a; Li et al., 2003a).

On the contrary, Zhou et al. (2002a,b) and Wang et al. (2004b) argued that both the western and eastern margins of the Yangtze Block were active continental margins during much of the mid-Neoproterozoic time because there are some arc-like geochemical signatures in the ~860–760 Ma igneous rocks. In Guibei, the Sanmenjie basaltic suites and gabbroic intrusions are considered to be typical arc magmatism (Zhou et al., 2003, 2004b), and the ~820 Ma granites there were re-interpreted as products of a collisional orogeny between the Yangtze and Cathaysia blocks (Wang et al., 2006).

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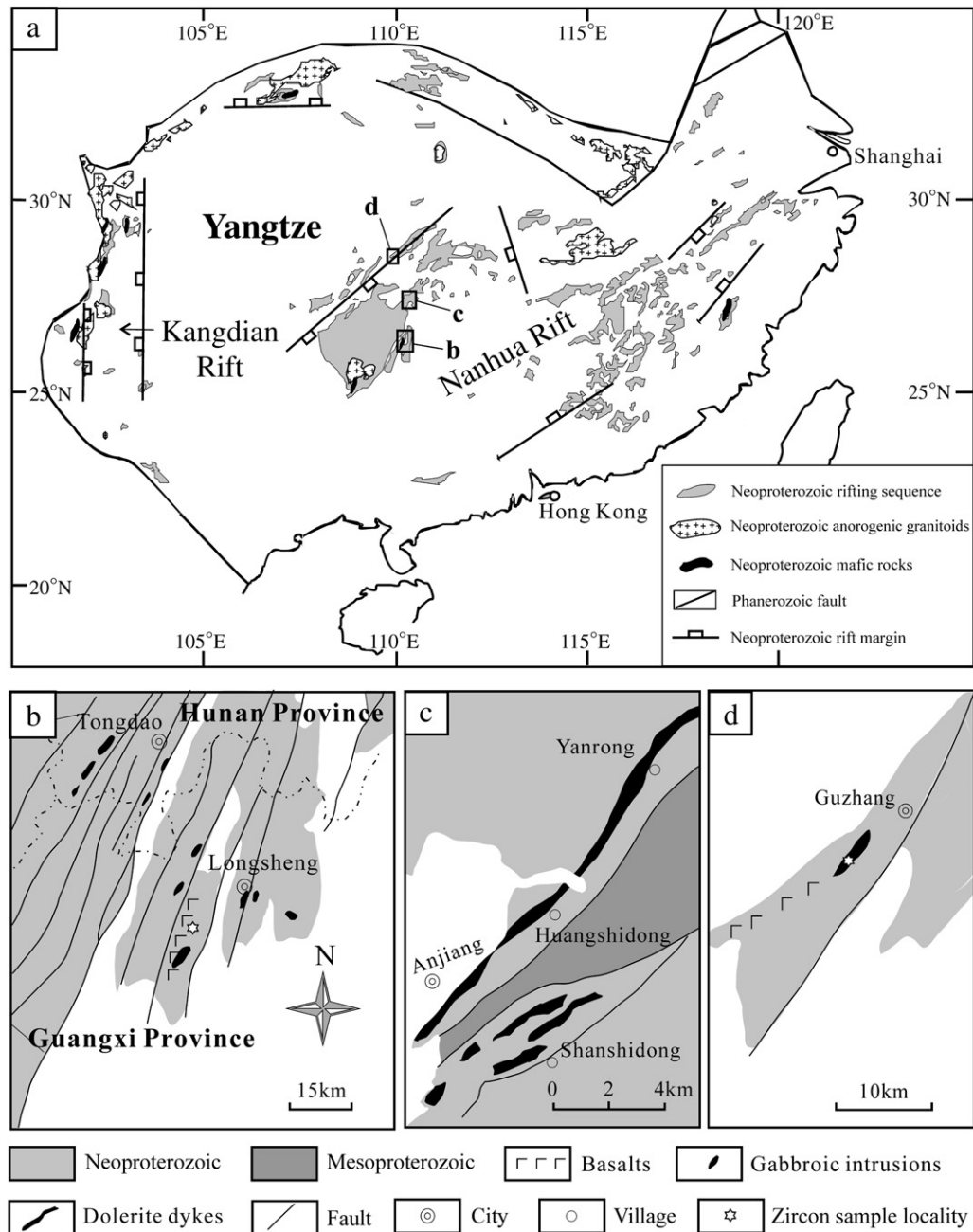


Fig. 1. Simplified Precambrian geological map of (a) South China emphasizing two Neoproterozoic continental rift systems and distribution of Neoproterozoic anorogenic magmatic rocks (after Li et al., 2003b), (b) the Longsheng–Tongdao region in the border area of Guibei and Xiangxi, (c) the Anjiang area of Xiangxi, and (d) the Guzhang area of Xiangxi.

The competing petrotextonic interpretations of these igneous rocks have different implications to the location of South China in the Rodinia, i.e., whether the South China was located at a central location of Rodinia as a “missing link” between Australia–East Antarctica and Laurentia (Li et al., 1995), or on the periphery of Rodinia (Wang et al., 2006; Zhou et al., 2006).

In this paper, we report SHRIMP U–Pb zircon ages, and geochemical and Sm–Nd isotopic results for the Neoproterozoic volcanic and mafic intrusive rocks in Guibei and dolerite dykes in the neighboring western Hunan Province (or “Xiangxi” in Chinese) along southern Yangtze Block. Our new data

demonstrate that the Sanmenjie basalts in Guibei were formed in a continental rift setting at ~ 765 Ma, rather than the products of arc magmatism formed in early Neoproterozoic (Gan et al., 1996; Zhou et al., 2004b). They are synchronous with the Xiangxi alkaline dolerite dykes, likely related to the plume activities during the breakup of Rodinia.

2. Geological background and sampling

The South China Block consists of two major tectonic blocks, the Yangtze block to the northwest and the Cathaysia

block to the southeast (Fig. 1a). The oldest rock unit in the Yangtze Block is the Kongling Complex near the Three Gorge Dam site, consisting of Archean to Paleoproterozoic high-grade metamorphic tonalite, trondhjemite and granodiorite gneisses, amphibolites and metamorphic supercrustal rocks (e.g., Qiu et al., 2000). Despite Archean inherited zircons have been identified from various rock types in Proterozoic and younger rocks, the oldest known crystalline basement rocks in the Cathaysia Block are the granitic rocks and amphibolites of ca. 1.8 Ga in southwestern Zhejiang and northwestern Fujian Provinces (e.g., Li, 1997b; Li and Li, in press). The two blocks were amalgamated during the late Mesoproterozoic–earliest Neoproterozoic Sibao orogeny, forming the unified South China Block (Li et al., 2002b; Ye et al., 2007).

There are three major Precambrian rock units in the Guibei–Xiangxi region along the southern margin of the Yangtze Block. (1) The oldest rocks are the strongly-deformed late Mesoproterozoic to earliest Neoproterozoic greenschist–facies successions, including metasediments, siltstones and slates with metamorphosed mafic–ultramafic volcanic intercalations. They are termed as the Sibao Group in Guibei and the Lengjiaxi Group in Xiangxi. (2) The pre-rifting, generally non-deformed granitic and mafic intrusions that intruded the Sibao Group at 820–830 Ma (Li, 1999; Li et al., 1999, 2003a). (3) The Nanhua rift successions which unconformably overlie the Sibao/Lengjiaxi Group and the pre-rifting igneous intrusions (Wang and Li, 2003). The Nanhua rift successions consist of four sequence-sets (Wang and Li, 2003). The first sequence-set contains a lower fluvial/alluvial clastic unit interbedded with volcanoclastic rocks, and an upper continental to littoral-shallow-marine siliciclastic unit with platform carbonate and carbonaceous shale. The lower boundary of the Nanhua rift is determined by SHRIMP U–Pb zircon technique at 814 ± 12 Ma from a dacitic volcanic unit in the Cangshuipu Formation in Xiangxi (Wang et al., 2003). The second sequence-set consists of continental and/or marine volcanic eruptions (e.g., the Sanmenjie Formation in Guibei) and littoral to shallow-marine siliciclastic rocks (e.g., the Gongdong Formation in Guibei). The third sequence-set consists of glaciomarine gravity-flow deposits (the Chang'an Formation) and manganese-bearing carbonaceous and siliceous clastic unit (the Fulu Formation) during the first Neoproterozoic glacial–interglacial interval. The fourth sequence-set consists of the Nantuo tillites and carbonaceous shales and siliceous rocks (the Silikou, Doushantuo and Dengying/Laobao Formations) formed during the second Neoproterozoic glacial interval and post-glacial marine transgression. A representative Neoproterozoic stratigraphic column from Guibei is shown in Fig. 2.

