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Detrital Zircon Records of the Banxi Group in the Western Jiangnan Orogen: Implications for Crustal Evolution of the South China Craton

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Abstract: The Neoproterozoic evolution of the Jiangnan Orogen is important for understanding the tectonic history of South China. As a volcanic-sedimentary sequence developed in the Nanhua rift, the Banxi Group preserves the records of important magmatic and tectonic events linked to the assembly and breakup of the Rodinia supercontinent. In this study, we report the results from whole-rock major- and trace-element concentrations, with zircon LA-(MC)-ICP-MS U-Pb ages, trace elements and Lu-Hf isotopic compositions of sandstones from the Banxi Group. The rocks are characterized by high SiO_2 (65.88%–82.76%, with an average of 75.50%) contents, moderate ($Fe_2O_3^T$ + MgO) (1.81%–7.78%, mean: 3.79%) and TiO_2 (0.39%–0.54%, mean: 0.48%), low K_2O/Na_2O (0.03–0.40, mean: 0.10) ratios and low Al_2O_3/SiO_2 (0.11–0.24, mean: 0.15) ratios. The sandstones have high ΣREE contents (mean: 179.1 ppm), with chondrite-normalized REE patterns similar to the upper crust and PAAS, showing enriched LREE ($(La/Yb)_N$ mean: 14.85), sub-horizontal HREE curves and mild Eu (Eu/Eu*: 0.75–0.89, mean: 0.81) negative anomalies. Their geochemical characteristics resemble those of passive continental margin sandstones. Most of the zircons are magmatic in origin and yield a U-Pb age distribution with three peaks: a major age peak at 805 Ma and two subordinate age peaks at 1990 Ma and 2470 Ma, implying three major magmatic sources. The Neoproterozoic zircons have $\varepsilon_{Hf}(t)$ values ranging from −47.4 to 12.4 (mostly −20 to 0), suggesting a mixture of some juvenile arc-derived material and middle Paleoproterozoic heterogeneous crustal sources. The Hf model ages of middle Paleoproterozoic zircons (~1990 Ma) with negative $\varepsilon_{Hf}(t)$ values (−12.65 to −6.21, Ave. = −9.8) concentrated around the Meso-Paleoarchean (mean T_{DM}^C = 3.3–3.1 Ga). For late Neoarchean detrital zircons (~2470 Ma), $\varepsilon_{Hf}(t)$ values are divided into two groups, one with negative values (−9.16 to −0.6) with model ages of 3.5–2.9 Ga, the other featuring positive values (1.0 to 3.9) with model ages of 2.9–2.7 Ga, recording a crustal growth event at ~2.5 Ga. Neoproterozoic zircons show volcanic arc affinities with partly intraplate magmatic features. We propose that the Banxi Group formed in a rift basin within a passive continental margin setting, which derived detritus from felsic to intermediate rocks from the Yangtze Block and a small amount of arc volcanic rocks. The middle Paleoproterozoic detrital zircon data suggest Columbia-aged basement lies beneath the western Jiangnan orogen.

Key words: detrital zircon, U-Pb age, Lu-Hf isotope, episodic magmatism, Jiangnan Orogen

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1 Introduction

The South China Craton (SCC), one of the major crustal blocks in East Asia, is composed of two distinct tectonic units, the Yangtze Block in the northwest and the Cathaysia Block in the southeast (Yao et al., 2014a), separated by the Jiangnan Orogen. The major crustal components in the SCC are three layers of Phanerozoic caprocks and two distinct units of Precambrian basement, composed of middle Paleoproterozoic and Archean crystalline rocks (Zhang et al., 2013). These are represented by the Kongling complex (3.4–2.9 Ga), Houhe complex (~2.0 Ga) and Dahongshan Group (~1.7 Ga) in the Yangtze Block, with the Badu complex (2.5–1.9 Ga)

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in the Cathaysia Block (Qiu et al., 2000; Greentree and Li, 2008; Wu et al., 2012; Yu et al., 2020). Zircon U-Pb ages indicate the occurrence of Archean to middle Paleoproterozoic rocks in different regions of the SCC, further revealing ancient crustal components (Zheng and Zhang, 2007). During the assembly of the Rodinia continent, the unified SCC continental plate formed in the Neoproterozoic, through the combination of the Yangtze plate and the Cathaysia plate.

The Neoproterozoic igneous rocks within the Yangtze Block have been taken as evidence for subduction and break-up events, with three models having been proposed to explain the tectonic evolution, including mantle-plume, arc-related and plate-rift (Zhou et al., 2002; Li et al., 2003b; Wang X L et al., 2004, 2006, 2012; Wang X C et al., 2007; Zheng et al., 2008a, b; Zhang C L et al., 2013b). For the Jiangnan Orogen, a double-sided subduction was model proposed by Zhao (2015). Recent geochronological and geochemical studies in the Jiangnan Orogen have identified multiple ophiolite suites (e.g., the South Anhui and Northeast Jiangxi ophiolites), MORB (e.g., basalts interlayered in the Shuangxiwu, Shuangqiaoshan, Lengjiaxi and Fanjingshan groups) and a series of syn-collisional as well as post-collisional Neoproterozoic granites (e.g. South Anhui, Northwest Jiangxi and Northeast Hunan, North Guangxi and Northeast Guizhou) (Li and Li, 2003; Wang et al., 2004, 2006, 2014; Ding et al., 2008; Li et al., 2008a, b; Zhou et al., 2009; Bai et al., 2010; Xue et al., 2012; Zhang C L et al., 2013a; Zhang Y Z et al., 2013, Yao et al., 2014a, b; Du et al., 2017). The other lines of evidence relating to the collision between the Yangtze and Cathaysia blocks in the Neoproterozoic include blueschist with an Ar/Ar age of 866 ± 14 Ma in Dexing, showing foreland basin and back-arc basin deposition (Shu et al, 1994; Wang et al., 2017). Some available data and geological observations show the development of the early Neoproterozoic (~840 Ma) continental arc-basin system along the central Jiangnan Orogen (Zhang et al., 2015; Zhang and Wang, 2016, 2020). Although the specific time duration of the orogeny is still controversial, the two blocks are proposed to have collided in the Neoproterozoic, during 840–800 Ma, forming a unified SCC (Li et al., 2007, 2008b). After the orogeny, post-orogenic extension occurred along the Jiangnan Orogen, leading to the formation of the Nanhua rift system (Wang X L et al., 2008, 2012).

The early Neoproterozoic metamorphosed volcanic-sedimentary strata consist of the Shuangxiwu Group in west Zhejiang, the Xikou Group in south Anhui, the Shuangqiaoshan/Jiuling Group in northwest Jiangxi, the Lengjiaxi Group in central Hunan, the Fanjingshan Group in northeast Guizhou and the Sibao Group in north Guangxi (Wang et al., 2004; Wang X L et al., 2007; Shu, 2012; Zhao and Cawood, 2012). There is considerable research on the basement rocks of the Jiangnan Orogen (Wang et al., 2013), the main controversies being formation age and tectonic setting. The previously considered Mesoproterozoic basement rocks were newly-dated as Neoproterozoic (Zhou et al., 2009), recent studies giving more precise limits on the deposition time of the Banxi Group and its equivalent strata (Zhang et al., 2015; Wang et al., 2017). Detrital zircon U-Pb ages demonstrate that all of these were formed during 850–825 Ma (Wang X L et al., 2007, 2008, 2012, 2017; Gao et al., 2011), whereas the overlying sedimentary caps and their equivalent strata formed at ~815 Ma (Gao et al., 2011, Song et al., 2017), suggesting that the collision between the Yangtze and Cathaysia blocks occurred during 825–815 Ma (Zhao and Cawood, 2012; Zhao, 2015). In addition to disputes regarding the time of deposition, disagreement on the background sedimentary structures in the Jiangnan Orogen has existed for a long time (Zhang et al., 2015). Some researchers regard the Lengjiaxi and Banxi groups as the sediments of a trench arc-basin set (Guo et al., 1980), while others see them as the sediments of an early rifting stage following the splicing of Cathaysia with the Yangtze Block (Li et al., 2003a).

In order to verify the tectonic characteristics and process of the Banxi evolutionary groups in the western Jiangnan Orogen, additional detailed geochemical studies are needed. Compared to the eastern Jiangnan Orogen, studies on the detrital zircons from the Western part have received less attention. The age spectra of detrital zircons provide important insights into the source rocks, as well as the sedimentary and tectonic evolution of the sedimentary basins. In this study, we carried out whole-rock major- and trace-element as well as detailed U-Pb dating, trace elements and Hf isotopic analysis on detrital zircons from the sandstones of the Banxi Group in the western Jiangnan Orogen. Our results provide new insights into Precambrian crustal evolution and the regional tectonic setting of the Xuefengshan area.

2 Geological Setting and Stratigraphy

The boundary between the eastern part of the JO and the Cathaysia Block is clear and basically undisputed, principally along the Jiangshao fault zone to Pingxiang–Shuangpai fault zone (Fig. 1; Shu, 2012). However, compared with the eastern JO, there are only a few outcrops of Neoproterozoic mafic–ultramafic rocks in the western JO. The southern boundary of the Jiangnan Orogen has not therefore been precisely defined. In northern Guangxi Province, the mafic-ultramafic suites (~855 Ma) from the Yuanbaoshan area display the geochemical signatures of an arc setting (Yao et al., 2014a) with ~830 Ma high-Mg diorites in the Dongma Pluton, implying the existence of Neoproterozoic subduction-related metasomatism (Chen et al., 2014). The granitoids formed at 835–800 Ma from northern Guangxi are classified as collision-related S-type granites related to the continent-continent collision between Yangtze and the Cathaysia blocks (Wang et al., 2006; Yao et al., 2014b). A series of bimodal and alkaline rocks in the Longsheng area (~760 Ma) were considered to be the products of mantle-derived magma generated in the process of the evolution of the Neoproterozoic Nanhua rift (Ge et al., 2001; Wang et al., 2004). In the Fanjingshan area of eastern Guizhou Province, the Neoproterozoic mafic–ultramafic rocks include pillow lavas (~840 Ma), mafic–ultramafic sills and hypabyssal intrusive gabbro (~821 Ma) (Xue et al., 2010).

