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Zircon U–Th–Pb–Hf isotopes of the basement rocks in northeastern Cathaysia block, South China: Implications for Phanerozoic multiple metamorphic reworking of a Paleoproterozoic terrane

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ABSTRACT

The Cathaysia block records a complex tectonic history, the understanding of which is central to the debate on the evolution of the South China Block and its position in various supercontinent assemblies. Here we investigate two key formations from this block, the Mayuan Group in the northern Fujian Province, northeastern Cathaysia block and its equivalent the Badu Group in southwestern Zhejiang Province. Previous studies traced the Paleoproterozoic records from the Badu Group whereas a Neoproterozoic age was proposed for the Mayuan Group. The rocks sampled in this study from both groups show similar mineral assemblages of garnet + sillimanite + biotite + plagioclase + quartz ± K-feldspar ± muscovite ± graphite as well as high contents of SiO_2 and Al_2O_3, typical of amphibolite- to granulite-facies metapelitic rocks. Zircon U–Pb data yield two discordia intercept ages of ~1990 Ma and ~2450 Ma from one sample and discordia intercept ages of ~3.5 Ga, 2.5 Ga, 1.86 Ga and 233 Ma from another in the Badu Group. Zircons in two samples from the Mayuan group yield intercept ages of 1859 Ma and 249 Ma in one sample and ~2.6 Ga, 1.87 Ga, 257 Ma and a weighted mean $^{206}Pb/^{238}U$ age of 248 Ma in the other. The ca. 1.86–1.87 Ga and 230–250 Ma ages are interpreted to represent the time of metamorphic reworking because zircon grains of these ages tend to have low Th/U ratios, flat HREE patterns and unzoned internal texture as revealed by cathodoluminescene (CL) images. These results confirm that the Badu Group is a Paleoproterozoic lithostratigraphic unit and also suggest that at least part, if not all, of the Mayuan Group is Paleoproterozoic.
Evidence for Paleozoic metamorphic reworking that is considered to have affected the whole of Cathaysia block is not revealed in this study; in contrast our data clearly show obvious Mesozoic metamorphic reworking at ca. 230–250 Ma. Zircon $\varepsilon_{Hf}(t)$ values range from −19 to +11 with a peak at −5.5 and show $T_{DM}^{C}(Hf)$ ranging from 1.9 to 4.1 Ga with a peak at ca. 2.7–3.0 Ga suggesting that a major crustal growth took place during this time. This interpretation is consistent with the previously suggested crustal growth peaks of ~2.7 Ga and ~2.9Ga. A synthesis of the reliable geochronological data gathered so far on Phanerozoic metamorphic reworking of the northeastern Cathaysia block reveals that the imprints of these tectonothermal events is differently distributed in the different zones. Rocks metamorphosed during the Paleozoic tectonothermal event dominantly occur in the western zone whereas those reworked by high-grade metamorphism during the Mesozoic tectonothermal event mainly outcrop in the eastern zone. Our study alerts the previous notion of a uniform distribution of the reworked rocks by high-grade metamorphism all across the northeastern Cathaysia block and provides new insights on the evolution of the South China Block.

1. Introduction

The Cathaysia block is one of the two constituent blocks of the South China Block (SCB, also called the South China Craton by some geologists), the other one being the Yangtze block (Fig. 1A). It is generally accepted that the two blocks amalgamated during early Neoproterozoic to form the SCB (Shu and Charvet, 1996; Zhao and Cawood, 1999; Li et al.,

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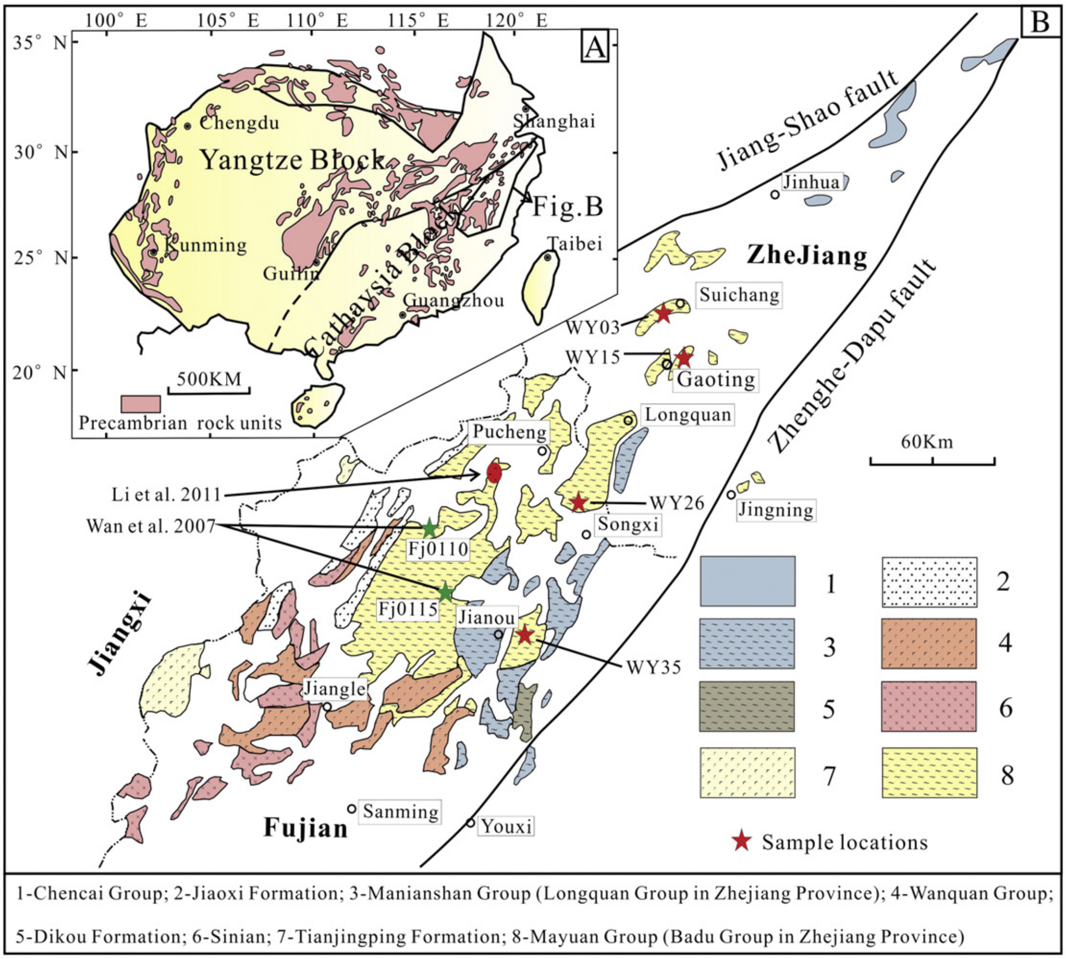