The Sanmenjie volcanic rocks in Guibei's Longsheng region comprise predominantly pillow basalt and basaltic andesite (>200 m thick), with minor intercalation of rhyodacite (<30 m thick). The volcanic rocks were intruded by the 761 ± 8 Ma Tangtou gabbro (Ge et al., 2001b). Although these volcanic and plutonic mafic–ultramafic rocks were collectively referred to as the “Longsheng ophiolite” by previous studies (e.g. Xia, 1984; Li, 1997a), more recent work by Ge et al. (2000) demonstrated that they cannot be part of an ophiolite suite. Dolerite dykes

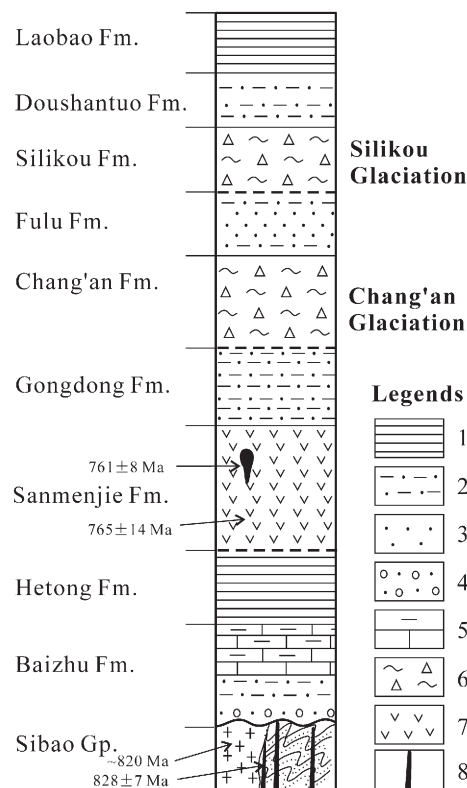


Fig. 2. Simplified Neoproterozoic stratigraphy in Guibei (modified after Wang and Li, 2003). 1 = mudstone and shale; 2 = muddy-siltstone; 3 = sandstone; 4 = conglomerate; 5 = carbonate; 6 = glacial diamictite; 7 = volcanic rocks; 8 = mafic dyke.

occurred sporadically in Xiangxi. They intruded the Wuqiangxi Formation of the second sequence-set, and were overlain by the Chang'an Formation of the third sequence-set (Zheng et al., 2001).

Samples for geochronological and geochemical analyses in this study were collected from the Sanmenjie volcanic rocks and gabbroic intrusions in Guibei, and from dolerite dykes in Xiangxi (Fig. 1b, c and d). These rocks have been variably deformed, and have experienced lower greenschist–facies metamorphism.

3. Analytical methods

Zircons were separated from two samples using standard density and magnetic separation techniques. Zircon grains, together with zircon standard TEMORA, were mounted in epoxy, and then polished down to half sections. Measurements of U, Th and Pb in zircon were conducted using the SHRIMP II ion microprobe at the Beijing SHRIMP Center, Chinese Academy of Geological Sciences. Instrumental conditions and analytical procedures were similar to those described by Compston et al. (1992). U–Th–Pb ratios were determined relative to the TEMORA zircon standard ($^{206}\text{Pb}/^{238}\text{U} = 0.0668$ corresponding to 417 Ma, Black et al., 2003), and the U and Th absolute abundances relative to the SL13 zircon standard (U = 238 ppm). Measured compositions were corrected for common Pb using non-radiogenic ^{204}Pb , and an average crustal

Table 1
SHRIMP U–Pb zircon data

Spot#	U (ppm)	Th (ppm)	Th/U	$f_{206\%}$	$^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ($\pm\%$)	$^{207}\text{Pb}^*/^{235}\text{U}$ ($\pm\%$)	$^{206}\text{Pb}^*/^{238}\text{U}$ ($\pm\%$)	$^{206}\text{Pb}^*/^{238}\text{U}$ Age (Ma) $\pm 1\sigma$				
<i>GB04-59 (25°49'48.0"N, 109°47'53.2" E)</i>												
1.1	70	74	1.06	0.88	0.061	1.9	1.094	4.1	0.1289	3.7	782	17
2.1	51	41	0.80	0.74	0.066	2.2	1.301	4.3	0.1424	3.6	858	17
3.1	278	175	0.63	0.13	0.065	0.9	1.182	3.6	0.1320	3.5	799	15
4.1	352	521	1.48	0.48	0.121	0.4	6.150	3.4	0.3670	3.4	2017	37
5.1	156	209	1.34	0	0.069	1.1	1.355	3.6	0.1413	3.4	852	18
6.1	247	198	0.80	0.25	0.164	0.4	9.920	3.4	0.4370	3.4	2338	37
7.1	300	55	0.18	0	0.072	0.2	1.401	3.5	0.1405	3.4	848	14
8.1	192	119	0.62	0.42	0.064	1.1	1.099	3.6	0.1245	3.4	757	14
9.1	324	447	1.38	0.85	0.063	1.1	1.121	3.7	0.1273	3.5	772	17
10.1	186	146	0.78	0.56	0.065	1.1	1.315	3.6	0.1448	3.4	872	16
11.1	53	52	0.98	0.35	0.063	2.4	1.133	4.7	0.1287	4.0	781	17
12.1	75	87	1.16	0.78	0.063	2.0	1.074	4.1	0.1233	3.6	750	16
13.1	118	82	0.69	0.62	0.062	1.8	1.044	3.9	0.1205	3.5	733	14
14.1	38	32	0.84	2.04	0.065	3.2	1.130	4.8	0.1262	3.6	766	16
15.1	334	247	0.74	0	0.066	0.9	1.143	3.5	0.1248	3.4	758	14
16.1	50	67	1.34	1.35	0.065	2.5	1.146	4.5	0.1270	3.7	771	18
<i>HN04-29 (28°29'41.8"N, 109°49'06.5" E)</i>												
1.1	770	2509	3.26	0.05	0.064	0.6	0.999	1.2	0.1117	1.1	683	7
2.1	597	1674	2.81	0.13	0.065	2.1	0.921	2.4	0.1019	1.1	626	7
3.1	609	4432	7.27	0.73	0.064	2.6	0.596	2.9	0.0668	1.2	417	5
4.1	601	2994	4.98	0.54	0.064	1.5	0.630	1.9	0.0709	1.1	442	5
5.1	1106	3491	3.16	0.30	0.067	1.0	0.695	1.5	0.0749	1.1	465	5
6.1	992	4463	4.50	0.34	0.064	1.2	0.524	1.6	0.0590	1.1	369	4
7.1	952	4727	4.97	0.29	0.068	1.1	0.465	3.5	0.0489	1.1	308	3
8.1	491	2465	5.02	0.31	0.066	1.0	0.877	1.5	0.0961	1.2	592	7
9.1	794	2583	3.25	0.05	0.064	0.7	1.124	1.3	0.1262	1.1	766	8
10.1	738	6067	8.22	0.43	0.067	1.1	0.441	2.6	0.0473	1.1	298	3
11.1	527	2233	4.23	0.11	0.065	1.3	0.870	1.7	0.0964	1.1	593	6
12.1	324	216	0.67	0.09	0.067	1.4	1.257	1.8	0.1356	1.1	819	9
13.1	409	249	0.61	0.06	0.152	0.5	6.135	1.2	0.2922	1.1	1653	16
14.1	629	3114	4.95	0.21	0.068	1.7	0.539	2.1	0.0570	1.2	357	4
15.1	1100	5696	5.18	0.12	0.069	0.9	0.479	2.5	0.0502	1.1	316	3

Note: $f_{206\%}$ is the proportion of common ^{206}Pb in the measured ^{206}Pb , estimated using ^{204}Pb . Pb* indicates radiogenic Pb.

composition (Stacey and Kramers, 1975) appropriate to the age of the mineral was assumed. Uncertainties on individual analyses in data tables are reported at 1σ level; mean ages for pooled $^{206}\text{Pb}/^{238}\text{U}$ analyses are quoted with 95% confidence, except where noted otherwise, by using the Isoplot software (Ludwig, 2001). U–Pb zircon data are listed in Table 1.