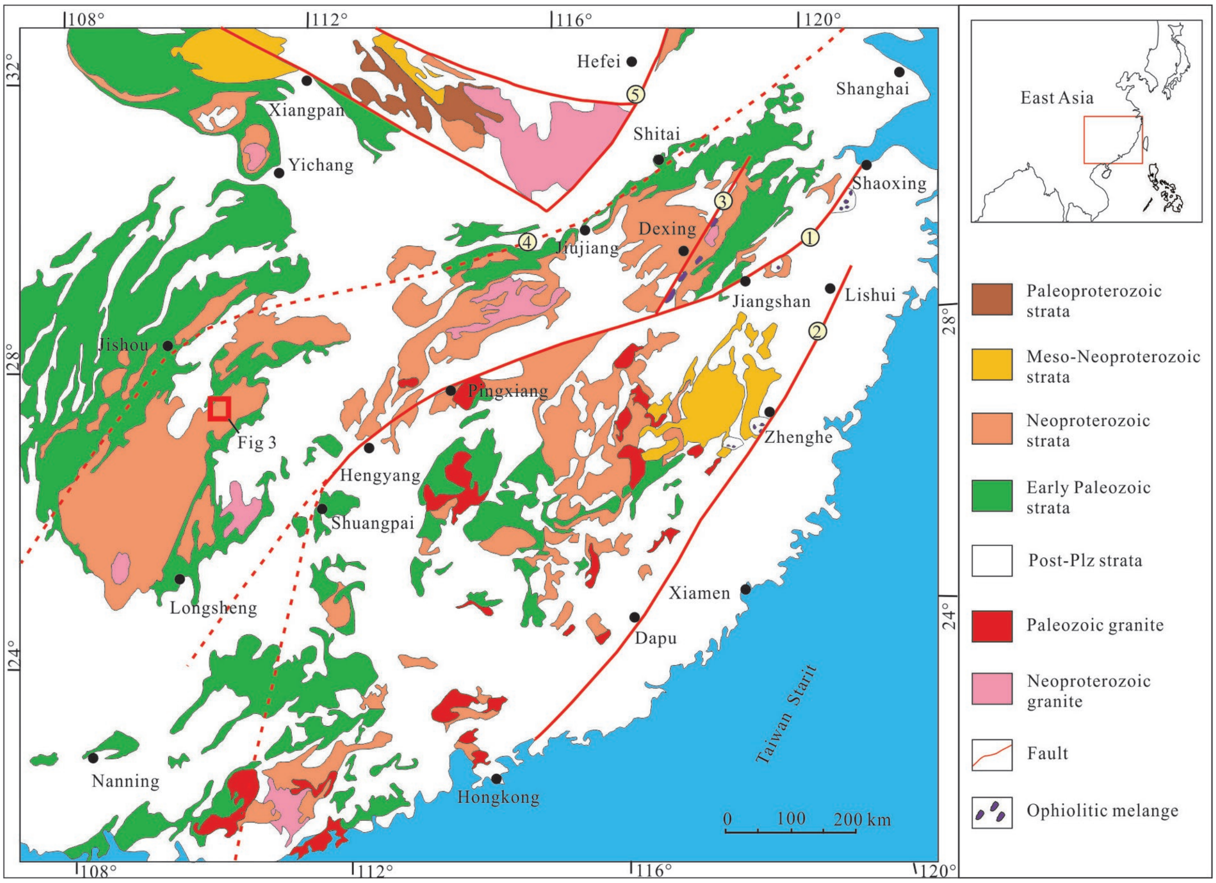

Fig. 1. Geological sketch map of the Jiangnan Orogen, South China Craton (modified from Yao et al., 2014a).
1: Shaoxing–Jiangshan-Pingxiang–Shuangpai fault; 2: Zhenghe–Dapu fault; 3: Northeast Jiangxi fault; 4: Jiujiang–Shitai fault; 5: Tanlu fault; SECCLMVZ=Southeast China coastal late Mesozoic volcanic zone.

Numerous muscovite-bearing leucogranites (838.5 ± 1.5 Ma) intruded into the Fanjingshan Group, likely resulting from high temperature (> 875°C) partial melting of clay-rich psammitic rocks (Wang et al., 2011). In northwest Hunan Province, it is proposed that Yiyang komatiitic basalts (~823 Ma) and mafic–ultramafic dykes from Aikou (~831 Ma) are the product of rift magmatism related to the mantle plume (Wang X L et al., 2007; Zhang et al., 2009). The Qianyang alkaline gabbro–diabase (~747 Ma), the Guzhang alkaline diabase (–768 Ma) and the Tongdao mafic rocks (~756 Ma), with typical arc signature, were possibly derived from the mantle wedge metasomatized by subducted materials (Wang et al., 2004, 2008; Xia et al., 2018; Wan et al., 2019). Peraluminous calc–alkaline felsic granitoids in the Chengbu area (811–805 Ma), formed in an island arc environment, as a result of the break-off and delamination of the subducted slab (Bai et al., 2010; Du et al., 2017).

The trend of the Jiangnan Orogen is that of a change from northeast to east to southwest in Hunan Province, the Xuefengshan area being located in the southwest direction of the turning end. Since the Neoproterozoic, this area experienced intense tectonic movements. From bottom to top, the Neoproterozoic strata in the Xuefengshan area is composed of the Lengjiaxi Group, the Banxi Group and the Nanhua Group. As a basement-developed closed fold, the Lengjiaxi Group has a upper deposition age limit at ~825 Ma (Gao et al., 2012; Zhang et al., 2015; Wang et al., 2017). The Banxi Group as a sedimentary cap is a high-angle unconformity covering the Lengjiaxi Group, with open wide folds developed. The age limit of the sedimentation for the Banxi Group is constrained from 810 Ma to 720 Ma through recent detrital zircon U-Pb ages (Wang et al., 2013, 2017; Zhang et al., 2015). The relationship between the Banxi Group and the Nanhua Group is defined by a parallel unconformity or disconformity.

From bottom to top, the Banxi Group is divided into Zhuanqiangwan Formation, Jiajiantian Formation, Yanmenzhai Formation in the study area, northwest of Hunan. The Banxi Group is composed of low metamorphic clastics and a few tuffs, such as a pelagic to littoral-offshore sedimentary sequence, intruded by Neoproterozoic basic and ultrabasic rocks (Chen et al., 2014). A similar sequence is mapped in the Lengjiaxi Group. The Banxi Group shows low grade metamorphism (greenschist facies). It has been proposed that the tectonic environment was related to the Jinning movement (Wang X L et al., 2007, 2008). However, another model suggests that the Banxi Group may be a sedimentary product after the transition from post-arc basin to rift basin environment, which is related to the break-up of the

Table 1 Summary of detrital zircons from the Banxi Group and its equivalents in the West JO

Group	Formation	Rock type	Major peak (Ma)	Minor peak (Ma)	$\varepsilon_{Hf}(t)$	Area	Reference
Xiajiang	/	Sandstone	~791, ~843	/	/	Fanjingshan area, Guizhou	
Banxi	Madiyi	Sandstone	~798, ~856	/	/	Madiyi area, Hunan	Yan et al., 2019
Danzhou	/	Sandstone	850–930	1600–1800, ~2500	/	Sibao area, Guangxi	
Banxi	/	Sandstone	~830	~1800, ~2500	/	Hengshan area, Hunan	
Banxi	/	Sandstone	~780	~2000, ~2500	/	Xuefengshan area, Hunan	Su et al., 2014
Xiajiang	/	Sandstone	~830, ~740, ~900	~2000, ~2500	/	Fanjingshan, Guizhou	
Banxi	Xinzhai	tuff	815–809	~2018, ~2485	/	Fanjingshan, Guizhou	Zhang et al., 2019
Banxi Banxi	Hengluchong Jiajiantian	tuff Lithic sandstone	825–800 780–760	/	−20 to +13	North Hunan	Meng et al., 2013
Banxi	Wuqiangxi	Sandstone	~780, ~820	~910	/	Zhangjiajie area, Hunan	Song et al., 2017
Banxi	Laoshanya	Quartz sandstone	~858	/	−12.7 to +14.6	Shimen County, western Hunan	Wang et al., 2010b
Banxi	Xieshuihe	Sandstone	2300–2560, 1900–2100	770–1000	−32.5 to +12.6	North Hunan	Wang et al., 2012a
Banxi	Madiyi	Feldspathic sandstone	~ 826, ~865	~1857	−17 to +12	East-central Hunan	Wang et al., 2017
Banxi	Madiyi	Tuffaceous siltstone tuff and tuffaceous slate	~770	1122–1387, 1952–2605	−16.5 to +16.7	Banxi area, Hunan	Li et al., 2019

Rodinia supercontinent (Zhang et al., 2015; Wang et al., 2017). Recent studies on detrital zircons from the Banxi Group and its equivalents in Hunan Province and surrounding areas are summarized in Table 1. The magmatic zircon grains yield a U-Pb age distribution with three peaks (Fig. 2): (1) Neoproterozoic (760–930 Ma), (2) Paleoproterozoic (1800–2100 Ma) and (3) Neoarchean–Paleoproterozoic (2300–2600 Ma). These detrital zircon ages in the western Jiangnan Orogen could be used to decipher the integrated sedimentary and tectonic histories (Zhang et al., 2019).

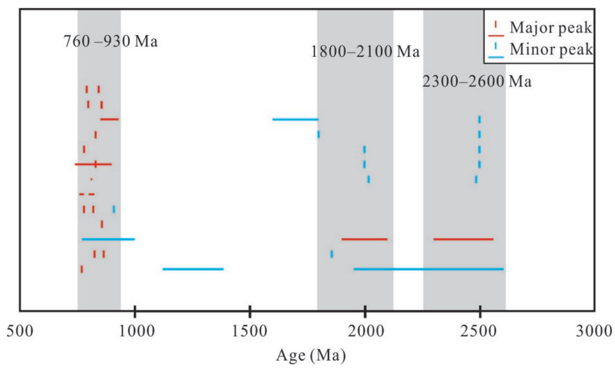

Fig. 2. Graph of detrital zircons from the Banxi Group and its equivalents in the western JO.

3 Petrography and Analytical Methods

In this study, ten sedimentary rock samples were collected from the sandstone layer sandwiched between the medium-thick slate in the Jiajiantian Formation in Zhongfang County (Fig. 3; GPS: 110° 19'04.07", 27° 29'01.95") and two sandstone samples among them were selected for detrital zircon study. A total of 7 sandstone samples were analyzed for whole rock major- and trace-element compositions at the Guangzhou ALS Laboratory, China.

After each sample was cut and polished into a thin section, the freshest parts of the remaining material were crushed into small grains, then powdered to 200-mesh using a vibration agate ball mill. Major elements were analyzed using X-ray fluorescence (XRF) spectroscopy. Rare earth and other trace elements were analyzed using inductively coupled plasma mass spectroscopy (ICP-MS).

The major minerals of the sandstone include quartz and a small amount of plagioclase, with chlorite. Metamorphic hydrothermal veins composed of recrystallized calcite and quartz are developed (Fig. 4).

Zircons from two sandstone samples (84H-1 and 84H-4) were separated in the Mineral Laboratory of Geological Exploration Technology Services Limited Company of Langfang, Hebei Province, China. Fresh rock samples were manually sorted and washed after artificial crushing. According to preliminary classification of zircon by color, degree of morphology, morphology and transparency, the zircon particles for dating were hand-picked under a binocular microscope and embedded in epoxy resin then polished, in order to take CL and backscatter photographs.