Fig. 1. Simplified geological map of South China (A) and basement areas of the northeastern Cathaysia block (B). (A) Distribution of Precambrian rock units in South China. (B) Precambrian lithostratigraphic units of the northeastern Cathaysia block showing sample locations of present study. The map is modified after Hu et al. (1991); Fujian, BGMR (Bureau of Geology and Mineral Resources of Fujian Province) (1985); Wan et al. (2007); Yu et al. (2010).

2002; Li and Li, 2007; Zhao and Cawood, 2012; Cawood et al., 2013; Li et al., 2013; Zhai, 2013; Zheng et al., 2013). Basement rocks of the Yangtze block are exposed in the Kongling terrane (Gao et al., 1999; Qiu et al., 2000; Zhang et al., 2006 and references therein) and in the Huji region (Z. Wang et al., 2013). However, the issue of spatial and temporal distribution of the basement rocks in the Cathaysia block has remained controversial.

Huang (1960) referred to the Cathaysia block as a Caledonian Fold belt which suggested that the Archaean to Proterozoic basement rocks proposed by Grabau (1924) might not exist. However, in the 1990s, Hu et al. (1991), Fu et al. (1991), Gan et al. (1993, 1995) and several others reported Archaean to Paleoproterozoic ages from rocks outcropping in the Fujian and Zhejiang Provinces, northeastern Cathaysia block, using conventional single- or multi-grain TIMS or Sm–Nd and Rb–Sr isotopic methods. These studies established occurrence of the Neoarchean Tianjingping Formation, Paleoproterozoic Badu and Mayuan Groups, Dikou and Taoxi Formations, Mesoproterozoic Mamianshan, Longquan and Wanquan Groups, and Jiaoxi Formations (Fig. 1B). The results showed that the Cathaysia block possesses Archaean to Paleoproterozoic basement. However, the models from these new findings lasted only for less than a decade when Li (1997), Yu et al. (2005), Wan et al. (2007) and Xu et al. (2010) published in-situ zircon U–Pb results and argued that the rocks in many of the groups and formations mentioned above are younger than the timings assigned to them previously. Thus, the Tianjingping Formation might be Paleoproterozoic (younger than 1766 Ma, Li, 1997; Wan et al., 2007), and the Mayuan, Wanquan and Mamianshan Groups, the Dikou, Tiaoxi and Jiaoxi Formations might all be Neoproterozoic. However, the Badu Group, which is the equivalent lithostratigraphic unit of the Mayuan Group in Zhejiang Province, has been considered to be Paleoproterozoic (Yu et al., 2009; J.-H. Yu et al., 2012; Zhao et al., 2014). The rock assemblages of the two groups extend continuously across the two provinces without any fault or stratigraphic unconformity, although distinct ages were proposed for them.

The metasedimentary rocks of the Badu Group are believed to have experienced an episode of granulite-facies metamorphism during late Paleoproterozoic (1.85–1.89 Ga; J.-H. Yu et al., 2012; Zhao et al., 2014). J.-H. Yu et al. (2012) concluded that this episode of metamorphic reworking caused extensive zircon overgrowth and the formation of the kyanite + K-feldspar + biotite + garnet + quartz assemblage. Zhao and Zhou (2012) studied the metamorphic evolution of the pelitic granulites of the Badu Group and they gave the peak P and T conditions of 0.6–0.7 GPa and ~850 °C. Also, the metamorphic P–T path of the granulites is clockwise. Charnockites formed synchronously with the Paleoproterozoic metamorphism have also been found in the Badu Group whose formation temperatures are believed to be >850 °C (Zhao et al., 2014). Zhao and Cawood (1999) studied the metamorphic rocks sampled from the Mayuan Group and they gave peak metamorphic P and T conditions of ~1.2 GPa and ~650 °C and these samples also recorded a clockwise P–T path.

Phanerozoic reworking related to amphibolite- to granulite-facies metamorphism has also been identified as an important feature of the Cathaysia block (Lin et al., 2008; Faure et al., 2009; Li et al., 2010; Zhao and Cawood, 2012; Y. Wang et al., 2013a and references therein), like the Paleozoic granulite-facies metamorphism and synchronous

Charnockites in the Yunkai and Nanling area, southwestern Cathaysia block (Yu et al., 2005; J.H. Yu et al., 2007; Wan et al., 2010; D. Wang et al., 2013a and references therein), the Mesozoic amphibolite- to granulite-facies metamorphism in the Badu Group (J.-H. Yu et al., 2012; Y. Wang et al., 2012). Li et al. (2010), based on a synthesis of their own and some of the previous results on geochronology and metamorphic evolution, developed the model of Caledonian fold belt proposed by Huang (1960) and argued that most of the Cathaysia block belongs to a Paleozoic orogen, the Wuyi-Yunkai orogenic belt, which is similar to the classic Caledonian orogen in Europe. However, new evidence is accumulating which show that a significant part of the so-called Wuyi-Yunkai orogenic belt might not belong to the Paleozoic reworked zone. Rather, it shows more obvious characteristics of Mesozoic metamorphic reworking and the rocks exposed in this area show very few evidence for Paleozoic metamorphic reworking (Shu et al., 2008; Y. Wang et al., 2012; Zhao and Cawood, 2012; Mao et al., 2013; Y. Wang et al., 2013a and references therein). Thus, more work is needed to resolve the spatial distribution of the basement rocks, particularly those in the Badu and Mayuan Groups, and also to demarcate the zones reworked by the two episodes of Phanerozoic metamorphism of the Cathaysia block. These issues have important implications on the evolution and configuration of the Eurasian continent and the geodynamics processes of the region.