Major element oxides, trace elements and Nd isotope analyses were carried out at the Guangzhou Institute of Geochemistry, Chinese Academy of Science. Major element oxides were analyzed using a Rigaku RIX 2000 X-ray fluorescence spectrometer (XRF) on fused glass beads. Calibration lines used in quantification were produced by bivariate regression of data from 36 reference materials encompassing a wide range of silicate compositions (Li et al., 2005), with analytical uncertainties ranging from 1% to 5%. A loss-on-ignition (LOI) measurement was undertaken on samples of dried rock powder by heating in a pre-ignition silica crucible to 1000 °C for 1 h and recording the percentage weight loss. Trace elements were determined using a Perkin-Elmer Sciex ELAN 6000 inductively coupled plasma mass spectrometer (ICP-MS), following the procedures similar to those

described by Li (1997a). About 40 mg sample powders were dissolved in high-pressure Teflon bombs using an HF+HNO₃ mixture. An internal standard solution containing the single element Rh was used to monitor signal drift during counting. The USGS standards W-2 and G-2 and Chinese national standards GSR-1, GSR-2 and GSR-3 were used for calibrating element concentrations of unknowns. The analytical precision for most trace elements is typically 2% to 5%. Major and trace element data are listed in Table 2.

For Nd isotope analyses, about 150 mg sample powders were dissolved in Teflon beakers using an HF+HNO₃ mixture for 7 days at ca. 80 °C. Nd fraction was separated by passing through cation columns followed by HDEHP columns. Nd isotopic compositions were determined using a Micromass Isoprobe multi-collector ICP-MS (MC-ICP-MS). Analytical procedures were similar to those described by Li et al. (2004b). Measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$. The reported $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are normalized relative to the Shin Etsu JNdi-1 standard of 0.512115, corresponding to the La Jolla standard value of 0.511860 (Tanaka et al., 2000).

Table 2
Major and trace elements data for the samples

Sample#	97GX51	97GX50	97GX52	97GX64	SM-54*	SM-55*	GB04-65	GB04-66	GB04-68	GB04-80	97GX57-3	97GX57-8	97GX66
Rock type	S	S	S	S	S	S	G	G	G	G	G	G	G
Location	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS	LS
<i>Major elements (%)</i>													
SiO ₂	50.1	47.6	49.7	55.7	52.0	54.7	47.9	54.9	47.6	53.5	49.3	52.3	50.8
TiO ₂	1.01	1.55	1.29	1.25	0.93	1.27	0.80	1.28	0.65	1.11	0.73	1.01	1.04
Al ₂ O ₃	15.4	17.4	15.6	17.0	15.8	14.6	12.1	14.8	8.21	16.2	16.3	17.2	16.5
Fe ₂ O ₃ ^T	9.71	12.5	12.4	9.19	10.7	11.1	11.9	8.06	11.6	10.0	9.63	9.56	11.1
MnO	0.14	0.14	0.20	0.11	0.15	0.14	0.17	0.13	0.18	0.21	0.13	0.12	0.21
MgO	7.43	10.3	9.24	6.22	8.04	5.32	18.6	8.48	24.5	8.60	10.5	7.36	9.11
CaO	15.9	5.35	7.20	5.40	9.81	7.30	8.00	6.31	7.10	5.03	9.79	6.76	5.91
Na ₂ O	0.18	4.31	4.11	4.02	1.73	4.97	0.19	4.85	0.00	4.42	1.96	4.50	4.35
K ₂ O	0.05	0.69	0.16	0.91	0.70	0.37	0.31	1.09	0.02	0.89	1.49	1.11	0.83
P ₂ O ₅	0.10	0.17	0.14	0.12	0.18	0.19	0.11	0.15	0.07	0.10	0.12	0.14	0.11
LOI	4.14	6.43	4.34	3.22	3.13	2.33	4.47	3.38	5.29	2.54	2.82	2.49	2.46
Mg#	64.1	65.9	63.4	61.2	63.7	52.8	78.5	71.0	83.1	66.7	71.8	64.2	65.7
<i>Trace elements (ppm)</i>													
Sc	27.2	36.5	38.3	37.8	26.8	29.2	17.7	27.5	17.2	31.1	19.6	28.1	36.0
V	186	254	258	203	—	—	121	172	116	176	132	170	218
Cr	360	447	281	332	399	103	938	311	2079	234	465	328	321
Ni	185	215	116	108	176	25.1	379	102	981	93.9	201	104	136
Ga	21.4	21.7	18.3	17.2	—	—	12.1	13.5	8.46	13.9	17.1	18.7	18.1
Rb	0.58	31.2	3.53	37.4	14.0	8.13	7.43	24.3	0.37	12.5	39.8	22.6	13.8
Ba	4.95	124	60.1	166	282	60.6	53.9	125	2.06	246	408	156	327
Th	2.61	2.03	1.43	3.80	2.20	4.32	3.13	3.32	1.01	2.99	3.23	4.39	3.48
U	0.81	0.45	0.34	0.46	0.89	0.89	0.65	0.75	0.22	0.46	0.60	0.88	0.50
Nb	3.76	4.57	4.08	4.31	3.85	5.69	4.64	7.27	2.07	4.24	3.97	5.76	4.46
Ta	0.35	0.39	0.34	0.39	0.35	0.79	0.33	0.48	0.15	0.29	0.36	0.47	0.37
La	7.58	8.27	6.14	9.64	11.6	16.9	9.72	9.19	5.43	10.6	9.27	11.7	10.1
Ce	18.6	21.3	16.2	24.4	23.6	33.7	21.8	22.6	13.0	23.0	22.0	27.2	23.6
Pr	2.68	3.11	2.50	3.37	3.98	5.04	2.91	3.14	1.80	3.02	2.92	3.66	3.19
Sr	471	167	158	303	115	94.9	133	186	13.5	137	540	307	226
Nd	11.8	14.2	12.1	14.9	13.4	19.1	11.7	13.1	7.83	12.4	12.3	15.0	13.3
Zr	89.8	101	92.9	110	67.9	110	94.6	119	46.7	89.3	80.4	117	102
Hf	2.52	2.68	2.62	3.21	1.94	2.81	2.45	3.09	1.30	2.46	2.25	3.12	2.88
Sm	3.05	4.07	3.47	3.97	3.45	4.61	2.68	3.33	1.85	2.93	2.92	3.69	3.33
Eu	1.07	1.27	1.13	1.11	0.97	1.17	0.89	1.01	0.37	0.76	0.95	0.97	0.98
Gd	3.90	4.13	3.74	4.16	4.17	5.23	2.99	4.07	2.58	3.63	2.94	3.60	3.55
Tb	0.61	0.78	0.71	0.78	0.62	0.76	0.47	0.66	0.39	0.59	0.52	0.64	0.65
Dy	3.66	4.62	4.50	5.01	3.63	4.46	2.70	3.93	2.27	3.53	3.07	3.92	3.93
Y	18.8	25.4	25.7	30.1	19.9	23.6	14.1	20.7	15.7	19.3	17.0	22.1	22.2
Ho	0.71	0.89	0.90	1.02	0.75	0.91	0.53	0.76	0.47	0.73	0.60	0.79	0.84
Er	1.96	2.40	2.48	2.84	1.81	2.21	1.41	2.08	1.22	2.04	1.59	2.11	2.34
Tm	0.28	0.34	0.35	0.41	0.29	0.34	0.20	0.29	0.17	0.28	0.23	0.30	0.34
Yb	1.83	2.09	2.19	2.49	1.82	2.20	1.30	1.88	1.00	1.87	1.43	1.91	2.19
Lu	0.27	0.32	0.33	0.39	0.30	0.34	0.19	0.28	0.16	0.28	0.22	0.28	0.35

Mg# = Mg/(Mg + Fe²⁺), assuming Fe₂O₃/Fe₂O₃^T = 0.15. Total iron as Fe₂O₃^T. *Data are from Zhou et al. (2004a,b). Major oxides were recalculated to 100% on a volatile-free basis. D = dolerites; S = spilites; G = gabbros; LS = Longsheng in Guibei; GZ = Guzhang in Xiangxi; AJ = Anjiang in Xiangxi; TD = Tongdao in Xiangxi.

4. Results

4.1. U–Pb zircon ages

The rhyodacite sample GB04-59 was collected from the Sanmenjie volcanic rocks in Guibei (Figs. 1b and 2), where rhyodacite is intercalated with basaltic rocks. All zircons from this sample are euhedral to subhedral, transparent and colorless. Sixteen analyses of 16 zircons were obtained. Measured U concentrations vary from 50 to 352 ppm, and Th concentrations range from 32 to

447 ppm. Th/U ratios range from 0.18 to 1.48. Six analyses give ²⁰⁶Pb/²³⁸U ages older than the lower age limit of ~814 Ma for the Nanhua rift sequence (Wang et al., 2003), thus these zircons are interpreted as xenocrysts. The remaining 10 analyses form a single, concordant population with a weighted mean ²⁰⁶Pb/²³⁸U age of 765 ± 14 Ma (MSWD = 1.6, Fig. 3), which is interpreted as the best estimate of eruptive age of the rhyodacite.

Dolerite sample HN04-29 was collected from Guzhang in Xiangxi (Fig. 1c). Zircons from this sample are subhedral, gray to colorless. Fifteen analyses of 15 zircons were obtained.