Trace element analyses and U-Pb dating of zircon were conducted synchronously by LA-ICP-MS at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang. Laser sampling was performed using a GeoLas Pro 193 nm ArF excimer laser. An Agilent 7500x ICP-MS instrument was used to acquire ion-signal intensities. Helium was applied as a carrier gas, which was mixed with Argon via a T-connector before entering the ICP-MS. Each analysis incorporated a background acquisition of approximately 30 s (gas blank) followed by 60 s of data

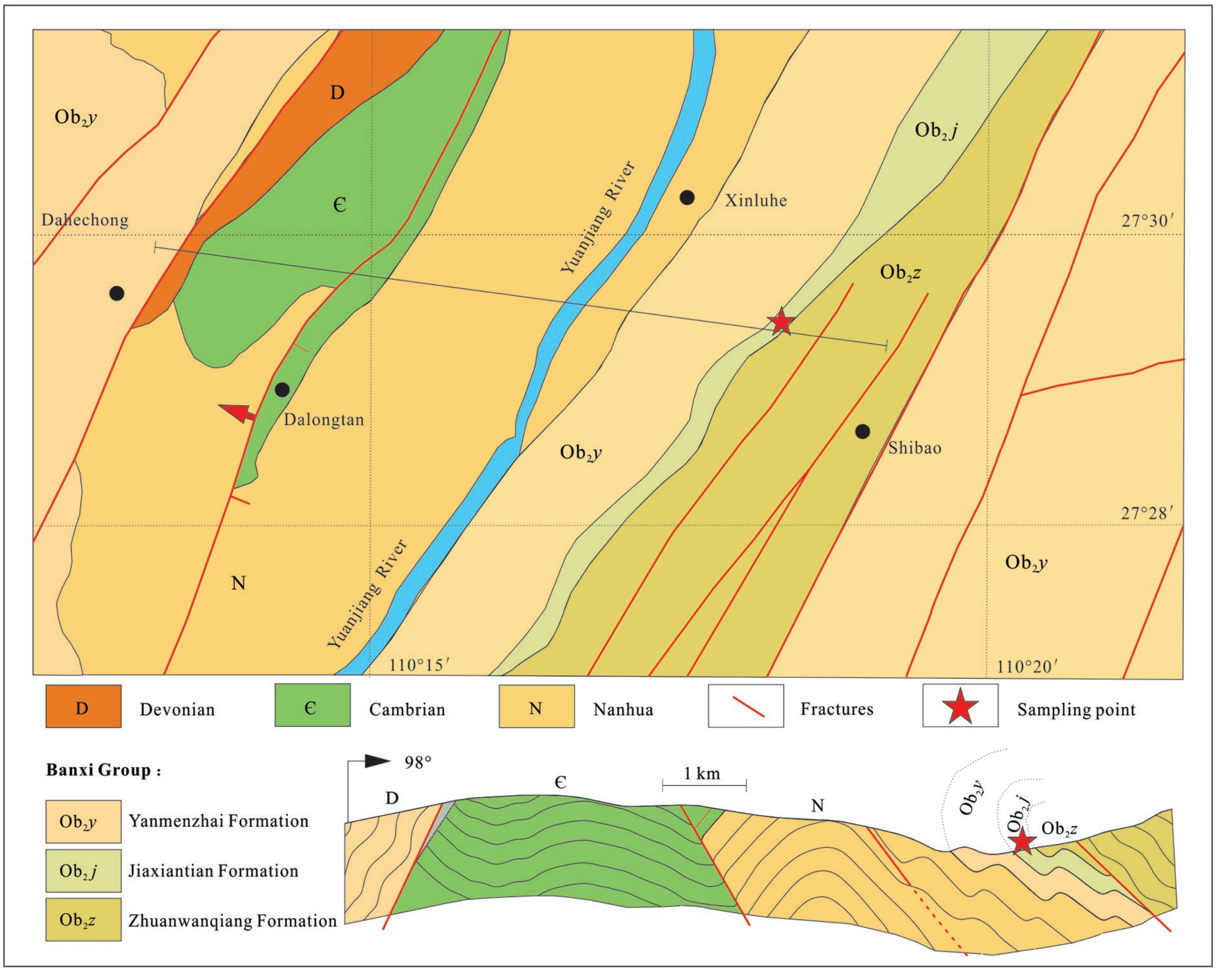

Fig. 3. Geological sketch map of the sampling locations.

acquisition from the sample. Off-line selection and integration of background and analytical signals, time–drift correction and quantitative calibration for trace element analyses and U-Pb dating were performed by ICP-MS-Data-Cal (Liu Y S et al., 2008; Liu et al., 2010). Zircon 91500 was used as the external standard for U-Pb dating and was analyzed twice every 6–8 analyses (e.g., 2 zircon 91500 + 6–8 samples + 2 zircon 91500). Uncertainty of preferred values for the external standard 91500 was propagated to the final results of the samples. Concordia diagrams and weighted mean calculations were made using Isoplot (Ludwig, 2003). Trace element compositions of zircons were calibrated against multiple-reference materials (NIST 610, BHVO-2G, BCR-2G, BIR-1G), combined with Si internal standardization. The preferred values of element concentrations for USGS reference glasses are from the GeoReM database (http://georem.mpch-mainz.gwdg.de/).

The in-situ Hf isotope analysis of zircon was performed using LA-MC-ICP-MS in the isotope laboratory of the School of Resources and Environmental Engineering, Hefei University of Technology. The system is composed of the Cetac Analyte HE laser ablation system and the Thermo Fisher Neptune Plus MC-ICP-MS. During the laser ablation process, helium is used as the carrier gas, argon being used as the compensation gas to adjust the sensitivity. The two are mixed through a T-joint before entering the MC-ICP-MS. During sample analysis, standard zircons GJ-1 (Morel et al., 2008), Penglai (Li et al., 2010), PLE (Sláma et al., 2008) and Qinghu (Li et al., 2013) were used as external standards. The offline processing of the analytical data is done using LAZrnHf-Calculator @ HFUT (Gu et al., 2019). The laboratory quality monitoring sample results show that the laboratory's long-term accuracy error (relative to the reference value) is less than 2σ units.

4 Results

4.1 Whole-rock major and trace elements

Major- and trace-element compositions of the Banxi Group sandstones are given in Suppl. Table 1. Although the sandstone has been subjected to low-grade metamorphism and weathering alteration, the loss-on-ignition (LOI) for most samples is less than 3 wt%, indicating that the rocks have not undergone significant alteration. The rocks show varying chemical compositions, with SiO_2 = 65.88%–82.76%, Al_2O_3 =

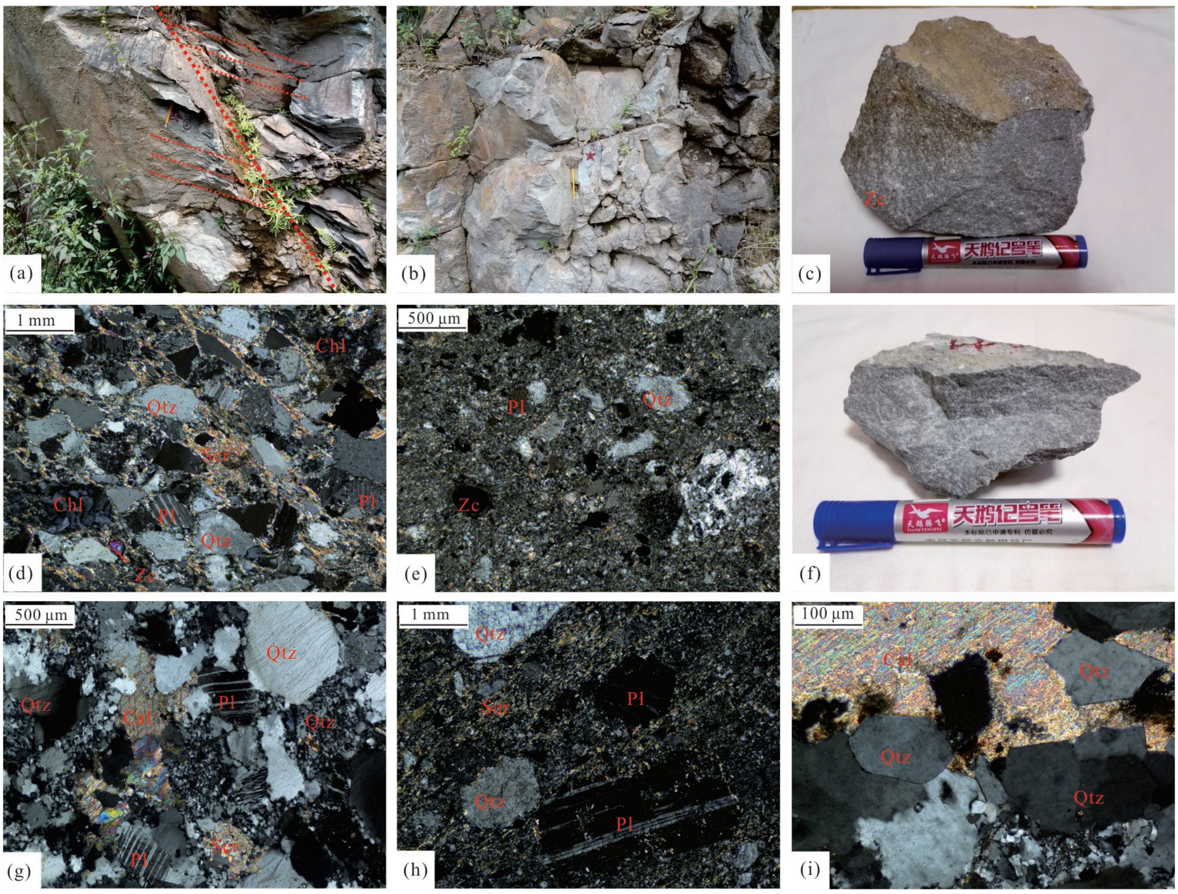

Fig. 4. Field photographs and photomicrographs of sandstones from the Jiajiantian Formation, Banxi Group.
(a, b) Field photographs; (c, f) hand-specimen photographs of sandstone samples; (d, g, i) sandstone with high recrystallization; (e, h) sandstone with low recrystallization. Qtz–quartz; Pl–Plagioclase; Chl–chlorite; Zc–Zircon; Ser–Sericite; Cal–Calcite.

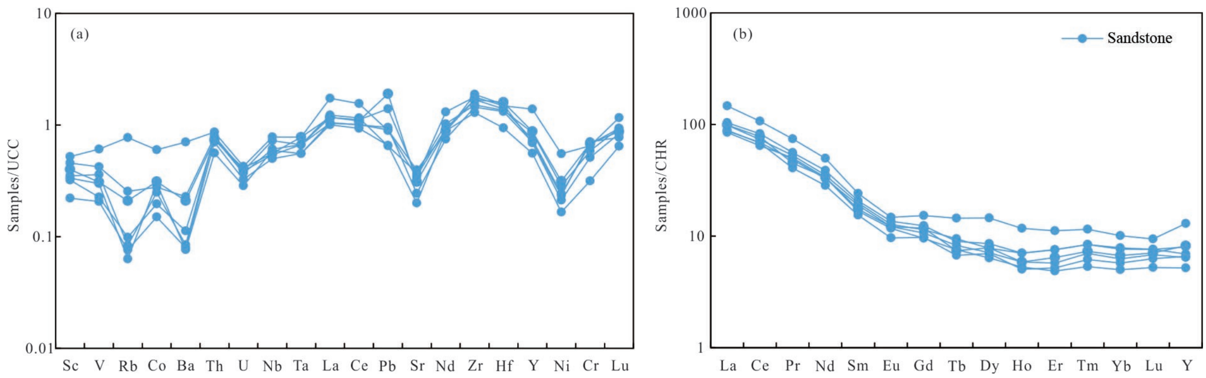

Fig. 5. Upper crust-normalized spider diagram of sandstone from the Banxi Group, northwest Hunan Province.
Upper crust-normalizing data from Rudnick and Gao (2003), chondrite values from Taylor and McLennan (1985).

9.30%–15.65%, K_2O = 0.16%–1.9%, Na_2O = 4.76%–5.85%, CaO = 0.19%–1.85%, $Fe_2O_3^T$ = 1.67%–6.36%, MgO = 0.14%–1.42%, P_2O_5 = 0.04%–0.07% and TiO_2 = 0.39%–0.54%. The SiO_2/Al_2O_3 ratio of the sandstones ranged from 4.21 to 8.90, with an average of 6.87, the Na_2O/ K_2O ratio ranged from 25.1 to 32.81, with an average of 18.49, while the Al_2O_3/(CaO + Na_2O) ratio ranged from 1.42 to 3.13, with an average of 1.90.