In this paper, we present petrographic observations, whole rock geochemistry and zircon U–Th–Pb–Hf and trace element analyses of metasedimentary rocks from both the Badu and Mayuan Groups. The results show that at least part, if not all, of the Mayuan Group is Paleoproterozoic, with records of Paleoproterozoic and Mesozoic metamorphic reworking similar to the rocks in the Badu Group.

2. Geological background

The study area lies in the northeastern Cathaysia block, and is a northeast–southwest trending region bounded by the Jiao-Shao fault in the northwest with the Neoproterozoic Jiangnan Orogen and by the Zhenghe-Dapu fault in the southeast with the coastal areas of the Cathaysia block. The Jiangnan Orogen, which is mainly composed of Neoproterozoic ophiolites, granitoids, volcanic and sedimentary rocks, is believed to be the suture zone along which the Yangtze and Cathaysia blocks amalgamated to form the SCB (Gao et al., 2009; Li et al., 2009; Q. Wang et al., 2010; W. Wang et al., 2012; X.-L. Wang et al., 2012; A. Zhang et al., 2012; S.-B. Zhang et al., 2012; Y. Zhang et al., 2012; Cawood et al., 2013; Li et al., 2013; W. Wang et al., 2013; D. Wang et al., 2013b; Yao et al., 2013; Yin et al., 2013; C.L. Zhang et al., 2013; Y. Zhang et al., 2013;). The coastal areas of the Cathaysia block are dominated by Yanshanian (140–100 Ma) magmatic rocks (Xu et al., 2007).

The Badu Group is located in the southwestern Zhejiang Province and was first established by Hu et al. (1991). The metamorphosed lithostratigraphic units occur as tectonic windows in the Phanerozoic cover (Fig. 1) (Xu et al., 2007; Yu et al., 2009; Yu et al., 2010; J.-H. Yu et al., 2012; Zhao et al., 2014). The Mayuan Group which is located in the northern Fujian Province was first established by Fujian, BGMR (Bureau of Geology and Mineral Resources of Fujian Province) (1985). Apart from the Mayuan Group, some Meso- to Neoproterozoic rock units were also established, like the Jiaoxi Formation, Wanquan and Mamianshan Groups (Fig. 1) (Fujian, BGMR (Bureau of Geology and Mineral Resources of Fujian Province), 1985; Li et al., 1997).

Hu et al. (1991) and Fujian, BGMR (Bureau of Geology and Mineral Resources of Fujian Province) (1985) gave similar descriptions for the rock assemblages of the Badu and Mayuan Groups. The Badu Group is dominantly composed of a series of metamorphosed terrestrial clastics. The rock types include biotite–plagioclase gneiss, amphibolites, amphibole–plagioclase gneiss, biotite–plagioclase–quartz gneiss, mica schist, and mica–quartz schist. Graphite, garnet, sillimanite, and sometimes kyanite are pervasive metamorphic minerals in the metasedimentary units mentioned above (Hu et al., 1991). The Mayuan Group is composed of a series of proximal terrestrial clastics that experienced low- to medium-grade metamorphism and can be divided into three formations. From bottom up, these are the Huixiangdian Formation, Dajinshan Formation and Nanshan Formation (Li et al., 1997). The Huixiangdian Formation (location of stratigraphic type locality: 118°27′, 28°10′) consists of migmatized biotite gneiss, biotite–plagioclase gneiss that is conformably overlain by the Dajinshan Formation (location of stratigraphic type locality: 117°47′, 27°17′) composed of biotite gneiss, biotite–plagioclase gneiss, and two-mica gneiss. The Dajinshan Formation is conformably overlain by the Nanshan Formation (location of stratigraphic typelocality: 118°04′, 27°22′) whose rock assemblage is mainly mica schist and minor gneiss. Rock assemblages of the Mayuan Group are typically composed of a series of metamorphosed terrestrial clastics like those of the Badu Group. Also, metamorphic minerals like garnet, sillimanite and kyanite are often found in these rocks. Graphite is reported to occur only in the Dajinshan Formation (Li et al., 1997). Granitoids, that are believed to have intruded into the Badu and Mayuan Groups and possessing Paleoproterozoic emplacement ages (~1.85–1.93Ga), have been found mainly in Zhejiang Province (Hu et al., 1991; Gan et al., 1993, 1995; Yu et al., 2009; Xia et al., 2012; Zhao et al., 2014). Li et al. (2011a) also reported a Paleoproterozoic granitoid in Fujian Province (Fig. 1). Amphibolites and some meta-volcanic rocks have also been found both in the Badu Group and in the Mayuan Group with ages ranging from 1.77 Ga to ~0.8 Ga (Li, 1997; Chen et al., 2008; J.-H. Yu et al., 2012; Y. Wang et al., 2012 and references therein). Some of these rocks might be intrusions (like the 1.77 Ga amphibolite, Li, 1997), while some others might be allochthonous rocks folded together with the autochthonous rocks during Phanerozoic deformation. Chen et al. (2008) and Xia et al. (2014) reported some Paleozoic granitoids in the area where the basement rocks of the Cathaysia block outcrop. Apart from these granitoids, the Paleozoic tectonothermal event did not apparently affect the Paleoproterozoic basement rocks of the Cathaysia block (Chen et al., 2008).