97GX67	HN04-25	HN04-29	HN04-34	HN04-36	HN04-37	HN04-38	HN04-41	HN04-43	HN04-45	HN04-47	HN04-48
G	D	D	D	D	D	D	D	D	D	D	D
LS	GZ	GZ	AJ	AJ	AJ	AJ	AJ	AJ	AJ	TD	TD
46.3	50.2	51.7	49.3	51.4	54.7	55.0	48.6	51.2	54.5	52.5	53.0
1.19	1.90	1.98	2.02	2.19	3.28	2.15	2.95	3.55	3.52	1.80	1.31
16.5	14.8	15.6	13.9	16.3	16.2	16.8	15.9	15.4	14.5	17.4	17.2
15.7	13.1	12.5	13.1	10.1	12.9	12.9	12.9	14.9	12.9	11.8	9.34
0.35	0.17	0.18	0.18	0.16	0.16	0.17	0.12	0.24	0.24	0.23	0.16
11.3	7.11	6.05	11.8	6.92	3.69	2.54	9.76	7.22	3.96	8.45	6.84
5.00	7.74	7.49	6.84	7.86	2.74	3.91	5.64	4.64	4.85	3.87	7.53
3.45	5.36	4.13	2.58	3.64	5.67	6.81	4.34	3.78	5.54	3.94	4.48
0.10	0.64	1.28	1.17	1.98	1.25	0.20	0.52	0.11	0.91	0.97	0.94
0.10	0.19	0.24	0.35	0.27	0.55	0.65	0.44	0.36	0.37	0.20	0.14
4.38	5.59	2.58	4.15	2.69	4.57	5.40	3.95	7.15	6.91	7.25	3.19
62.8	54.3	51.3	66.3	59.8	38.3	29.9	62.2	51.4	40.2	61.0	61.5
51.7	27.9	27.6	26.3	28.6	26.7	16.7	19.9	31.6	30.6	32.7	31.4
339	264	249	194	210	332	76.6	188	296	341	210	198
160	257	181	446	248	5.09	5.63	180	105	7.03	195	225
53.6	90.9	60.7	262	97.9	10.8	2.25	151	45.8	11.4	96.0	89.4
19.6	19.7	21.5	18.3	16.5	23.3	29.9	23.8	21.2	19.4	16.9	17.7
89.6	11.9	18.7	14.0	24.0	17.6	4.17	12.7	1.34	11.5	22.9	13.0
612	497	297	700	1400	327	90.3	176	92.1	255	373	556
5.52	3.75	4.50	4.00	3.90	7.85	10.4	6.51	4.38	6.77	3.34	3.58
0.97	0.85	0.97	0.85	0.83	1.69	2.15	1.33	0.90	1.34	0.67	0.70
6.63	18.6	23.8	29.1	29.9	47.5	69.9	60.8	42.4	43.7	15.4	11.2
0.55	1.12	1.43	1.69	1.75	2.85	3.81	3.57	2.44	2.78	0.99	0.73
14.5	19.8	24.8	26.3	24.4	44.3	60.5	47.0	28.0	34.0	16.0	15.4
31.7	41.1	50.6	56.3	50.5	91.3	120	93.6	57.2	69.6	34.2	31.0
3.95	5.22	6.43	7.42	6.48	11.7	15.3	11.8	7.27	8.60	4.59	4.20
326	354	349	186	854	290	222	502	261	231	109	170
16.3	20.5	25.6	29.0	25.2	45.6	57.6	43.7	29.0	33.8	18.9	17.1
70.2	128	159	173	179	283	403	253	178	222	139	119
2.26	3.37	4.15	4.43	4.51	7.45	9.54	5.98	4.92	6.12	3.80	3.30
4.05	4.39	5.28	6.03	5.22	9.00	11.0	7.80	5.96	6.85	4.34	3.95
1.08	1.29	1.84	2.34	1.60	2.72	3.02	1.92	1.74	2.04	1.33	1.21
4.21	4.67	5.20	5.66	5.00	8.41	9.77	6.28	5.91	6.42	5.01	4.49
0.78	0.70	0.78	0.84	0.75	1.26	1.50	0.90	0.89	1.01	0.82	0.74
5.01	3.81	4.19	4.38	4.11	7.17	8.30	4.53	4.77	5.53	4.72	4.29
29.2	19.0	21.2	20.3	19.5	33.9	41.6	19.9	23.3	27.3	24.6	22.7
1.05	0.72	0.78	0.80	0.74	1.30	1.56	0.79	0.88	1.07	0.93	0.86
2.96	1.79	2.02	1.99	1.94	3.36	4.01	1.78	2.24	2.74	2.59	2.26
0.44	0.24	0.27	0.26	0.24	0.44	0.54	0.21	0.30	0.36	0.36	0.32
2.96	1.53	1.79	1.63	1.60	2.77	3.51	1.18	1.86	2.42	2.39	2.06
0.46	0.23	0.26	0.22	0.23	0.41	0.50	0.16	0.27	0.36	0.35	0.31

Measured U and Th concentrations are highly variable, with U ranging from 324 to 1106 ppm, and Th from 216 to 6067 ppm, and Th/U ratios from 0.61 to 8.22. Two analyses have significantly lower Th/U ratios (0.61–0.67), with $^{206}\text{Pb}/^{238}\text{U}$ ages older than the lower age limit of ~ 814 Ma for the Nanhua rift sequence (Wang et al., 2003), are interpreted to be xenocrysts. The remaining 13 analyses are uniformly high in Th/U ratios (2.8–8.2), indicative of crystallization from mafic melts. Apart from spot 9.1, all other 12 analyses gave discordant U–Pb data. These 13 analyses form a linear trend with upper

and lower intercepts at 768 ± 28 Ma and -81 ± 66 Ma (MSWD=2.3, Fig. 4), respectively. The lower intercept age is geologically meaningless, likely indicative of a modern radiogenic Pb loss due to high content of Th and U. The upper intercept age is consistent well within analytical errors with the concordant analysis of spot 9.1 that has $^{206}\text{Pb}/^{238}\text{U}$ age of 766 ± 8 Ma (1σ). Thus, the dolerite sample HN04-29 from Xiangxi is interpreted to have emplaced at 768 ± 28 Ma, which is consistent with the field contact relationships as described earlier.

4.2. Major and trace elements

The Sanmenjie mafic volcanic rocks are basalt to basaltic andesite in composition with SiO_2 ranging from 47.6% to 55.7%. They are strongly altered to spilite with high Na_2O of $\sim 3.5\%$. The Guibei gabbro and Xiangxi dolerite samples also show a wide range of major element compositions, with $\text{SiO}_2=46.3\text{--}54.9\%$ and $48.6\text{--}55.0\%$, and $\text{MgO}=7.36\text{--}24.5\%$ and $3.96\text{--}11.8\%$, respectively. The Xiangxi dolerites are high in TiO_2 (averaging at $\sim 2.4\%$). Because all these samples experienced lower greenschist-facies metamorphism during which mobile elements, such as K, Na and low-field-strength elements (LFSE: Cs, Rb, Sr, Ba) were possibly remobilized, only immobile elements, such as the high-field-strength elements (HFSE: Ti, Zr, Y, Nb, Ta, Hf), Th and rare earth elements (REE) are used for petrochemical classification and petrogenetic discussions.

On the Nb/Y vs. Zr/TiO₂ plot of Pearce (1996), the Sanmenjie spilites and Guibei gabbros plot in the sub-alkaline basalt field (Fig. 5a), whereas all but two Xiangxi dolerite samples plot in the alkaline basalt field. On the FeO^T/MgO vs. SiO_2 diagram of Miyashiro (1974), the Sanmenjie spilites and Guibei gabbros are transitional in compositions between tholeiitic and calc-alkaline series (Fig. 5b). On the Harker diagrams (Fig. 6), they are variably high in Fe_2O_3^T and low in P_2O_5 . Two Guibei gabbro samples have the highest Ni contents, which are likely cumulative in olivine (Pearce, 1996). The Xiangxi dolerites show a positive correlation between Ni and MgO, indicating fractional crystallization of olivine.

The Sanmenjie spilites show a relatively small range of total REE contents and similar chondrite-normalized REE patterns (Fig. 7), with moderate LREE-enrichment ($\text{La}_N=26\text{--}41$; $\text{La}_N/\text{Yb}_N=2.01\text{--}2.98$) and insignificant Eu anomalies ($\delta\text{Eu}=0.84\text{--}0.96$). On the primitive mantle-normalized incompatible element spidergrams (Fig. 7), the spilites also show similar patterns with significant positive anomaly of Th and negative anomalies of Nb, Ta and, to lesser extent, Ti ($\text{Ti}/\text{Ti}^*=0.71\text{--}0.87$). Apart from these anomalies, the spilites exhibit generally “flattened” patterns similar to that of E-MORB.