The trace element content of the samples is generally lower than that of the average post-Archean Australian shale (PAAS). In the upper crust-normalized incompatible -element diagram (Fig. 5a), the samples show varying degrees of enrichment of Th, La, Ce, Pb, Zr, Hf, and depletion of Rb, Ba, U, Sr and Ni. The sandstones all have a rightward-inclined REE distribution pattern, with relatively enriched LREE (La_N/Yb_N) = 12.54–17.00, Avg 14.58) and a slight Eu deficit (0.75–0.89) (Fig. 5b). The La/Sc values of the sandstone vary widely, ranging from 5.95 to 10.06, while the Co/Th values are relatively concentrated, ranging from 0.4 to 1.17.

4.2 Zircon CL images

Zircon grains from two Neoproterozoic sedimentary rock samples are light yellow to colorless and transparent to translucent, with grain-size ranging from 70 to 180 μm. The CL images (Fig. 6) reveal that radioactive abrasions are common in most of the detrital zircons. The internal structure of the zircons shows evident oscillatory zoning, indicating that the zircons are magmatic in origin (Hoskin and Schaltegger, 2003). Based on their morphology and internal structure, the zircon grains can be divided into two groups. One is Neoproterozoic zircon with euhedral morphology and clear oscillatory zoning, the other is pre-Neoproterozoic subhedral to rounded zircon with blurry oscillatory zoning. The Neoarchean zircon's internal structure is still not clear and some grains have developed thin-layer metamorphic rims.

4.3 Zircon U-Pb geochronology

A total of 246 U-Pb analyses were acquired from the 230 detrital zircon grains and the data show high concordance (> 90%), except for 38 grains, the results are shown in Suppl. Table 2 and Fig. 7. In general, the $^{206}Pb/^{238}U$ age is used for the young zircons (<1000 Ma) and the $^{206}Pb/^{207}Pb$ age is used for the old zircons (>1000 Ma) (Blank et al., 2003).

Except for 4 points, where the age results might be affected by inclusions (with high Ca and P content), the remaining 204 concordant U-Pb data have constrained an

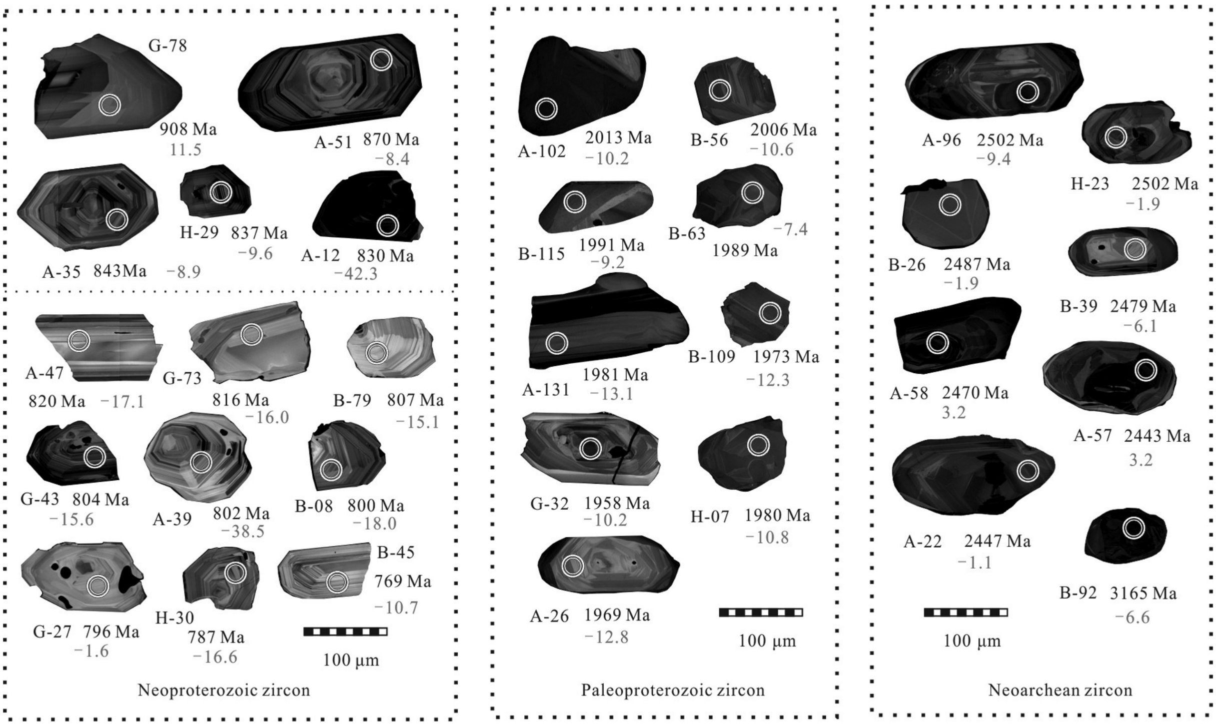

Fig. 6. Representative (CL) images of zircons for sampling from the Jiajiantian Formation, Banxi Group.

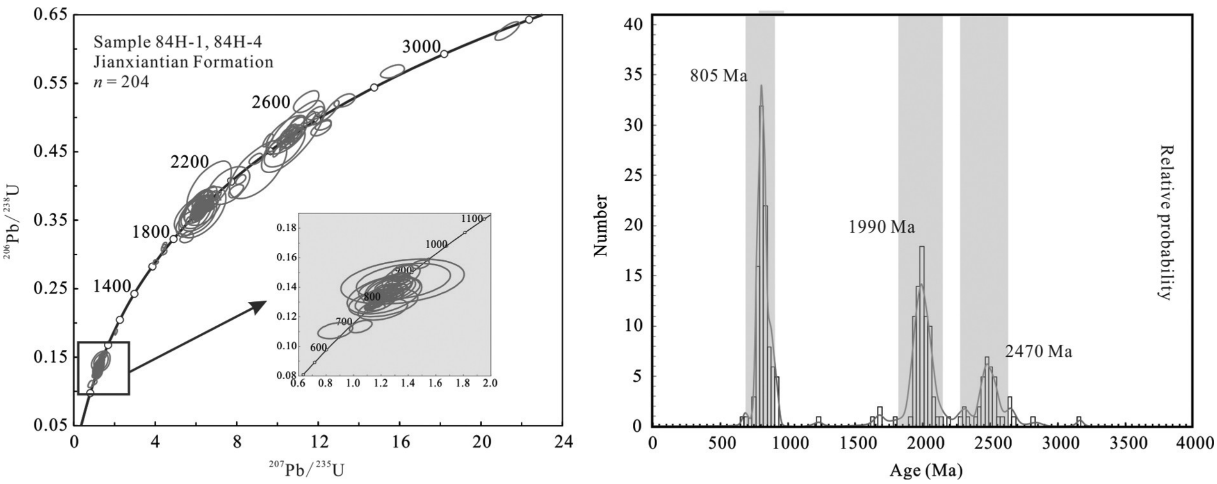

Fig. 7. U-Pb concordia diagram and corresponding U-Pb age distribution of detrital zircons from sandstone of the Jiajiantian Formation.

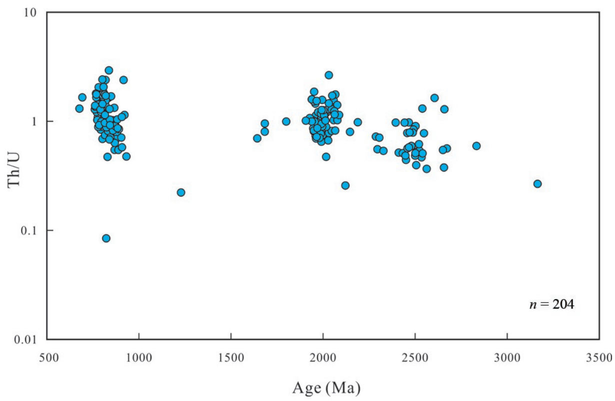

Fig. 8. Detrital zircon Th-U ratios vs. U-Pb ages diagram for sandstone samples.

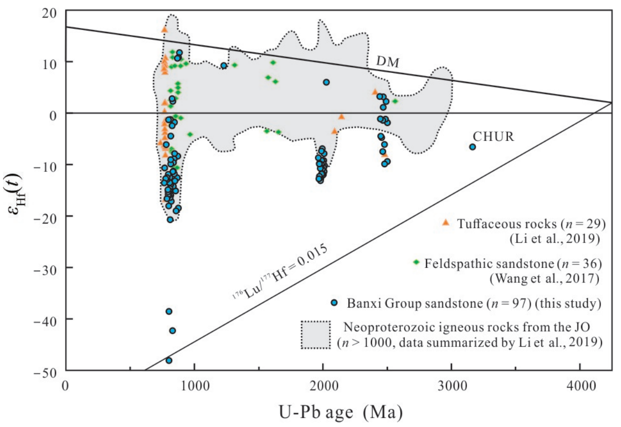

Fig. 9. Plot of $\varepsilon_{Hf}(t)$ versus U-Pb ages for the detrital zircons.

age group ranging from 677 to 3165 Ma. The data reconcentrated into three groups, i.e., 846–767 Ma, 2087–1906 Ma and 2563–2394 Ma. Each group has peak ages of ~805 Ma, ~1990 Ma, and ~2470 Ma, respectively.

4.4 Zircon Th/U ratios and trace elements

The zircon uranium content varies from 14.5 to 466.5 ppm, Th content ranging from 14.8 to 853.5 ppm. Most zircon grains have Th/U ratios greater than 0.1 (Fig. 8), implying that most of them were derived from igneous protoliths. Almost all zircon grains have similar chondrite-normalized rare-earth element (REE) patterns, which show strong enrichment in heavy REE (HREE) and depletion in light REE (LREE). All samples (Suppl. Table 3) show moderate negative Eu anomalies (δEu = 0.13–0.74) and a definite presence of positive Ce anomalies (δCe = 1.07–482.9), which further confirm that they are magmatic zircons (Hoskin and Schaltegger, 2003; Hoskin, 2005).

The younger zircons (846–767 Ma) are more enriched in heavy REE (HREE) and Y, Nb than older zircons (932–849 Ma) in the Neoproterozoic group.

4.5 In-situ Hf isotope composition

Lu-Hf isotope analyses were carried out on 94 dated zircons which showed concordant U-Pb ages from the two sandstone samples. The results are presented in Suppl. Table 4. For the Banxi Group sandstone, its Hf isotopic model ages mainly range from 3.6 to 1.0 Ga, with two age peaks at −3.2 Ga and 2.6–2.4 Ga. Most of the Neoproterozoic zircon $\varepsilon_{Hf}(t)$ values are negative (from −47.43 to −0.61, concentrated between −20 and 0, ave. −12, Fig. 9). The Neoarchean ages (mean T_{DM}^{C} = 2.6–2.5 Ga) suggest the involvement of an old crustal component in the magmas from which these zircons crystallized.