3. Samples

Samples of the metasedimentary units were collected from both the Badu and Mayuan Groups in Zhejiang and Fujian Provinces (Fig. 1). They show similar mineral assemblage of garnet (Grt) + sillimanite (Sil) + biotite (Bt) + plagioclase (Pl) + quartz ± K-feldspar (Kf) ± muscovite (Mus) ± graphite (Gra). Some of the biotite grains have been altered to form chlorite (Chl) (Fig. 3D). There is minor variation in the modal content of minerals among the samples. For example, the contents of Bt and Pl in WY03 are higher than those in the other samples and the contents of Grt in WY15 and WY26 are lower.

WY03 (119°11.983′, 28°33.559′) is a Grt-Sil-Bt gneiss (Figs. 2A and 3A, B) belonging to the Badu Group, and was sampled from the Suichang region, Zhejiang Province. WY15 (119°16.384′, 28°21.851′) is Grt-bearing Sil-Bt gneiss (Figs. 2B and 3C, D) of the Badu Group, and was sampled from the Gaoting region, Zhejiang Province. WY26 (118°35.951′, 27°36.878′) is a Grt and Sil-bearing Bt gneiss (Figs. 2C and 3E, F) of the Dajinshan Formation, Mayuan Group, and was sampled from the Songxi region, Fujian Province. WY35 (118°27.365′, 27°0.184′) is Grt-bearing Sil-Bt gneiss (Figs. 2D and 3G, H) of the Dajinshan Formation, Mayuan Group, and was sampled from the Jian'ou region, Fujian Province.

All the rocks experienced strong deformation and the primary sedimentary layers (S_0) have completely been replaced by well-defined lineation and foliation (S_1 and S_2) (Fig. 2). Quartz grains that show undulating extinction are commonly present in all these samples. For example, in sample WY35, the quartz grains were elongated and foliated during mylonitization to form S_1. Subsequently, ductile shear deformation twisted the elongated grains and fine-grained biotite grains filled in the between quartz grains to form S_2 (Fig. 3G). Evidence for the ductile shear deformation is shown in Fig. 3H. Pressure shadow

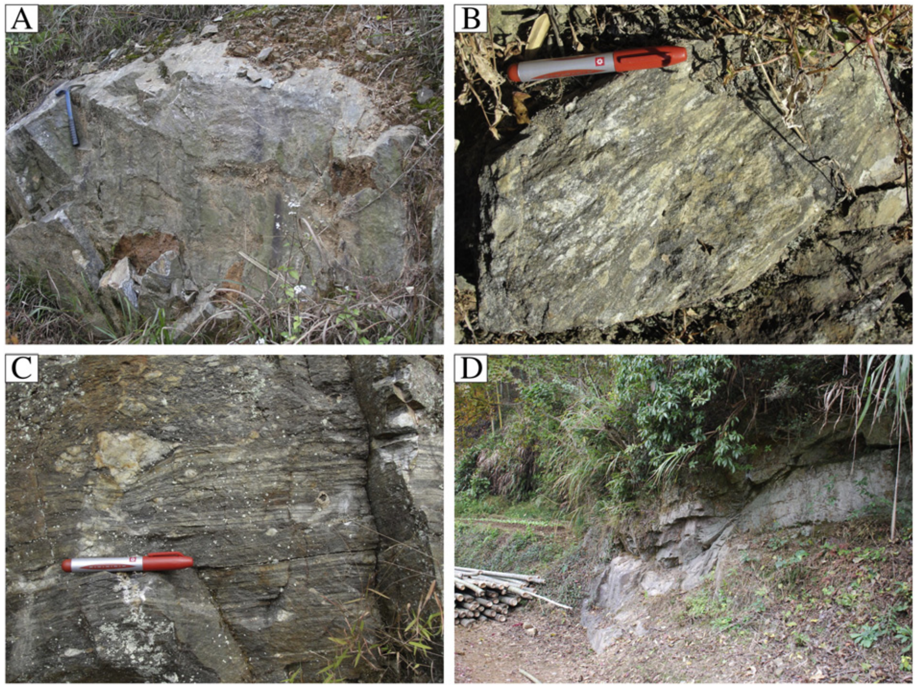

Fig. 2. Outcrop photographs of samples WY03 (A), WY15 (B), WY26 (C) and WY35 (D).

composed of biotite grains and sometimes fine-grained sillimanite is another evidence for the strong deformation (Fig. 3A). The two episodes of strong deformation might be related to two distinct tectonothermal events.

4. Analytical techniques

Major and trace element analyses of the studied samples were carried out at the State Key Laboratory of Lithospheric Evolution of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Major elements analyses were performed using X-ray fluorescence (Shimadzu XRF-1700/1500) after fusion with lithium tetraborate. The loss-on-ignition was measured as the weight loss of the samples after 1 h baking under a constant temperature at 1000 °C. The analyses were corrected using Chinese national standard sample GBW07101-07114. The precision was better than 0.2 wt.%. Trace element analyses were performed using an ELEMENT ICP-MS after HNO_3 + HF digestion of about 40 mg sample powder in a Teflon vessel. The accuracy and reproducibility during analyses were monitored using Chinese national standard samples GSR1 (granite), GSR2 (rhyolite) and GSR3 (basalt). The relative standard deviation was better than 5% above the detection limits.

Zircons grains were separated using standard heavy-liquid and magnetic techniques, and then handpicked under a binocular microscope in the Mineral Separation Laboratory of the Institute of Regional Geological Survey in Langfang, Hebei Province, China. The grains were then embedded in 25 mm epoxy discs, and then were ground and polished to expose the grain cores for CL imaging, U–Pb dating and Lu–Hf isotope analyses. The internal zoning was examined using a CL spectrometer (Garton Mono CL3+) equipped on a Quanta 200 F ESEM with 2-min scanning time at conditions of 15 kV and 120 nA at Peking University.