The Guibei gabbros have very similar REE and trace element patterns to the spilites. The Xiangxi dolerites, on the other hand, are characterized by OIB-type, “humped” primitive mantle-normalized trace element patterns with significant enrichment in most highly incompatible trace elements (such as LILE, HFSE and LREE). Their Nb contents are high and variable, with Nb/La ranging from 0.73 to 1.46.

4.3. Nd isotopes

Thirteen samples were analyzed for Nd isotopes, and the results are listed in Table 3. Two Sanmenjie spilite samples show a relatively wide range of $\epsilon\text{Nd}(T)$ between -1.2 and 3.2 . The Guibei gabbros also have a similar range of $\epsilon\text{Nd}(T)$ between -1.7 and 2.9 . Whereas, the Xiangxi dolerites display high and positive $\epsilon\text{Nd}(T)$ of $2.9\text{--}5.3$. Apart from one highly-evolved dolerite sample from Tongdao (sample HN04-47), which has the lowest $\epsilon\text{Nd}(T)$ of 2.9 and Nb/La=0.73, all other dolerite samples have high $\epsilon\text{Nd}(T)$ values of $3.3\text{--}5.3$ and Nb/La ratio >1 .

5. Discussions

5.1. Petrogenesis

5.1.1. Xiangxi dolerites

In a MgO vs. $\epsilon\text{Nd}(T)$ diagram (Fig. 8) for the Xiangxi dolerites, $\epsilon\text{Nd}(T)$ value generally decreases with decreasing MgO, with a few samples showing constant $\epsilon\text{Nd}(T)$ of ~ 3 over a wide range of MgO (between 10% and 4%). Such correlations between MgO and $\epsilon\text{Nd}(T)$ is best explained by crustal contamination and fractional crystallization of these dolerites. Despite the varying degrees of contamination, the least-contaminated dolerite samples (with $\epsilon\text{Nd}(T)>3$ and Nb/La >1) still display geochemical characteristics similar to alkaline basalts derived from OIB-like mantle sources in continental rifts, such as the modern East African Rift (Stewart and Rogers, 1996; Pik et al., 1999) and the Neoproterozoic Kangdian Rift in South China (Li et al., 2002a). For instance, the Xiangxi dolerites have trace element spidergrams similar to that of typical OIB (Fig. 9a). On the Nb–Zr–Y plot of Meschede (1986), most samples plot in the field of within-plate alkali basalts (Fig. 9b), although two samples falling into the field of volcanic arc basalts due to significant crustal contamination. On the diagrams of $(\text{La}/\text{Sm})_N$ vs. Nb/La and V vs. Ti, most dolerites plot into the OIB field (Figs. 10 and 11). We conclude, therefore, that the parent magma of the Xiangxi dolerites was derived from an OIB-like mantle source in a continental rift environment. Negative correlation between Th/Nb and $\epsilon\text{Nd}(T)$ (Fig. 12) suggests variable degrees of crustal contamination in the origin of these dolerites (Puchtel et al., 1997).

5.1.2. Sanmenjie spilites and Guibei gabbros

The Sanmenjie spilites and Guibei gabbros have broadly similar geochemical and Nd isotopic compositions. In particular, these rocks are characterized by significant depletion in Nb and Ta on their trace element spidergrams (Fig. 7), an often-quoted “diagnostic” feature of arc basalts. On the diagram of $(\text{La}/\text{Sm})_N$ vs. Nb/La, these rocks mostly plot in the continental-arc basalt field (Fig. 10). Similar arc-like geochemical features led Zhou et al. (2003, 2004b) to interpret the Sanmenjie spilites as typical arc basalts formed in an active continental margin. However, it should be noted that depletion of Nb and Ta relative to La have also been observed in many intraplate rift and/or mantle-plume related magmas that were derived from subduction-modified lithospheric mantle sources, or were contaminated by crustal materials (e.g., Hergt et al., 1991; Hawkesworth et al., 1995; Li et al., 2002a, 2006a). Thus, depletion in Nb and Ta relative to La should not be used as a unique, diagnostic criterion for discriminating arc basalts from intraplate basalts. On the other hand, depletion in Zr relative to Sm is another common feature for arc basalts that usually have Zr/Sm ratios lower than the chondritic value of ~ 25 (Sun and McDonough, 1989). For instance, the Aleutian arc basalts have an average Zr/Sm of ~ 20 (McCulloch and Gamble, 1991). By contrast, intraplate basalts are characterized by Zr/Sm >25 (Sun and McDonough, 1989). Crustal contamination will not reduce this ratio, as the lower, middle and upper crusts have Zr/Sm

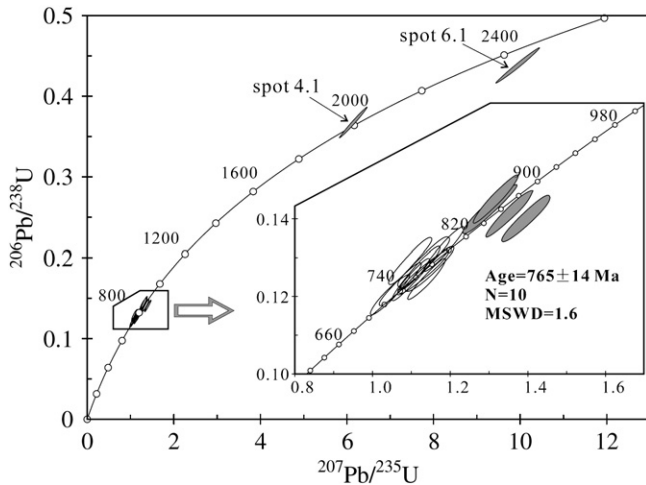


Fig. 3. U–Pb zircon concordia plot for the Sanmenjie rhyodacite sample (GB04-59) from Guibei. Six solid spots were from xenocrysts and were excluded from age calculation. MSWD = mean square of weighted deviates.

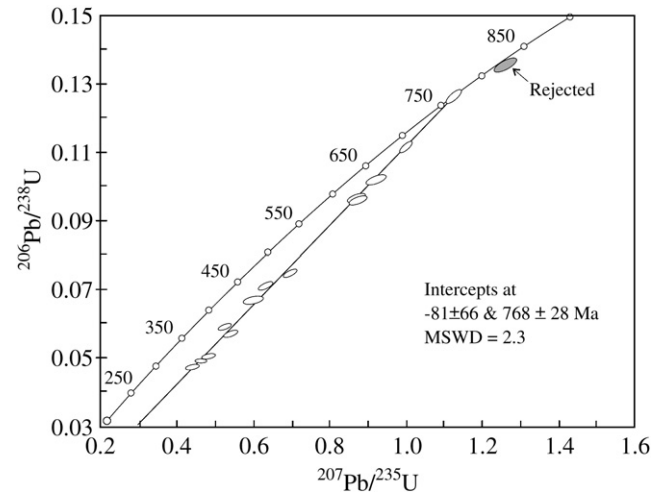


Fig. 4. U–Pb zircon concordia plot for the Guzhang dolerite sample (HN04-29) from Xiangxi. MSWD = mean square of weighted deviates. Analysis 13.1, a Paleoproterozoic xenocryst with $^{206}\text{Pb}/^{238}\text{U}$ age of 1653 Ma, is not shown in the plot.

between 24 and 42, with the average continental crust having Zr/Sm of 34 (Rudnick and Gao, 2003). The Sanmenjie spilites have Zr/Sm between 27 and 35, in line with values for intraplate basalts.

The Ti/V ratio is also useful for diagnosing the tectonic setting of basaltic rocks, as it is a function of the oxygen fugacity of the magmas and their sources, the degree of partial melting and fractional crystallization (Shervais, 1982). Island arc basalts typically have $\text{Ti}/\text{V} < 20$, whereas MORB and within-plate basalts have Ti/V ratios ranging from 20 to > 50 . The Sanmenjie spilites and Guibei gabbros display Ti/V ratio mostly between 30 and 40, significantly higher than arc basalts, plotting into the MORB and back-arc basin basalt field on a modified plot of Ti vs. V (Fig. 11, Vermeesch, 2006). Thus, their geochemical characteristics share many affinities to intraplate basalts, apart from the depletion of Nb and Ta relative to La.