Two grains with U-Pb ages of 832 Ma, 826 Ma, yield positive $\varepsilon_{Hf}(t)$ values of +3.0 and +3.5, which is evidence of the addition of mantle material. Three early Neoproterozoic grains yield ages of 908–868 Ma with high positive $\varepsilon_{Hf}(t)$ values from +11.3 to +12.4, which are very close to their crystallization age (mean T_{DM} = 0.97–0.94 Ga, mean T_{DM}^{C} = 1.03–0.97 Ga), suggesting crystallization from juvenile mantle magmas. Except for one grain with a U-Pb age of 2027 Ma yielding a positive $\varepsilon_{Hf}(t)$ value of +6.73, all the middle Paleoproterozoic zircons have negative $\varepsilon_{Hf}(t)$ values (−12.65 to −6.21, Ave. −9.8), with model ages focused on Meso-Paleoarchean (mean T_{DM}^{C} = 3.3–3.1 Ga). For Neoarchean zircons, $\varepsilon_{Hf}(t)$ values could be divided into two groups, i.e., the negative values (−9.16 to −0.6) with model ages 3.5–2.9 Ga and the positive values (1.0 to 3.9) with model ages 2.9–2.7 Ga.

5 Discussion

5.1 Provenance of the Banxi Group

The index of compositional variability (ICV = 1.17–1.48) being >1 indicates that the sandstone samples have a low content of clay minerals with high compositional maturity and chemical maturity, indicating their first deposition in the tectonic active zone (Cullers, 2000). The CIA (45.22–60.33) and CIW (45.75–65.54) values of the sandstones reflect a low degree of chemical weathering in the sedimentary environment, which was mainly a cold, dry and strongly tectonic environment (Nesbitt and Young, 1982). The correlation between ICV and CIA is poor (R2 = 0.55), although the source of Jiajiantian Formation is involved in the recycling of ancient sediments, indicating that the chemical alteration index CIA is not affected by the sedimentary recycling, which can reflect the true degree of chemical weathering.

Considering that the rocks underwent metamorphic recrystallization, the rare earth elements (REE), high field strength elements and some transition elements (such as Co) were chosen to identify the source composition of the clastic rocks. In general, elements Sc, Ni, Co, Cr and V tend to be enriched in mafic rocks, while elements La, Th, Zr and Hf tend to be enriched in felsic rocks (Taylor and McLennan, 1995). Sandstone samples from the Banxi Group have medium ($Fe_2O_3^T$ + MgO) (1.81%–7.78%, mean: 3.79%), low Al_2O_3/SiO_2 (0.11–0.24, mean: 0.15) ratios and show high concentrations of Th, Zr and LREE. In the Th/Sc-Zr/Sc (McLennan et al., 1993) (Fig. 10a) and Co/Th–La/Sc diagrams (Gu et al., 2002) (Fig. 10b), the samples all fall in the felsic rock-acidic rock (granite) area, with an obvious tendency towards deposition recirculation. The REE content of the sandstone samples also suggests that the source rocks are mainly granitoids (Allègre and Minster, 1978) (Fig. 10d). In the Hf-La/Th diagram (Floyd and Leveridge, 1987) (Fig. 10c), the

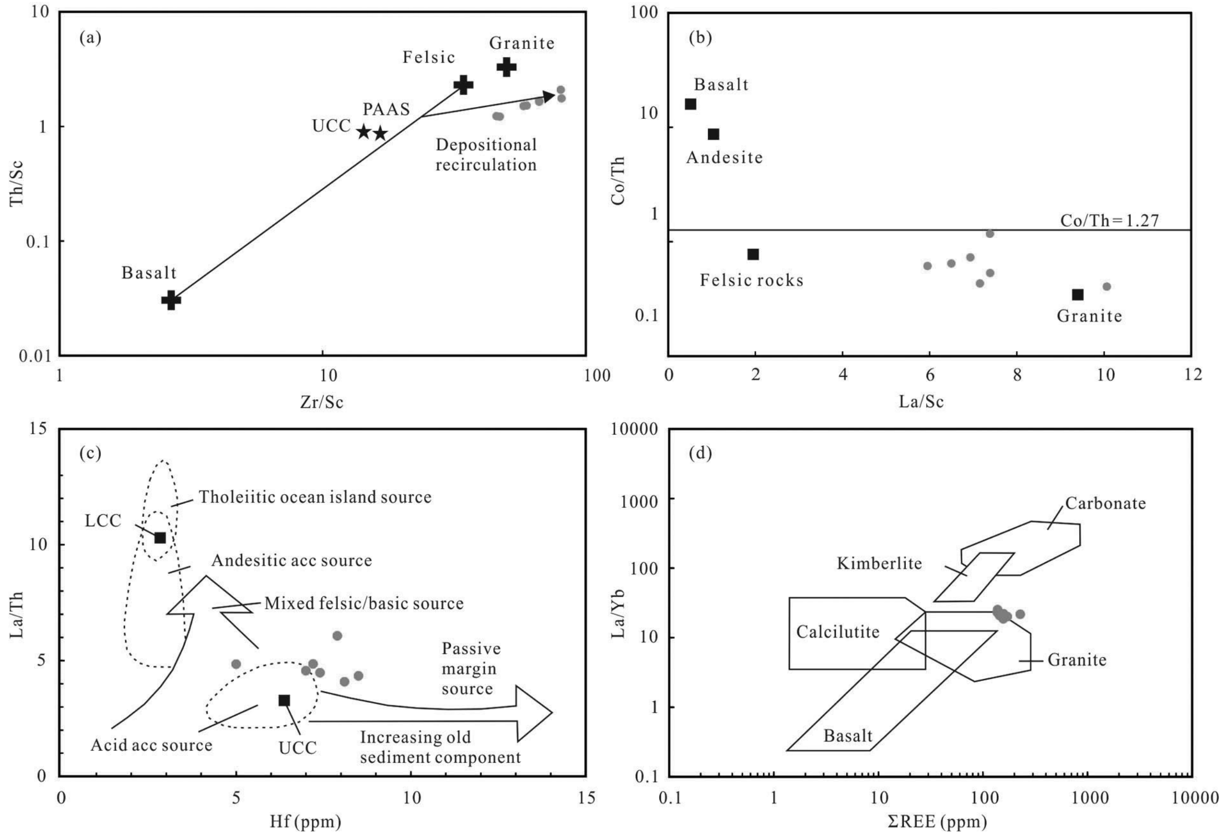

Fig. 10. Geochemical diagram of trace elements of the Banxi Group sandstone.
(a) Zr/Sc-Th/Sc diagram of sandstone from the Banxi Group northwest Hunan Province (modified from McLennan et al., 1993); (b) La/Sc-Co/Th diagram of sandstone from the Banxi Group northwest Hunan Province (modified from Gu et al., 2002); (c) Hf-La/Th diagram of sandstone from the Banxi Group northwest Hunan Province (modified from Floyd and Leveridge, 1987); (d) ΣREE-La/Yb diagram of sandstone from the Banxi Group northwest Hunan Province (modified from Allègre and Minster, 1978).

samples have the characteristics of upper crustal rocks, a small amount of felsic and basic rocks being added, along with a large amount of ancient continental crustal material.

U-Pb ages of detrital zircons from the Banxi Group reveal that the rocks were derived from a variety of sources, including Neoproterozoic, middle Paleoproterozoic and Neoarchean components. Previous studies have shown that, in contrast to the Yangtze plate, the Neoproterozoic age peak of detrital zircons from the Cathaysia plate is concentrated in the early Neoproterozoic (~960 Ma). The age peaks of Neoproterozoic and Paleoarchean detrital zircons from the eastern (~858 Ma, ~812 Ma; ~2480 Ma) and western ends of the Yangtze Block (~920 Ma, ~810 Ma; ~2320 Ma) are also different (Li et al., 2012). Recent studies have shown that the pattern of the detrital zircon age spectrum of the Jiangnan Orogen is almost consistent with that of the Yangtze Block, but significantly different from that of the Cathaysia Block (Yan et al., 2019). According to the three age peaks of the zircons, the source rocks were closer to the eastern Yangtze Block than to the western Yangtze Block and the Cathaysia Block (Wu et al., 2010; Li et al., 2012; Wang et al., 2014; Zhang et al., 2015).

Previous research results showed that during 945 Ma to 740 Ma, large-scale magmatic activities occurred in the Yangtze Block range (Zhou et al., 2004, 2009), which could largely be related to the aggregation and cracking of the Rodinia supercontinent (Li et al., 2003b). Based on collision events, these magmatic activities can be divided into subduction-collision and post-collision rifting (extensional) stages, including subduction-related ophiolites and island arc magmatic rocks, collision-related granites, and post-collision bimodal magmatic rock (Shu, 2012). These magmatic activities are thought to correspond to various tectonic processes, including ocean-ocean subduction, arc-continent collision, ocean-continent subduction, opening of back-arc basins and post-orogenic extension (Wang et al., 2017), with different models dividing the corresponding tectonic setting for magmatic activities of different duration.

The Neoproterozoic volcanic rocks in the Western JO are mainly distributed in North Guangxi and Southwest Hunan, including the 830 to 800 Ma syn-or post-collisional granitic rocks (Yao et al., 2014b) and 828–805 Ma ‘arc-related’ granitic rocks (Bai et al., 2010; Du et al., 2017), as well as a few mafic-ultramafic intrusive rocks. However, the coeval zircons with obviously positive $\varepsilon_{Hf}(t)$ values, which were from the magmatic rocks in the northeast of Hunan, the central part of the Jiangnan Orogen, were derived from distinct sources (Zhang et al., 2011; Shan et al., 2017; Xin et al., 2017). The several early Neoproterozoic zircons with positive $\varepsilon_{Hf}(t)$ and a young modal age are probably related to the volcanic arc in the central and eastern JO. In our research, the Neoproterozoic euhedral zircon grains imply a proximal source for the sediments, these rocks probably being the dominant provenance for the abundant detrital zircon grains from the Neoproterozoic sedimentary rocks.

Corresponding to the assembly and breakup of the Columbia supercontinent (Zhao et al., 2002, 2004; Rogers and Santosh, 2002), middle Paleoproterozoic zircons with $\varepsilon_{Hf}(t)$ values of −12.1 to −6.1 accounted for 30% of the studied zircons, indicating that the middle Paleoproterozoic rocks make up a significant part of the study region. Middle Paleoproterozoic magmatic and metamorphic rocks with ages of 1900–1700 Ma have been reported from the Cathaysia Block in South China (Li, 1997; Yu et al., 2009), while in the Yangtze Block, metamorphic-magmatic events occurred between 2100 Ma and 1850 Ma (Peng et al., 2009; Qiu et al., 2015). The Kongling Complex recorded structural and magmatic events from 2.1–2.0 Ga deposition to ~2.0 Ga collision (high-pressure metamorphism) and syn-collisional partial melting to ~1.85 Ga post-collisional extension (Yin et al., 2013). Zircons from middle Paleoproterozoic gneiss in the Kongling area are variably discordant and have relatively low Th/U ratios (Wu et al., 2008), suggesting that these zircon grains were magmatic in origin and underwent different degrees of metamorphic recrystallization (Hoskin and Black, 2000). Although there are contemporaneous magmatic zircons from S-type granites (Li et al., 2014), almost none of these are metamorphic zircons (Th/U < 0.1), indicating that the Kongling Complex was not the major source, but rather eroded or unexposed middle Paleoproterozoic basement, that was related to the magmatic event in the Kongling area at ~2.0 Ga. These results indicate a high possibility that the Columbia supercontinent-related orogen lies under the western Jiangnan Orogen (Su et al., 2014).