In-situ zircon U–Pb dating and trace element analyses were performed in the Geological Lab Center, China University of Geosciences (Beijing), using a laser ablation-split-stream inductively coupled plasma-mass spectrometry (LA-SS-ICP-MS) technique which enables zircon U–Pb dating and zircon trace element analyses at the same time. The instrument couples a quadrupole ICP-MS (Agilient 7500a) and an UP-193 Solid-State laser (193 nm, New Wave Research Inc.) with the automatic positioning system. The laser spot size we used was 40 μm for all analyses. The counting time for U, Th, ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb is 20 ms, 6 ms for Si and Zr and 15 ms for other elements. Calibrations for the zircon analyses were carried out using NIST610 glass as an external standard and Si as internal standard. U–Pb isotope fractionation effects were corrected using zircon 91500 (Wiedenbeck et al., 1995) as an external standard. Zircon standard TEMORA (417 Ma) from Australia (Black et al., 2003) is also used as a secondary standard to monitor the deviation of age measurements/calculations. The apparent ^{208}Pb/^{238}U ages for standard TEMORA we got scattered from 416 to 418 Ma, consistent with the recommended value of 417 Ma. NIST612 and NIST614 were also used to monitor the stability of the instrument during the analyses of trace element. The common lead was corrected following the method of (Andersen, 2002). Detailed Laboratory and instrument description and analytical procedures are presented in (Song et al., 2010). The analytical results were processed using the SQUID and ISOPLOT programs (Ludwig, 2003).

In situ zircon Hf isotope analyses were carried out using a Neptune MC-ICPMS in the State Key Laboratory of Lithospheric Evolution of the IGGCAS. A 40–63 μm spot size was applied during ablation with a 193 nm laser, using a repetition rate of 10 Hz in most cases. Detailed Laboratory and instrument description and analytical procedures are presented in (Wu et al., 2006). The domain of zircon grains chosen for Hf isotopic analyses is the same where the U–Pb dating was done. During analyses, GJ and Mud (two kinds of zircon standards, whose U–Pb ages and Hf isotope compositions are known and stable, and also they are quite uniform in isotope compositions) were used to monitor the stability of the machine. The weighted ^{176}Hf/^{177}Hf (c) value of GJ yielded from the analyses is 0.2820031 ± 0.0000048, and the weighted ^{176}Hf/^{177}Hf (c) of Mud yielded from the analyses is 0.282502 ± 0.000003, consistent with the value recommended elsewhere (Woodhead and Hergt, 2005; Zeh et al., 2007; Xie et al., 2008), after taking the analytical errors into consideration. Based on depleted mantle and chondrite sources, model ages (T_{DM}(Hf)) and $\varepsilon_{Hf}(t)$ of zircon grains were calculated. The value of ^{176}Hf/^{177}Hf and ^{176}Lu/^{177}Hf of the depleted mantle are 0.28325 and 0.0384 (Griffin et al., 2002). Those values of chondrite are 0.282772 and 0.0332 (Blichert Toft and Albarede, 1997). The decay constant of ^{176}Lu adopted in this paper is 1.867×10^{-11}per year (Söderlund et al.,