The Sanmenjie spilites and Guibei gabbros show a wide range of $\epsilon\text{Nd}(T)$ between -1.7 and 3.1 . $\epsilon\text{Nd}(T)$ is correlated negatively with Th/Nb ratio (Fig. 12), suggesting involvement of two major components in their origin. It is noted that they display a different $\epsilon\text{Nd}(T)$ –Th/Nb trend from the Xiangxi dolerites. As both Th and Nb are highly incompatible elements and their ratio generally remains constant in common magmatic processes of partial melting and fractional crystallization, Th/Nb ratio is very useful for characterizing mantle sources and identifying crustal contaminations (Condie, 2003). The Sanmenjie spilites and Guibei gabbros have Th/Nb ratios ranging from 0.46 to 0.88, similar to that of arc basalts in the Andes (Th/Nb averaging at 0.66; Hickey-Vargas et al., 1986), but significantly higher than that of MORB and OIB (Th/Nb < 0.1 ; Sun and McDonough, 1989). A few samples with high $\epsilon\text{Nd}(T) \approx 3$ also have Th/Nb between 0.45 and 0.69, which is best explained as inheritance from their mantle sources rather than influence of crustal contamination. Thus, these rocks were likely derived from a subcontinental lithospheric mantle

(SCLM) source, rather than from the same OIB-like mantle source for the Xiangxi dolerites. This SCLM source might be overprinted by some arc-like geochemical and isotopic compositions, such as $\text{Th}/\text{Nb} \approx 0.5$ and $\epsilon\text{Nd}(T) \approx 4$, as results of

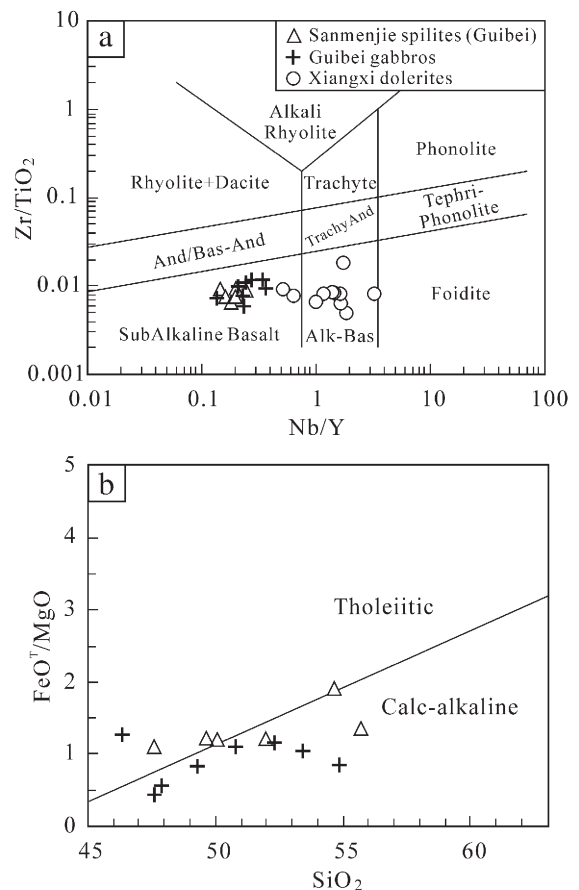


Fig. 5. (a) Zr/TiO₂ vs. Nb/Y diagram of Pearce (1996) and (b) FeO^T/MgO vs. SiO₂ diagram of Miyashiro (1974).

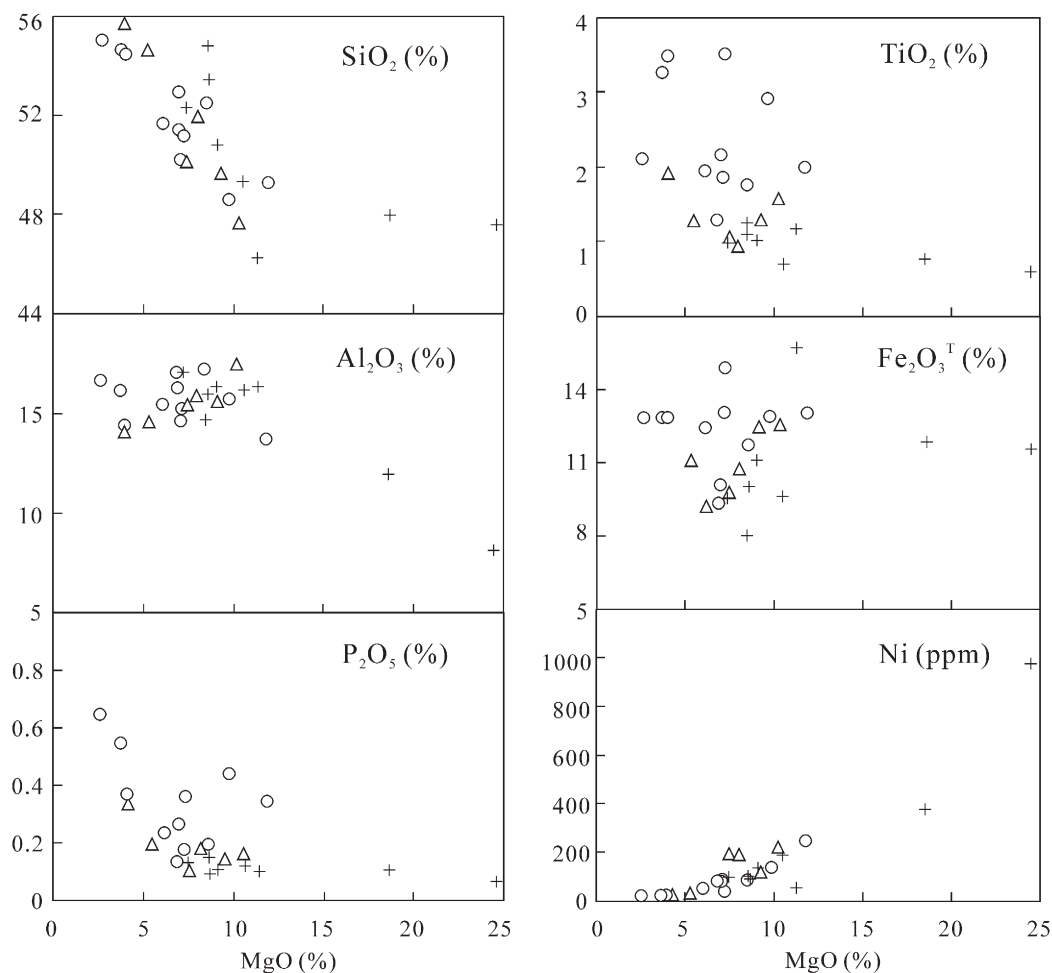


Fig. 6. Chemical variation diagrams. Symbols as in Fig. 5.

metasomatism by subduction-related fluids/melts during the Sibaoan orogenesis (Li et al., 2002b; Ye et al., 2007). In general, the Sanmenjie spilites and Guibei gabbros were likely derived from a SCLM source, and the mafic magmas were subjected to varying degrees of crustal contamination during ascent and emplacement/eruption.

5.2. Constraint on maximum depositional age of the Chang'an glaciation

The Chang'an Formation contains the lowest Neoproterozoic diamictites in South China, thus its depositional age is crucial for constraining the initiation of the Neoproterozoic glaciation. Previous investigations (e.g., Zhou et al., 2004a) used a U–Pb zircon age of 761 ± 8 Ma as the maximum deposition age of the Chang'an Formation. This age of 761 ± 8 Ma was originally reported by Ge et al. (2001b) for the Tangtou gabbro from Sanmenjie. The gabbro intruded the Sanmenjie spilites, but its contact relationship with the Chang'an Formation is unclear. Thus, using the crystallization age of 761 ± 8 Ma as the maximum age for the Chang'an Formation is suggestive, but not compelling.

The Sanmenjie volcanic rocks are overlain conformably by the Gongdong and Chang'an Formations. Thus, our SHRIMP U–Pb zircon age of 765 ± 14 Ma for the Sanmenjie volcanic rocks, identical within errors with the age of 761 ± 8 Ma for the Tangtou gabbro, provides a compelling constraint on the maximum depositional age of the Chang'an Formation. This maximum age constraint is consistent with a temporal correlation between the Chang'an and Sturtian glacial deposits (e.g., Zhou et al., 2004a).