The existence of the ~2.5 Ga zircon population in the Banxi Group has particular significance. Zheng et al. (2006) proposed a widespread Archean basement for the Yangtze Block, with other studies on detrital zircons confirming the existence of Archean basement in the Yangtze Block. The Kongling area is one of the main areas for these rocks, where the Kongling Complex is composed of TTG gneiss, Kuntz series and metamorphic rocks (Peng et al., 2012). In the northern margin of the Yangtze Block, numerous zircons with an age peak of about 2.49 Ga and negative $\varepsilon_{Hf}(t)$ values indicate the presence of corresponding source rocks in this area (Liu X M et al., 2008; Hu et al., 2013). However, the predominant Mesoarchean ages (3.2–2.6 Ga) of the Kongling Complex, representing magmatic events during an important period of the crustal growth of the Yangtze Craton, indicating an insignificant contribution of Kongling materials.

On the other hand, old detrital zircons from the Cathaysia Block (comprising the Badu Complex and middle Paleoproterozoic granites) yielded a single age peak of ~2.5 Ga, with large Hf-isotope variations (Yu et al., 2012). This may be one of the source areas for our Neoarchean detrital zircon population. Considering the existence of metamorphic edges, the transported zircons may be older than middle Paleoproterozoic.

In summary, sandstone samples from the Banxi Group are mainly composed of ancient continental clastic material, the little Neoproterozoic volcanic material present in the Western JO being the main provenance of the abundant detrital zircons, while the middle Paleoproterozoic zircons are derived from an earlier rock in the Yangtze Plate that has not experienced severe metamorphism. The Archean zircons may be derived from the Cathaysia Block, or from the northern margin of the Yangtze Block.

5.2 Implications for the magmatism

Zircon is particularly resistant to alteration and metamorphism, thus preserves the initial isotopic compositions of its source magma at the time of crystallization (Fedo et al., 2003; Griffin et al., 2004). Titanium content in zircon can be used for thermometry and trace element composition analysis, such as REE and Y of zircon, which can provide the chemical and physical conditions of the melt from which the zircon crystallized, with the objective of reconstructing the magmatic evolutionary history and constrain the properties of the magma source. In particular, for the igneous rocks which have been totally eroded or reworked, detrital zircon can be used as a powerful tool to constrain its age and the possible occurrence of magmatism in the surrounding area (Sun et al., 2008; Fralick et al., 2009).

In our data, Neoproterozoic zircons have a wide range of Hf and Ti contents, indicating crystallization from an evolving magma. Low Hf contents (<8000 ppm) for 17 of the 85 zircon grains suggest that their origins are related to a relatively mafic magma (basaltic). Rare HREE losses of zircons imply that the magma source area was free of a garnet residual phase. High Hf contents (all >8000 ppm and most >9000 ppm) of middle Paleoproterozoic and Neoarchean zircons imply their crystallization from moderately-evolved felsic magma (Fig. 11). The low Eu/Eu* ratios and Th contents suggest fractional crystallization of plagioclase and Th-rich mineral phases, such as monazite and allanite (Hoskin and Schaltegger, 2003; Pettke et al., 2005). The middle Paleoproterozoic and Neoarchean zircons HREE enrichment degree is lower than for the Neoproterozoic zircons. Some of the zircons have relatively high LREE concentrations, flat LREE patterns and minimal Ce anomalies, which suggest the effects of fluid alteration during later hydrothermal events (Hoskin, 2005) or later orogenic fluid modification (Xia et al., 2010).

An efficient way to identify the crystallization environment of detrital zircons is based on Hf vs. U/Yb and Y vs. Th/Yb diagrams (Grimes et al., 2007), because zircons in continental granitoids possess higher U/Yb ratios with lower Hf and Y concentrations, relative to those from oceanic settings. As shown in Fig 12a and b, most of the data points are located in zircons of continental crustal origin, these zircons being mainly from S-type granites in granitic rocks of the continental crust (Wang X L et al., 2012). Compared with MORB, U and Th are relatively enriched in the arc and continental crust, while HREE (Yb), Hf and Y are slightly depleted in the

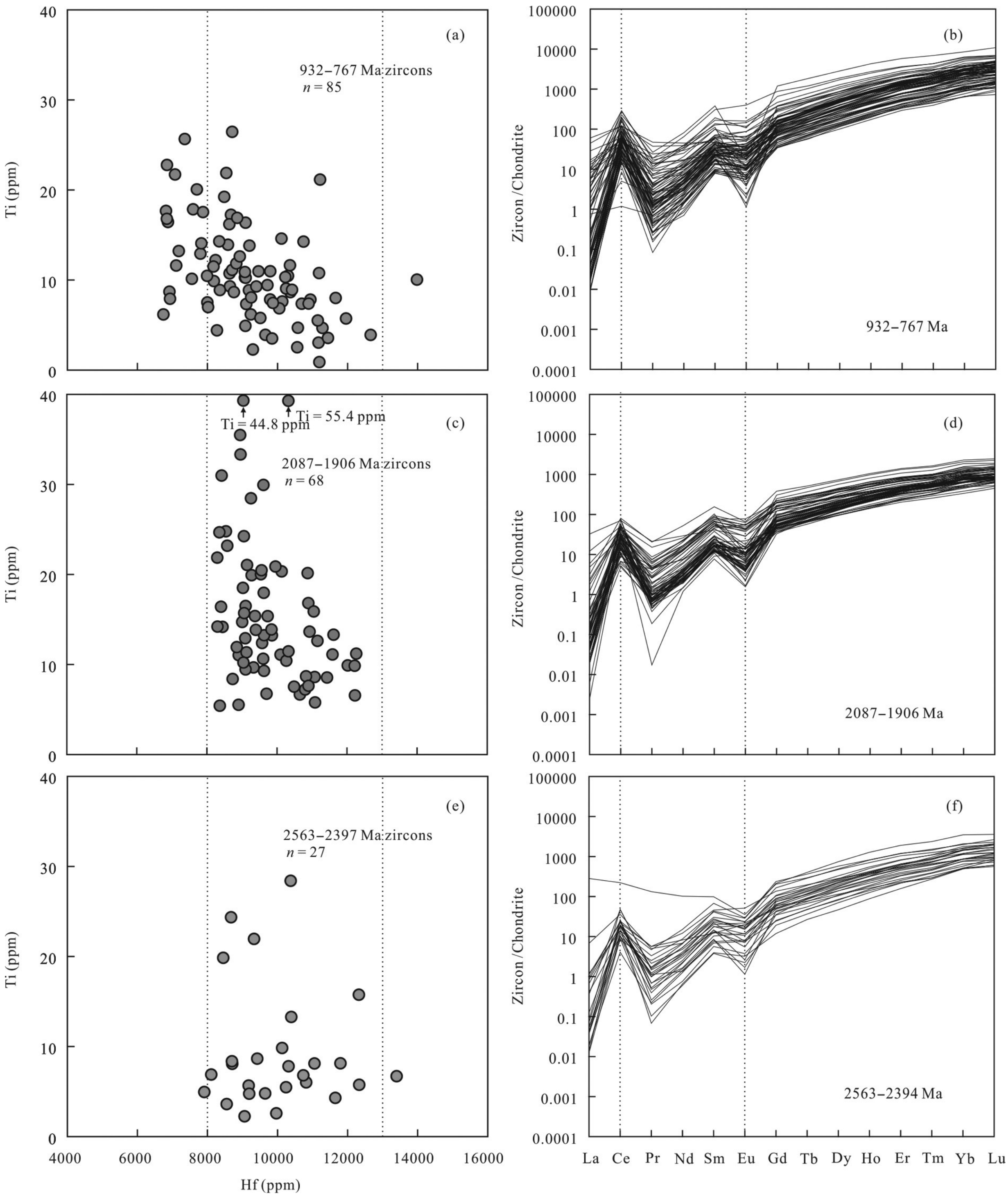

Fig. 11. Detrital zircon Ti-Hf and REE content characteristics.
(a) Neoproterozoic zircons; (b) Neoproterozoic zircons, REE compositions; (c) middle Paleoproterozoic zircons; (d) middle Paleoproterozoic zircons, REE compositions; (e) Neoarchean zircons; (f) Neoarchean zircons, REE compositions.

arc (Grimes et al., 2007). According to the zircon trace-element pattern, three types of tectonic environments, namely continental arc, mid-ocean ridge and ocean island were identified (Grimes et al., 2015). In our data, both middle Paleoproterozoic and Neoarchean zircon data plots into the VAB or continental arc area (Fig. 12f and g). Neoproterozoic zircons show the characteristics of a continental arc (Fig. 12g) and they have the same characteristics as the Neoproterozoic detrital zircons from the Madiyi Formation tuff of the Banxi Group in the Banxi area (Li et al., 2019), part of the Neoproterozoic zircons showing the characteristics of N-MORB or WPB.