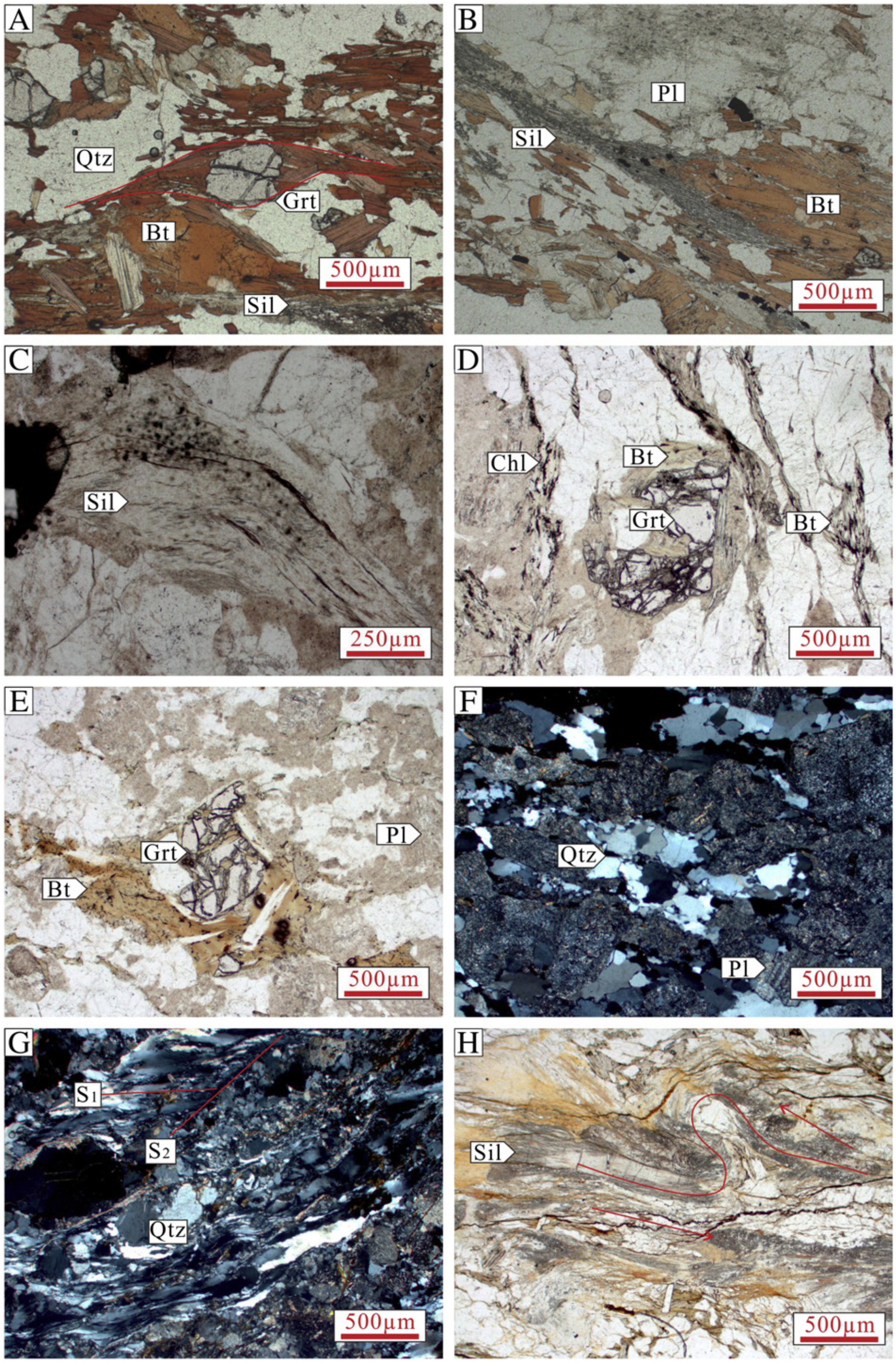

Fig. 3. Photomicrographs of samples WY03 (A and B), WY15 (C and D), WY26 (E and F) and WY35 (G and H). F and G in crossed nicols; all others in open nicols.

2004). Because T_{DM}(Hf) ages (calculated using the measured $^{176}Lu/^{177}Hf$ of the zircon grains) can only give a minimum age for the source materials of the host magma, two-stage "crustal" model ages (T^{C}_{DM}(Hf)) were calculated assuming that the parent magma of each zircon was derived from a source with $^{176}Lu/^{177}Hf$ of 0.015, corresponding to the average continental crust (Griffin et al., 2002).

5. Results

5.1. Whole rock major and trace element compositions

Whole rock major and trace element compositions are presented in Table 1 and Fig. 4. SiO_2 contents of almost all samples scatter in a narrow range of 71.6 to 75.9%, except sample WY26-1 which has a lower SiO_2 content of 64.7% and high loss-on-ignition (LOI) of 4.8%. In thin section and hand specimen of this sample, we found a thin-layer of carbonate vein which might explain the above features, together with the high CaO contents of this rock. The Al_2O_3 contents of the analyzed samples are high, ranging from 10.7 to 14.8% with A/CNK values ranging from 1.0 to 3.0 (Table 1).

The rocks show similar trend of chondrite-normalized REE patterns and depleted mantle normalized trace element patterns (Fig. 4). Their ΣREE values range from 45–378 ppm, with some rocks showing positive Eu anomaly (sample WY26) whereas others displaying negative Eu anomalies (sample WY35) (Table 1).

Table 1
Major and trace element compositions of the studied samples.

sample no.	WY03-1	WY03-3	WY15-1	WY26-2	WY26-1	WY35-2	WY35-1
SiO_2	73.6	73.4	74.8	71.6	64.7	75.9	74.5
Al_2O_3	13.9	10.7	11.6	14.4	14.8	12.7	14.0
Fe_2O_3	0.3	1.5	0.2	0.2	0.1	1.0	0.2
FeO	2.6	5.7	3.2	1.2	1.8	0.6	0.6
CaO	1.3	0.5	0.6	1.4	4.1	0.3	0.4
MgO	1.2	2.7	1.4	0.5	1.4	0.5	0.2
K_2O	2.9	1.7	3.1	4.3	4.9	5.5	5.8
Na_2O	1.9	0.5	2.1	3.6	1.7	1.5	3.0
TiO_2	0.3	0.5	0.5	0.1	0.3	0.2	0.1
MnO	0.1	0.1	0.0	0.0	0.1	0.0	0.0
P_2O_5	0.0	0.1	0.1	0.1	0.3	0.1	0.1
LOI	1.2	1.7	1.6	1.8	4.8	1.3	0.7
Sum	99.3	99.0	99.22	99.31	98.94	99.6	99.67
A/CNK	1.6	3.0	1.5	1.1	1.0	1.4	1.2
La	16	36	54	18	25	78	10
Ce	29	71	110	36	54	169	19
Pr	3	8	12	4	6	20	2
Nd	12	28	43	13	25	73	8
Sm	2	5	8	2	5	15	2
Eu	1	1	1	1	2	1	0
Gd	2	5	5	2	5	11	2
Tb	0	1	1	0	1	2	0
Dy	3	6	3	2	4	6	1
Ho	1	1	1	0	1	1	0
Er	2	4	2	1	2	2	0
Tm	0	0	0	0	0	0	0
Yb	2	3	1	1	2	1	0
Lu	0	1	0	0	0	0	0
ΣREE	73	170	240	80	132	378	45
Y	19	37	15	11	22	21	6
Sc	8	18	7	6	4	6	3
Cr	42	70	59	7	13	3	5
Co	7	20	9	2	9	2	1
Ga	20	16	20	18	19	24	18
Rb	122	88	111	203	231	229	198
Sr	148	53	158	222	145	103	183
Zr	147	232	199	107	43	176	71
Nb	4	8	13	3	2	10	3
Ba	633	420	646	743	2289	584	881
Hf	4	7	6	3	2	6	3
Ta	0	0	1	0	0	0	0
Pb	29	8	24	27	33	52	48
Th	3	11	24	6	2	49	4
U	0	1	3	1	0	8	2
δEu	1.6	0.4	0.5	1.3	1.1	0.3	0.9