5.3. Tectonic implications

Neoproterozoic igneous rocks with ages of ~ 830 – 740 Ma are widespread around the Yangtze Block. These igneous rocks are important for understanding the Neoproterozoic tectonic evolution of South China. Two major opposing interpretations exist regarding their petrogenesis and tectonic implications. Li et al. (1999, 2002a, b, 2003a, b, 2006b), Greentree et al. (2006) and Ye et al. (2007) proposed that the pre-900 Ma rocks were formed prior to or during the Sibao Orogeny related to the assembly of the supercontinent Rodinia, whereas those 830–740 Ma rocks, synchronous with the development of the Kangdian and Nanhua Rifts (Wang and Li,

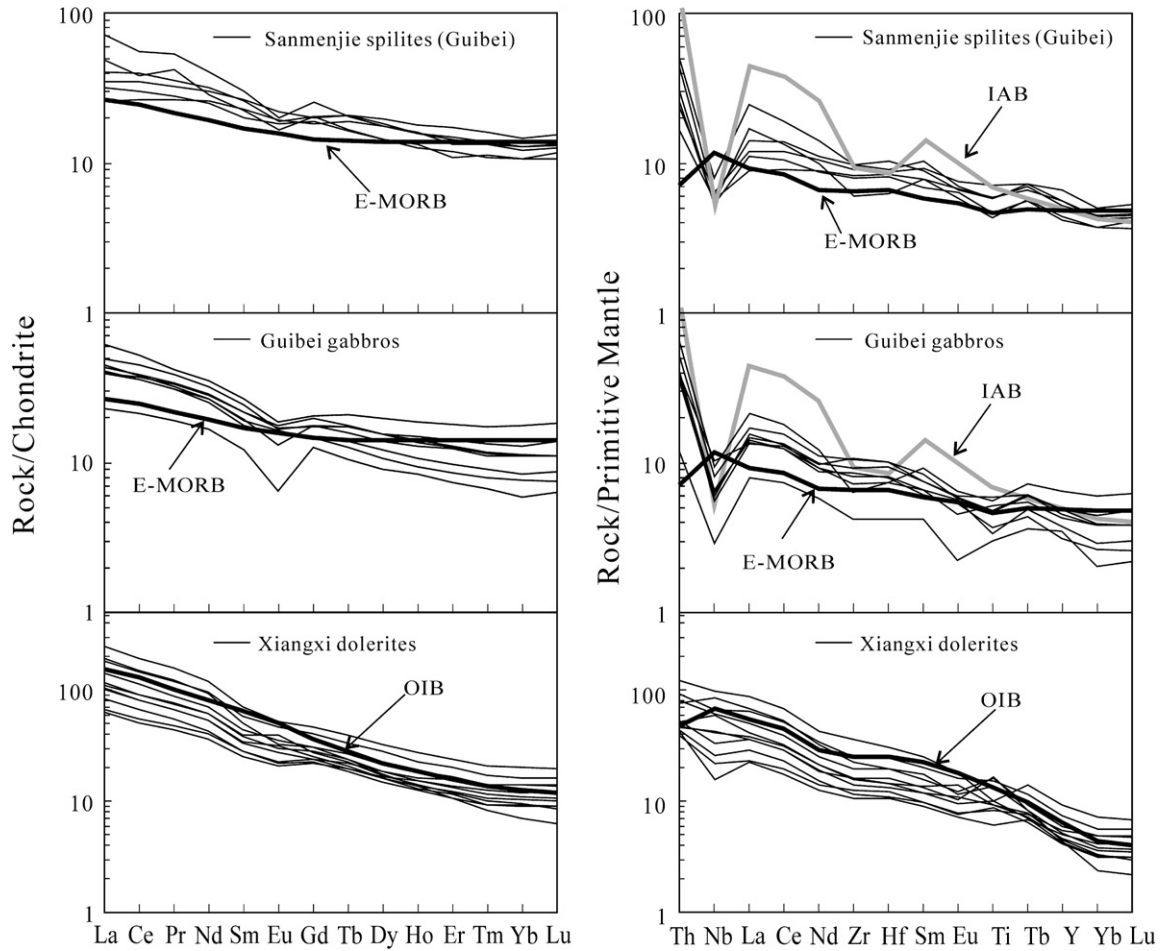


Fig. 7. Chondrite-normalized REE patterns and primitive-mantle-normalized incompatible element spidergrams. The primitive mantle and chondrite normalization values are from Sun and McDonough (1989). The average compositions of island arc calc-alkaline basalts (IAB), oceanic island basalt (OIB) and enriched mid-ocean ridge basalt (E-MORB) are from Tatsumi and Eggins (1995) and Sun and McDonough (1989).

2003), were anorogenic products related to mantle plume activities during the breakup of Rodinia. However, some other workers suggested that almost all these mid-Neoproterozoic igneous rocks

in South China were orogenic magmatism formed in active continental margins (e.g., Zhou et al., 2002a,b, 2006; Wang et al., 2004b, 2006), with the Sanmenjie spilites being interpreted as a

Table 3
Nd isotopic data for the igneous rocks in the study area

Sample#	Rock type	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma$	$\varepsilon_{\text{Nd}}(T)$
97GX51	Spilite	3.05	11.8	0.1563	0.512600 ± 0.000013	3.2
97GX64	Spilite	4.18	16.5	0.1531	0.512358 ± 0.000007	-1.2
GB04-65	Gabbro	2.68	11.7	0.1385	0.512473 ± 0.000012	2.5
GB04-66	Gabbro	2.93	12.4	0.1428	0.512517 ± 0.000012	2.9
GB04-80	Gabbro	3.33	13.1	0.1537	0.512528 ± 0.000013	2.1
97GX57-3	Gabbro	3.78	16.1	0.1419	0.512275 ± 0.000011	-1.7
97GX57-8	Gabbro	3.36	14.1	0.1441	0.512349 ± 0.000007	-0.5
97GX66	Gabbro	2.97	13.1	0.1371	0.512389 ± 0.000012	1.0
HN04-29	Dolerite	5.28	25.6	0.1247	0.512444 ± 0.000012	3.3
HN04-34	Dolerite	6.03	29.0	0.1257	0.512552 ± 0.000012	5.3
HN04-37	Dolerite	9.00	45.6	0.1193	0.512424 ± 0.000012	3.4
HN04-43	Dolerite	5.96	29.0	0.1242	0.512464 ± 0.000012	3.7
HN04-47	Dolerite	4.34	18.9	0.1388	0.512495 ± 0.000012	2.9

$T=765$ Ma, the formation age of the analyzed mafic volcanic and intrusive rocks.

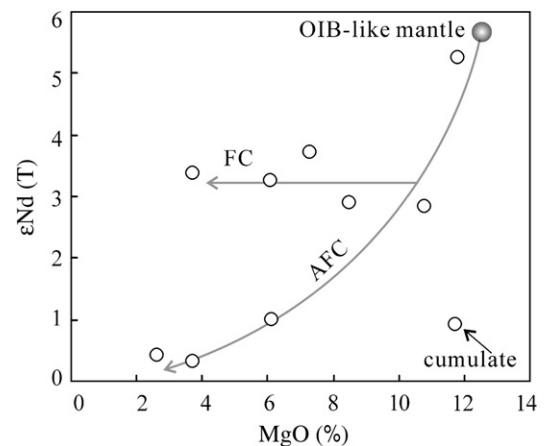


Fig. 8. MgO vs. $\varepsilon_{\text{Nd}}(T)$ plot for the Xiangxi dolerites. The data include those from Wang et al. (2004a,b). FC = fractional crystallization; AFC = assimilation and fractional crystallization.

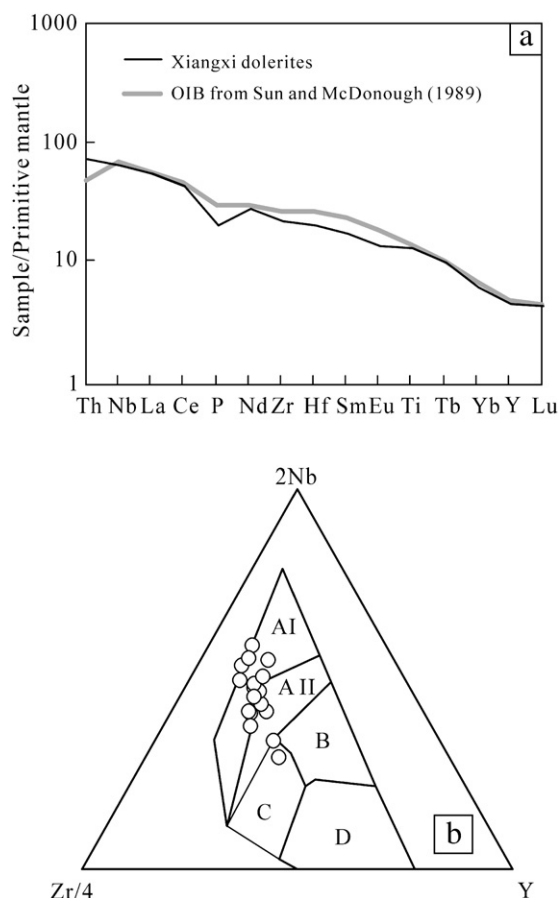


Fig. 9. (a) Comparison of spidergrams between the Neoproterozoic Xiangxi dolerites and the typical OIB. Trace element composition for the Xiangxi dolerite is the average of seven least-contaminated samples with Nb/La > 1.0; (b) Nb–Zr–Y discrimination diagram of Meschede (1986) for the Xiangxi dolerites. AI = within-plate alkali basalts; AII = within-plate alkali basalts and within-plate tholeiites; B = E-MORB; C = within-plate tholeiites and volcanic-arc basalts; D = N-MORB and volcanic-arc basalts. The data include those reported by Wang et al. (2004a,b).

typical arc basaltic suite along the southern margin of the Yangtze Block (Zhou et al., 2003, 2004b). Accordingly, they questioned the central location of the South China Block in the Rodinia reconstruction, and argued against the proposed Neoproterozoic South China mantle plume.