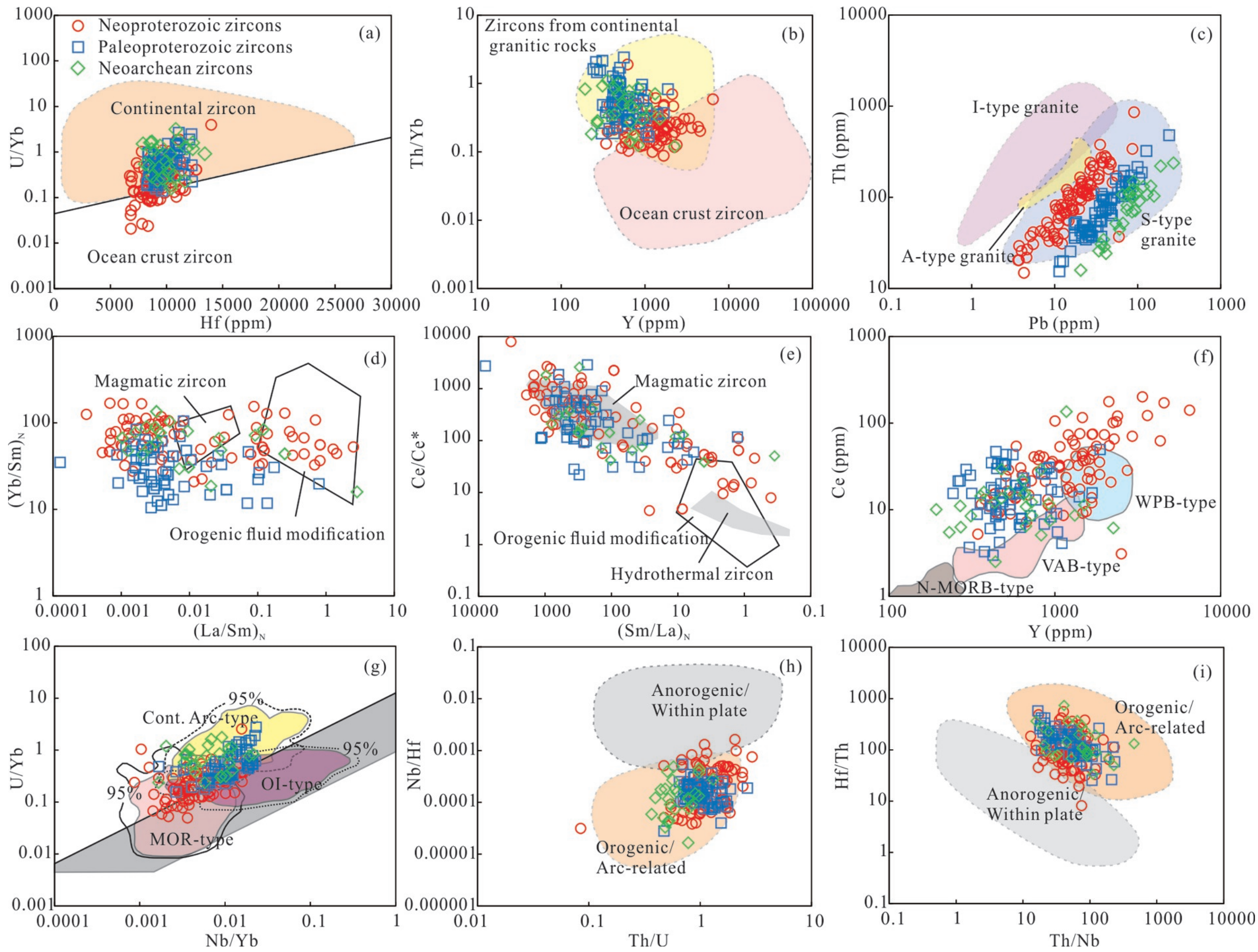

Fig. 12. Geochemical discriminant diagrams for detrital zircons from the Banxi Group in the Xuefengshan area.
(a) Hf-U/Yb diagram (modified from Grimes et al., 2015); (b) Y-Th/Yb diagram (modified from Grimes et al., 2007); (c) Pb-Th diagram (modified from Wang Q et al., 2012); (d) $(La/Sm)_N$-$(Yb/Sm)_N$ diagram and orogenic fluid modification' fields in (e) (modified from Xia et al., 2010); (e) $(Sm/La)_N$-Ce/Ce* diagram (modified from Hoskin, 2005); (f) Y-Ce diagram (modified from Schulz et al., 2006); (g) Nb/Yb-U/Yb diagram (modified from Grimes et al., 2015); (h) Th/U-Nb/Hf diagram and (i) Th/Nb-Hf/Th diagram (modified from Yang et al., 2012).

In arc magmas, Nb is generally depleted relative to within-plate settings (Sun and McDonough, 1989; Pearce and Peat, 1995). Zircons derived from such arc magmas have lower Nb/Hf and higher Th/Nb ratios than those from within-plate settings, magmatic fractionation not changing the Nb/Hf ratios in both of these two fields (Yang et al., 2012). The Neoproterozoic zircons of the Banxi Group plot in the orogenic (arc-related) field, based on their Th/Nb and Hf/Th ratios, but a few extend into the overlaps between the two fields (Fig. 12h and i). The results are consistent with the tectonic background of the coeval granites in the eastern part of the study area (Bai et al., 2010; Du et al., 2017), which were suggested to be related to ocean crust subduction, as with the S-type granites in northern Guangxi (Wang et al., 2006; Yao et al., 2014a), indicating the existence of Neoproterozoic arc volcanic activity in the area. The middle Paleoproterozoic zircons plot in the orogenic (arc-related) field, which might result from orogenic events during the convergence of the Columbia supercontinent (Zhang et al., 2006; Wang et al., 2015). Almost all the Neoarchean zircons fall within the orogenic (arc-related) field, consistent with continental crustal growth, such as the Badu Complex (a proximal volcanic arc) (Yu et al., 2012). When compared to middle Paleoproterozoic zircons and Neoarchean zircons, the content and ratio of trace elements in the Neoproterozoic zircons fluctuates greatly. This change was a result from the addition of crustal material and source region variation (Grimes et al., 2007), implying the complexity and multi-stage transition of tectonic regimes in the western Jiangnan Orogen.

5.3 Crustal evolution

Mesoarchean to Neoarchean magmatism in the Kongling area was mainly concentrated at 3.4–2.9 Ga, 3.0–2.7 Ga and 2.6 Ga (Gao et al., 1999; Guo et al., 2015; Qiu et al., 2016, 2019), this area then experiencing amphibolite to granulite facies metamorphism, corresponding to a strong collisional event, during 2.0–1.9 Ga (Li et al., 2014; Qiu et al., 2019). Furthermore, a 2.5 Ga magmatic event at the northern margin of the Yangtze craton found in the Douling Complex (Liu X M et al., 2008; Hu et al., 2013) and a 2.4 Ga granitic magmatism closely associated with the reworking of old crust are both known (Guo et al., 2015). The 2.6–2.5 Ga zircons reported in recent studies only account for a small part (15%) of modern river detrital zircons from the northern part of the Kongling area, yielding negative $\varepsilon_{Hf}(t)$ values mainly concentrated on ~3.0, corresponding to modal ages at 3.0 Ga (Han et al., 2017). In the Cathaysia Block, the Badu Complex has the oldest rocks. The positive $\varepsilon_{Hf}(t)$ of most Neoarchean zircons from the Badu Complex suggest that the detritus of its sedimentary protoliths came from a proximal volcanic arc, resulting from the growth of juvenile crust (Yu et al., 2012).

The oldest zircons found in the Banxi Group in this study yielded ages of 3165 Ma and Hf model ages near 3.9 Ga, implying the involvement of Archean continental crustal material in the magmatic evolution of the study area, similar to the oldest Archean rocks in the Kongling area (Jiao et al., 2009). The zircons of the 2.6–2.4 Ga age population have Hf model ages ranging from 2.7 Ga to 3.6 Ga in this study, which is consistent with zircons found in the contemporary sedimentary rocks from the Xiajiang Group and the Danzhou Group in the south of the Yangtze Block (Wang L J et al., 2010; Yang et al., 2015), also corresponding to the 2.5 Ga age peak of detrital zircons in the Nanhua Formation from the Yangtze Gorges area (Liu X M et al., 2008). Some zircons with positive $\varepsilon_{Hf}(t)$ values and model ages of 2.9–2.7 Ga record a crustal growth event in the source area at ~2.5 Ga.

This study has defined an important middle Paleoproterozoic event at 2.1–1.9 Ga, with an age peak of ~1990 Ma. Almost all the middle Paleoproterozoic zircon grains show negative $\varepsilon_{Hf}(t)$, with the Hf model ages ranging from 3.3 to 3.0 Ga, indicating Meso-and Paleoarchean crustal sources for the parental magmas of these zircons. In this study, it was identified that the source rocks of the Banxi Group mainly involved reworked Archean crust, with very little addition of juvenile crust. This event should be related to the magma-metamorphism event of ~2.0 Ga in the Kongling area, which, on the global scale, was associated with the assembly of the supercontinent Columbia, but the difference is that there is no record of a large-scale metamorphic event.

Early Neoproterozoic (908–857 Ma) zircons presented in this study can be subdivided into two groups, based on their Hf isotopic signatures. The first group has lower $^{176}Hf/^{177}Hf$ ratios and negative $\varepsilon_{Hf}(t)$; the second group has higher $^{176}Hf/^{177}Hf$ and positive $\varepsilon_{Hf}(t)$. The negative $\varepsilon_{Hf}(t)$ (−18.4 to −7.8) and corresponding model ages (2.9–2.3 Ga) for the first group suggest that their sources experienced a prolonged crustal evolution. The second group has positive $\varepsilon_{Hf}(t)$ (11.3 to 12.1) and Neoproterozoic model ages (1.0–0.9 Ga), indicating its origins from a 'juvenile' or mantle-derived source, which implies the occurrence of arc-related magmatism in the Western JO, resulting from arc-continent collision between the Yangtze Block and the Cathaysia Block during the assembly of the Rodinia supercontinent. The early Neoproterozoic (846–764 Ma) detrital zircons in this study have a wide range of $\varepsilon_{Hf}(t)$, which are relatively concentrated between −16 and −10. Their model ages focus on 2.6–2.5 Ga, suggesting that the magma from which these zircons crystallized was formed by re-melting of the Neoarchean crust. Some zircon $\varepsilon_{Hf}(t)$ values are close to zero, indicating the addition of mantle material or juvenile crust during the re-melting process. Several zircons with positive $\varepsilon_{Hf}(t)$ also suggest the involvement of mantle material.

In summary, Hf isotopes of detrital zircons indicate that there are three important crustal growth events in the Xuefengshan area. The ~2.5 Ga interval records a crustal growth event with the re-melting of the Mesoarchean and Paleoarchean crust. Hf model ages of middle Paleoproterozoic (~2.0 Ga) zircons range from 3.3 to 3.1 Ga, with $\varepsilon_{Hf}(t)$ lower than the new continental crust growth curve, which could be interpreted as a result of a crustal reworking event in this area (Fig. 9). The Neoproterozoic (0.9–0.7 Ga) crustal re-melting was accompanied by the addition of mantle material, manifested by significant positive $\varepsilon_{Hf}(t)$ values of numerous detrital zircons, especially those from the feldspathic litharenite (Meng et al., 2013).

5.4 Implications for the Neoproterozoic tectonic history of the western JO

At least three tectonic models have been proposed to explain the tectonic evolution of the JO, including mantle-plume (Li et al., 2003b; Wang X C et al., 2007), arc-related (Zhou et al., 2002; Wang et al., 2004, 2006; Wang et al., 2017) and plate-rift models (Zheng et al., 2008a, b; Zhang C L et al., 2013b). In the mantle-plume model, the non-orogenic magmatic activity related to mantle plume activity in South China is bimodal, there being two peak periods, one at 830–795 Ma, which occurred prior to the rifting process, the peak period being consistent with the start of the rifting process; the other is 780 to 745 Ma and is in the fracture stage (Li et al., 2003b). From the perspective of the arc-related model, the Jiangnan Orogen subsequently experienced various tectonic processes, including ocean-ocean subduction (970–880 Ma), arc-continent collision (880–860 Ma), ocean-continent subduction (860–825 Ma), the opening of back-arc basins (825–810 Ma) and post-orogenic extension (Wang et al., 2017). In the plate-rift model, the juvenile crust was reworked by several episodes of magmatism, due, respectively, to arc-continent collision at 960–860 Ma, post-collisional collapse at 830–800 Ma and rift anatexis at 780–740 Ma (Zheng et al., 2008a, b). All these models propose the convergence of the Yangtze and Cathaysia blocks, accompanied by subduction, but there are different explanations for the timing and subsequent extensional tectonics. As post-orogenic magmatism in South China is not significant and the mafic rock suites related to mantle plumes are absent, the mantle plume model (Zhou et al., 2005) may not be valid. Geochemical and Nd isotopic features of sedimentary rocks from the Neoproterozoic sedimentary sequences also imply that there was no Neoproterozoic flood basalt province in the Yangtze Block (Wang W et al., 2012). Additionally, neither the plume-rift model nor the slab-arc model is applicable to the origin of the magmatic rocks in the Jiangnan Orogen formed in cratonic rift settings from 825 Ma to 740 Ma (Zheng et al., 2008b).

Bhatia and Crook (1986) proposed a series of trace element discrimination diagrams, after comparing the REE characteristics of the greywacke in five strata of eastern Australia with the standard chondrite model of modern orogenic volcanic rocks. In these figures (Fig. 13 a–e), most of the samples fall into the passive continental margin region, indicating that the sedimentary environment of these sandstones is that of a passive continental margin. Differing from the Lengjiaxi Group, which was deposited in a back-arc basin, the Banxi Group formed during the uplift and collapse of the Jiangnan Orogen in a post-collisional stage (Wang W et al., 2010, 2012; Zhang et al., 2019).