5.2. Zircon U–Pb geochronology and trace elements

5.2.1. Grt-Sil-Bt gneiss (WY03) of the Badu Group

Zircons from sample WY03 have distinct grain sizes and shapes and are mostly subhedral to anhedral. Some of the grains are small and round with grain sizes of 60–70 × 60–70 μm or even smaller. These grains are typically detrital zircons which were abraded during long-distance transportation. Some grains are larger in size and are long prismatic in shape, with grain sizes of 30–70 × 100–200 μm. However, these grains also show obvious characteristics of abrasion caused by mechanical transportation. For example, both ends of prisms are rounded suggesting relatively short distance transportation of the grains. All the other zircons possess sizes and shapes in between the above two groups. Most zircon grains show core-rim structures in cathodoluminescene (CL) images, with the cores showing different shapes and sizes. Some of the cores are long prismatic and are oscillatory zoned whereas others are round and also show oscillatory zones (Fig. 5). The rims of zircon grains are mostly narrow and could not be analyzed using the large laser beam size for U–Pb analyses. The morphological characteristics of zircons show that they are typical detrital zircons which experienced metamorphic overprinting.

Zircon U–Pb analyses were mostly performed on zircon cores and some spots might have also extracted materials from zircon rims because of their small grain size. Zircon U–Pb and trace element results of WY03 are presented in Figs. 6 and 7 and Appendix Table. Most of the analyzed spots yield discordant results (Concordance <90%), resulting from Pb-loss, and they mainly plot along two poorly defined discordia with two upper intercept ages of 1990 ± 31 Ma and 2451 ± 63 Ma, respectively (Fig. 6). The several concordant results have $^{207}Pb/^{206}Pb$ ages ranging from 1914 to 2639 Ma. The discordant results have $^{207}Pb/^{206}Pb$ ages ranging from 1499 to 2770 Ma. Trace element data on the zircons show obvious LREE depleted and HREE enriched nature (Fig. 7). Th/U ratios are mostly >0.1 with a few grains <0.1. The grains that possess Th/U ratios below 0.1 tend to have young $^{207}Pb/^{206}Pb$ ages and show significant Pb loss suggesting metamorphic origin.

Normally, $^{207}Pb/^{206}Pb$ age of zircon which crystallized more than 1000 Ma ago is believed to be the closest to the real age and if zircons experienced recent Pb loss, the $^{207}Pb/^{206}Pb$ ages could still be interpreted to represent the real crystallization ages of zircons. However, if Pb loss occurred during an ancient tectonothermal event, then the upper intercept ages of the discordia defined by the results rather than $^{207}Pb/^{206}Pb$ ages should be considered to be the formation ages of the rocks studied. The two upper intercept ages of 1990 ± 31 Ma and 2451 ± 63 Ma might reflect the emplacement ages of two of sedimentary precursors of the Badu Group. Xia et al. (2012), Yu et al. (2009), J.-H. Yu et al. (2012) and Zhao et al. (2014) have reported similar ages of ~1.9 Ga and ~2.5 Ga. Evidence for extensive Mesozoic metamorphic overprinting recorded by the rocks from the Badu Group as reported in previous studies was not clearly found in this sample.

5.2.2. Grt-bearing Sil-Bt gneiss (WY15) of the Badu Group

Some of the zircon grains of WY15 are euhedral to subhedral, long prismatic with sizes and aspect ratios range from 50–120 × 100–300 μm and from 1:2 to 1:3, respectively. Some grains are ellipsoidal or even round, and anhedral in shape, features typical of detrital zircons. In CL images, they show obvious core-rim structures (Fig. 5). The rims are unzoned as well as some of the cores. Many cores show weakly oscillatory zones indicating their magmatic origin and metamorphic alteration.

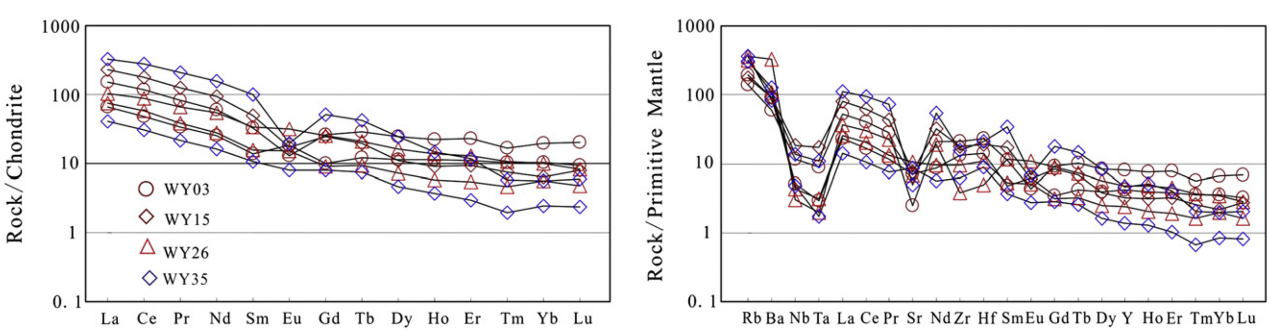

Fig. 4. Chondrite-normalized REE patterns and Primitive mantle-normalized multiple trace element diagrams of the samples. REE and Primitive mantle normalization factors after Sun and McDonough (1989).