Our results demonstrate that the Sanmenjie spilites, the Guibei gabbros and the Xiangxi dolerites were formed contemporaneously at ~765 Ma. The Xiangxi dolerites are typical continental rift-related alkaline basaltic rocks. The Sanmenjie spilites and Guibei gabbros also display geochemical affinities of intraplate basaltic rocks, and their Nb–Ta depletion was most likely inherited from their SCLM source that might have been metasomatised by previous subduction-released fluids/melts. In particular, they are closely associated in time and space with the Xiangxi dolerites. Thus, there is no evidence for any difference in tectonic settings between these comagmatic mafic rocks. Geochemical and Nd isotopic characteristics of these mafic rocks manifest their derivation from different mantle sources, but they were all anorogenic, rift-related magmatism.

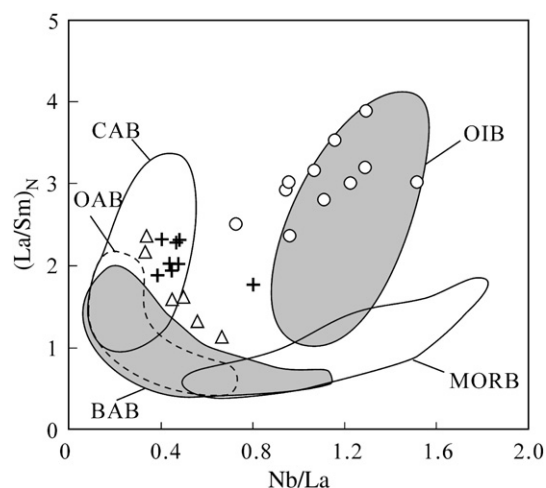


Fig. 10. (La/Sm)_N vs. Nb/La plot for the mafic igneous rocks from Guibei and Xiangxi. The fields of OIB, MORB (mid-ocean ridge basalts), OAB (ocean arc basalts), BAB (back arc basin basalts) and CAB (continental arc basalts) are formed by the probability more than ~85% of the basalts from the typical tectonic settings. Data of MORB and OIB are from compilation of Vermeesch (2006); CAB data from basalts in Andean arc basalts, and OAB data from Mariana arc basalts (<http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html>); BAB data from back-arc basin basalts (<http://www.petdb.org/>). Symbols as in Fig. 5.

Our results provide further evidence for a major phase of rift-related magmatism at ca. 780–750 Ma over much of the Yangtze Block, including the Sanmenjie Formation in the Hunan–Guangxi sub-basin, the Luokedong and Jingtian Formations in the Jiangnan Ridge sub-basin, and the Shangshu Formation in the northern Zhejiang sub-basin in southern Yangtze Block (Wang and Li, 2003), and the magmatic rocks in the Kangdian rift basin in western Yangtze Block (Li et al., 2003b). The ~765 Ma Sanmenjie volcanic rocks, the Guibei gabbros and the Xiangxi dolerites are most likely part of the extensive mid-Neoproterozoic mafic magmatism in response to a superplume event as recorded in many continental fragments of Rodinia (Fig. 13).

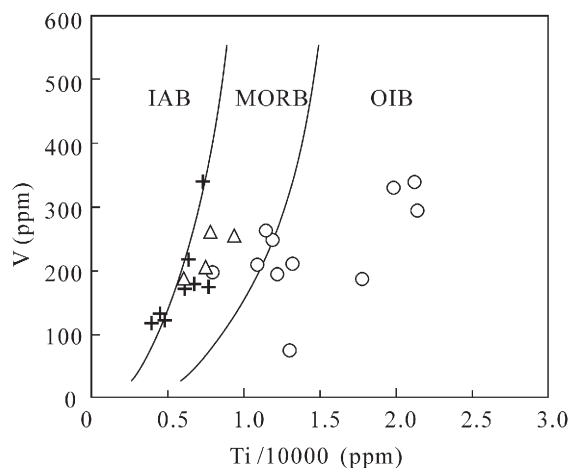


Fig. 11. V–Ti discrimination diagram of Vermeesch (2006) for the mafic igneous rocks from Guibei and Xiangxi. Symbols as in Fig. 5.

6. Conclusions

- (1) SHRIMP U–Pb zircon dating results suggest that the Sanmenjie spilites, the Guibei gabbros and the Xiangxi dolerites formed synchronously at ~ 765 Ma, which provides not only a precise age for the Sanmenjie Formation, but also a lower age limit for the Chang'an glaciation in South China.
- (2) The least-contaminated Xiangxi dolerites have geochemical and Nd isotopic features strikingly similar to alkaline basalts in oceanic islands and continental rifts. They were likely derived from an OIB-type mantle source. The

Sanmenjie spilites and Guibei gabbros were derived from a SCLM source that might have been metasomatised by previous subduction processes. They were generated in the same Neoproterozoic continental rift setting, rather than in an active continental margin as others have suggested.

- (3) The ~ 765 Ma mafic magmatic rocks were part of the extensive middle Neoproterozoic rift-related magmatism in South China in response to mantle plume activities during the break-up of Rodinia.

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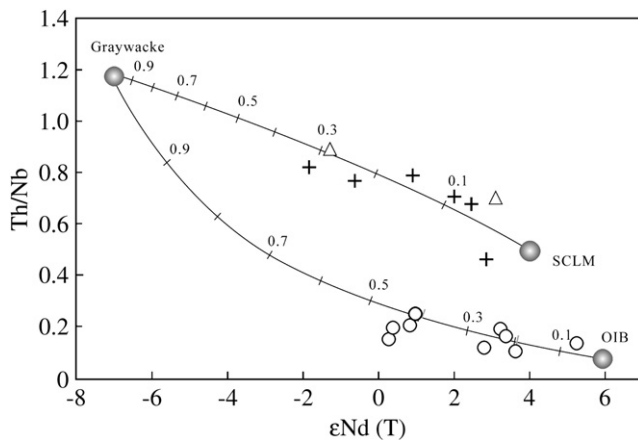


Fig. 12. Th/Nb vs. $\epsilon\text{Nd}(T)$ plot and the binary mixing modeling results. Numbers labeled on the mixing curves are fraction of average Proterozoic graywacke from the study area in the mantle-derived magma. The graywacke composition (Th = 14 ppm, Nb = 12 ppm, Nd = 35 ppm and $\epsilon\text{Nd}(T) = -7$) is the average of the Proterozoic metasedimentary rocks from the study area (Gu et al., 2002; Li and McCulloch, 1996); OIB composition (Th = 4 ppm, Nb = 48 ppm, Nd = 38 ppm and $\epsilon\text{Nd}(T) = 6$) is from Sun and McDonough (1989); SCLM represents the subcontinental lithospheric mantle metasomatized by the subduction-related fluids/melts with Th = 2 ppm, Nb = 4 ppm, $\epsilon\text{Nd}(T) = 4$ and Nd = 15 ppm, as for the Andes continental arc basalts reported by Hickey-Vargas et al. (1986). The data include those reported by Wang et al. (2004a,b). Symbols as in Fig. 5.

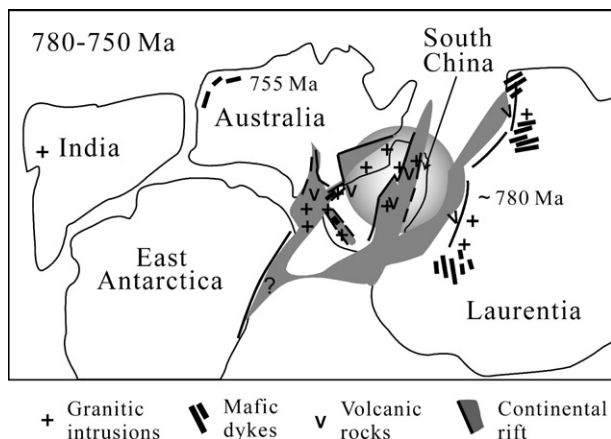


Fig. 13. Speculated ca. 780–750 Ma mantle plume beneath Rodinia, rift junctions and arms and anorogenic igneous rocks in South China and adjacent continents (modified after Li et al., 2003b; 2006c).

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