Understanding the tectonic environmental change from Lengjiaxi Group to Banxi Group and the tectonic setting of the magmatic rocks in the Western JO are critical to interpretation of the Neoproterozoic crustal evolution processes in South China. There are no significant differences in geochemical compositions (major and trace elements) between the Mesoproterozoic Lengjiaxi Group and the Neoproterozoic Banxi Group, except for the relatively higher concentrations of ferromagnesian elements in the former (Gu et al., 2002). The Banxi Group has slightly enriched Nd isotopic signatures relative to the Lengjiaxi Group, implying a higher percentage of old continental material in the sedimentary source (Wang W et al., 2010). Sediments in the Western JO may have been located far from arc terranes to the east and thus received more older recycled detritus from the southern part of the South China craton (Wang et al., 2014). The Hf-O isotopes and U-Pb ages of the zircon grains show early Neoproterozoic ages (1.0–0.7 Ga) and thus appear to have witnessed significant juvenile crustal growth in South China (Wang W et al., 2012; Wang et al., 2014). Zircons from the Lengjiaxi Group and the Banxi Group both exhibit a rapid increase in $\varepsilon_{Hf}(t)$ values during 850–800 Ma (Wang W et al., 2010; Meng et al., 2013; Wang et al., 2017), suggesting a large increase in mantle input. The 830–750 Ma zircons mainly crystallized from juvenile igneous rocks, while the 750–700 Ma zircons crystallized from new mantle-derived rocks (Wang W et al., 2012). Zircon U-Pb geochronological, elemental and Sr-Nd-Hf-O isotopic data from mafic-ultramafic rocks in the Jiangnan Orogen reflect the South China craton's transformation into a lithospheric extensional regime since ~785 Ma, in response to the Rodinia break-up (Wang C et al., 2019). In our data, Neoproterozoic zircons in the sandstone

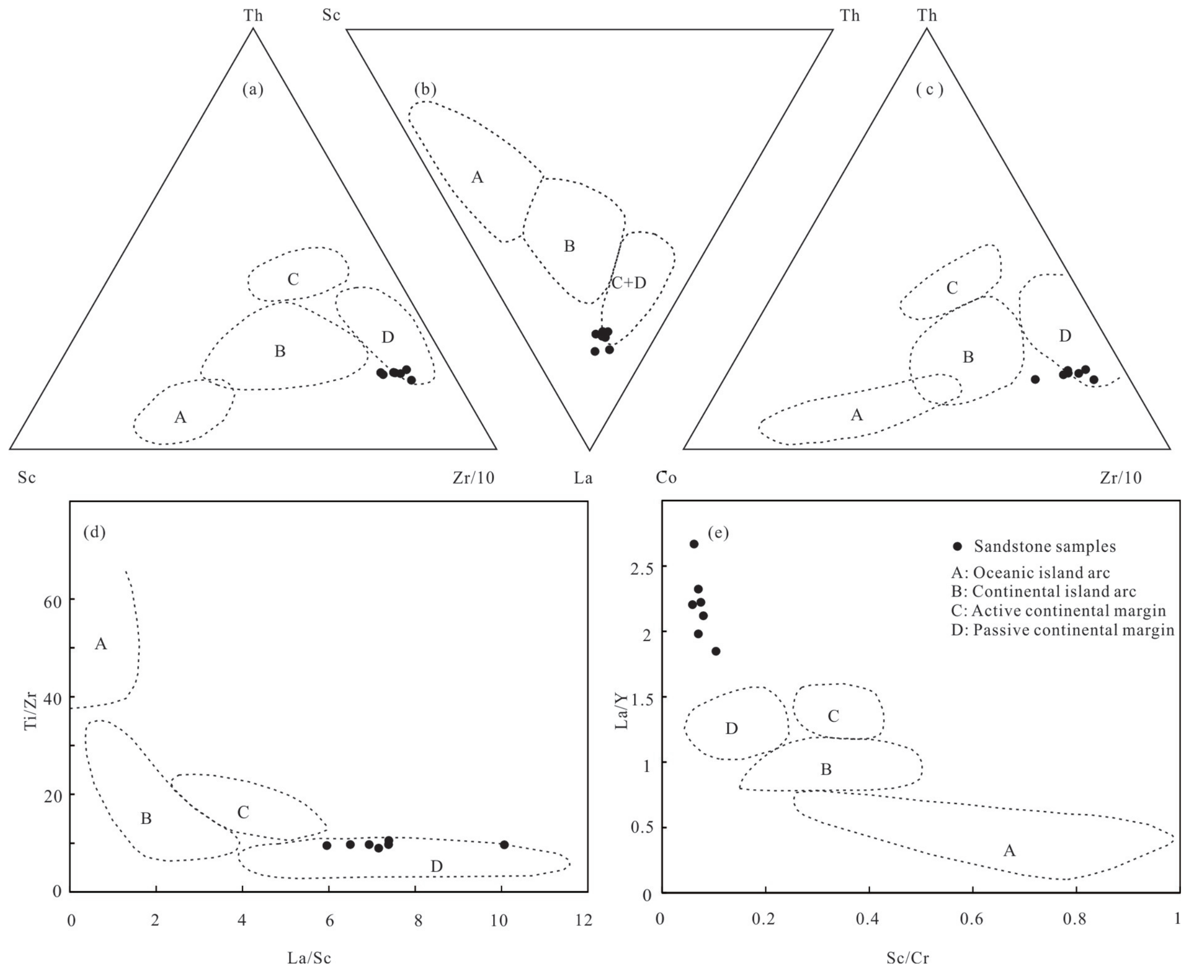

Fig. 13. Tectonic discrimination diagrams from the Banxi Group sandstone.
(a) Th-Sc-Zr/10; (b) La-Th-Sc; (c) Th-Co-Zr/10; (d) La/Sc-Ti/Zr; and (e) Sc/Cr-La/Y (modified from Bhatia and Crook, 1986)

samples with a peak age of 805 Ma show the characteristics of a continental arc, even though the sedimentary environment of these sandstone samples is that of a passive continental margin. This information can be fitted to a modified plate-rift model to describe the Neoproterozoic tectonic evolution of the western JO as follows.

(1) Ocean-continent subduction (860–825 Ma). Although the coeval (980–880 Ma) arc-related magmatic rocks in the central and Western JO remain to be further identified, the NW-dipping subduction (present coordinates) between Yangtze and Cathaysia blocks has been confirmed in previous studies (Wang et al., 2017). From 860–825 Ma, the active continental margin in the Yangtze Block is characterized by massive peraluminous granitic magmatism (Xia et al., 2018). Some arc related-ultramafic rocks have been identified in the Western JO, suggesting the continuous subduction effect, constraining the time of the final collision between the Yangtze Block and the Cathaysia Block to <830 Ma (Zhou et al., 2003, 2009; Chen et al., 2014; Yao et al., 2014a, b; Lin et al., 2016).

The Neoproterozoic igneous rocks in the Western JO are predominantly composed of granites and mafic intrusions with ages of 860–740 Ma (Wang et al., 2006; Xue et al., 2012; Chen et al., 2014; Yao et al., 2014a; Wang Y J et al., 2019) and these can be divided into three stages in southeastern Guizhou and northern Guangxi (Dai et al., 2019). The first stage of magmatic activity occurred from 861 to 822 Ma and was related to the arc and collision setting (Lin et al., 2016; Yao et al., 2014a, 2017), while the second stage (814–805 Ma) might indicate the post-collisional stage of the South China continent. The third stage (780–740 Ma) is related to either slab delamination (Wang X C et al., 2007; Wang X L et al., 2007; Wan et al., 2019) or mantle plume activity (Zhou et al., 2007).

(2) Continent-continent collision (825–805 Ma). The upper age limit of the Lengjiaxi Group in the central Jiangnan Orogen is probably ca. 825 Ma, which indicates that the closure time of the back-arc basin is also ca. 825 Ma (Wang et al., 2014, 2017) and zircon U-Pb age data for the Lengjiaxi Group and the Banxi Group and other contemporaries indicate that the collision occurred at 825–815 Ma (Zhao, 2015). A set of integrated geochemical and geochronological data for the high-Mg volcanic sequence bounded by the Lengjiaxi and Banxi groups implies that the final amalgamation of the Yangtze with the Cathaysia Block along the Jiangnan domain probably occurred between 815 Ma and 822 Ma (Zhang Y Z et al., 2012). According to the peak age of the formation of peraluminous granitic magmatism at 825 Ma (Charvet, 2013; Wang et al., 2014) and bimodal magmatism at 805 Ma (Wang X L et al., 2012; Yao et al., 2014b), Xia et al. (2018) proposed that the collision occurred at 825–805 Ma, the intra-oceanic arc zone and the active continental margin of the Yangtze Block changing to within-plate regime after 805 Ma. The final closure of the arc-trench-basin system was associated with the amalgamation of the intra-oceanic arc and the Yangtze Block, leading to the folding of the Lengjiaxi Group and its stratigraphically equivalent basement sequences. Zhao (2015) proposed that the Jiangnan orogenic belt was formed by soft collision between the Yangtze and Cathaysia blocks, without involvement of continental deep subduction, high-grade metamorphism of continental crust and uplift/exhumation of high-grade metamorphic rocks. There is also no imprint for the collision-related metamorphism in our Neoproterozoic zircons.

During the continent-continent collision, a fair quantity of post-collisional granitoids intruded the folded sedimentary sequences in the Yangtze Block (Xia et al., 2018), such as the 829–819 Ma post-collisional S-type granitoids commonly occurring in the Sanfang, Bendong and Yuanbaoshan areas in northern Guangxi Province (Wang et al., 2006; Wan et al., 2019). Neoproterozoic granites near the Xuefengshan area are characterized by island arcs (Bai et al., 2010; Du et al., 2017). It is likely that the source area has been affected by subduction, resulting from the partial melting of a mixed source of juvenile island arc crust and ancient basement (Xia et al., 2018).

(3) Post-collisional extension and continental rift development (805–750 Ma). Following continent-continent collision, the Jiangnan Orogen underwent post-collisional extension. A series of bimodal alkaline rocks at 780–750 Ma include the Qianyang and Longsheng alkaline gabbro-diabase, the Guzhang alkaline diabase and the Tongdao mafic rocks, which are suggested to have formed during the post-orogenic stage (Wang X L et al., 2004, 2007; Liu et al., 2019; Wan et al., 2019), consistent with the structural settings of slab break-off or delamination of the thickened subcontinental lithosphere as an intra-continental rift (Wan et al., 2019). These rocks serve as important indicators of the large-scale upwelling of the asthenospheric mantle and the transition from orogenic to post-orogenic tectonic setting (Liu et al., 2019).

6 Conclusions

(1) The sandstones of the Banxi Group in Zhongfang County, Western JO, formed in a passive continental margin environment, their clastic materials being derived from Neoproterozoic volcanic rocks and ancient continental crust materials to the southeast of the Yangtze plate.

(2) Detrital zircons from two sandstone samples show three age peaks, the main peak at 805 Ma and two sub-peaks of 1990 Ma and 2470 Ma, representing three important magmatic events.

(3) The Hf model ages of detrital zircons record three significant crustal growth events at ~0.9 Ga, ~2.0 Ga and ~2.5 Ga in this area, involving reworking of older crust, as well as mantle material addition. The middle Paleoproterozoic detrital zircon data suggest the probable existence of a Columbia-aged orogen under the western Jiangnan Orogen.

(4) Trace element characteristics of detrital zircons suggest that the magma that produced these zircons is related to continental arc but was emplaced in an extensional setting, related to the rift event.

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