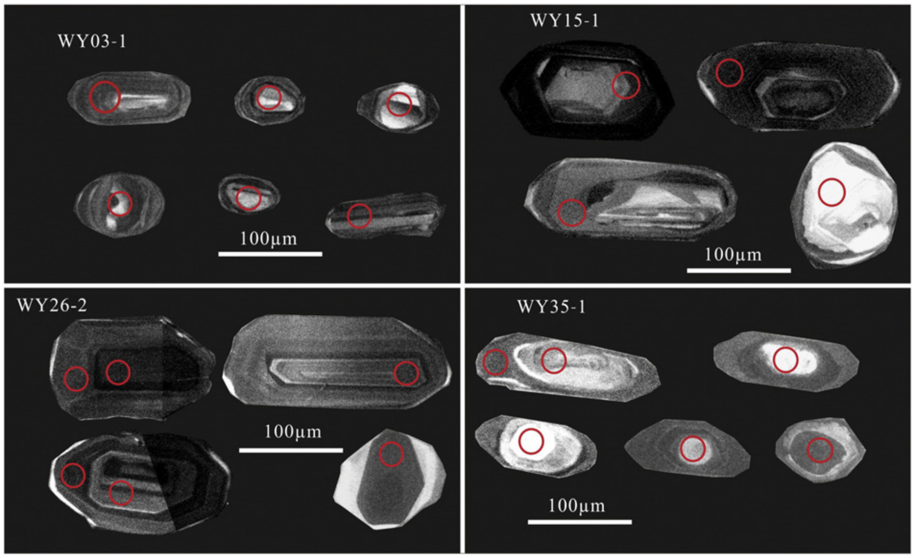

Fig. 5. CL images of zircons from different samples showing analytical spots.

A total number of 73 grains were analyzed on both rims and cores and zircon U–Pb and trace element analyses results are presented in Figs. 7, 8, and Appendix Supplementary Table. Cores and rims of the zircons show distinct Th/U ratios and Chondrite-normalized REE patterns (Fig. 7). Rims, irrespective of U–Pb ages, have Th/U ratios <0.1 and show flat HREE patterns whereas the cores tend to have Th/U ratios mostly >0.1 and show enriched HREE. The cores are evidently of magmatic origin and the rims are metamorphic (Schaltegger et al., 1999; Rubatto, 2002; Hoskin and Schaltegger, 2003; Kelly et al., 2006; Harley and Kelly, 2007). Although some of the cores also have Th/U rations <0.1, their REE patterns show enriched HREE so that they might still be magmatic.

Ages from the rims show two distinct clusters at ~ 230 Ma and ~1850 Ma and they form a well-defined discordia with an upper intercept age of 1894 ± 15 Ma and a lower intercept age of 233 ± 4 Ma. Results from cores show $^{207}Pb/^{206}Pb$ ages in the range of 1789–3403 Ma. Some of the results from zircon cores also form a discordia with upper intercept age of 3530 ± 80 Ma and lower intercept age of 1858 ± 39 Ma. Another discordia with upper intercept age of about 2500 Ma and lower intercept age of about 230 Ma is also well defined by the zircon cores and rims. After taking the analytical errors into consideration, the lower intercept age of the discordia defined by the cores is consistent with the upper intercept age of the discordia defined by the rims. The ages of ~230 Ma, 1850–1890 Ma and 2500 Ma are consistent with previously published ages of the Badu Group and the former two ages are interpreted to represent two tectonothermal events whereas the latter age of ~2500 Ma is considered to represent the age of the provenance of these metasedimentary rocks as has also been proposed by Xia et al. (2012), Yu et al. (2009) and J.-H. Yu et al. (2012) and Zhao et al. (2014). The age of ~3530 Ma might indicate another older source of these rocks. The zircon cores which are of detrital origin yielded concordant results (Concordance > 90%) and their $^{207}Pb/^{206}Pb$ ages range from 1969 Ma to 3403 Ma.

5.2.3. Grt and Sil-bearing Bt gneiss (WY26) of the Mayuan Group

Zircons of WY26 are mostly anhedral to subhedral and have distinct grain sizes ranging from 40–100 × 40–300 μm. Their aspect ratios range from 1:1–1:3. Some of the grains are small and round whereas the others are much larger and show and long cylindrical shape. In CL images, many of them show core-rim structures with unzoned rims and weakly zoned cores (Fig. 5). Some small grains that do not possess cores are unzoned. The cores are mostly small, irregular or angular or round, suggesting their detrital origin.

A total number of 111 grains were analyzed and U–Pb and trace element results are presented in Figs. 7, 9 and Appendix Table. Th/U ratios of zircons, including rims and some zircon cores,

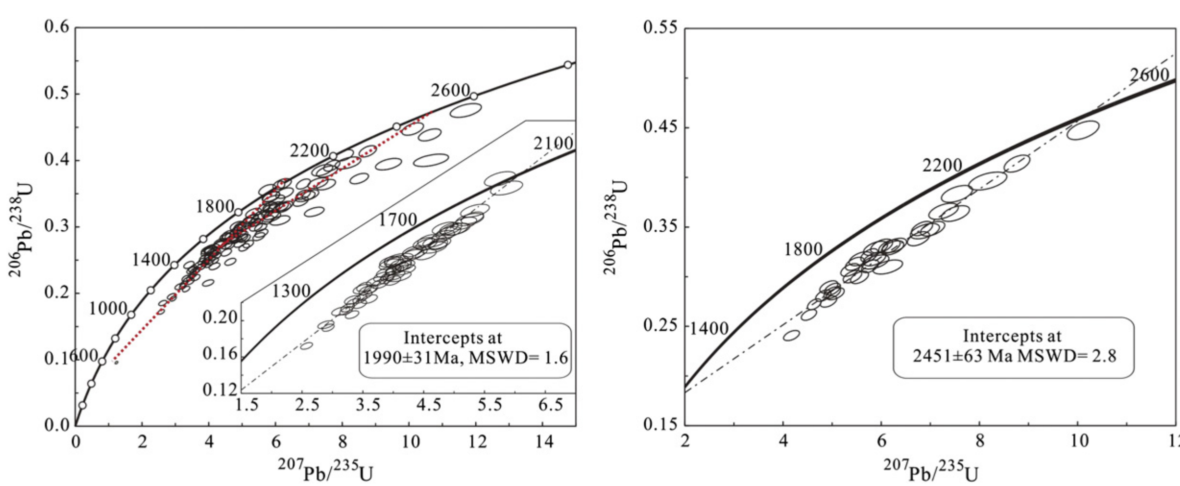

Fig. 6. Zircon U–Pb concordia diagrams for sample WY03 from the Badu Group.

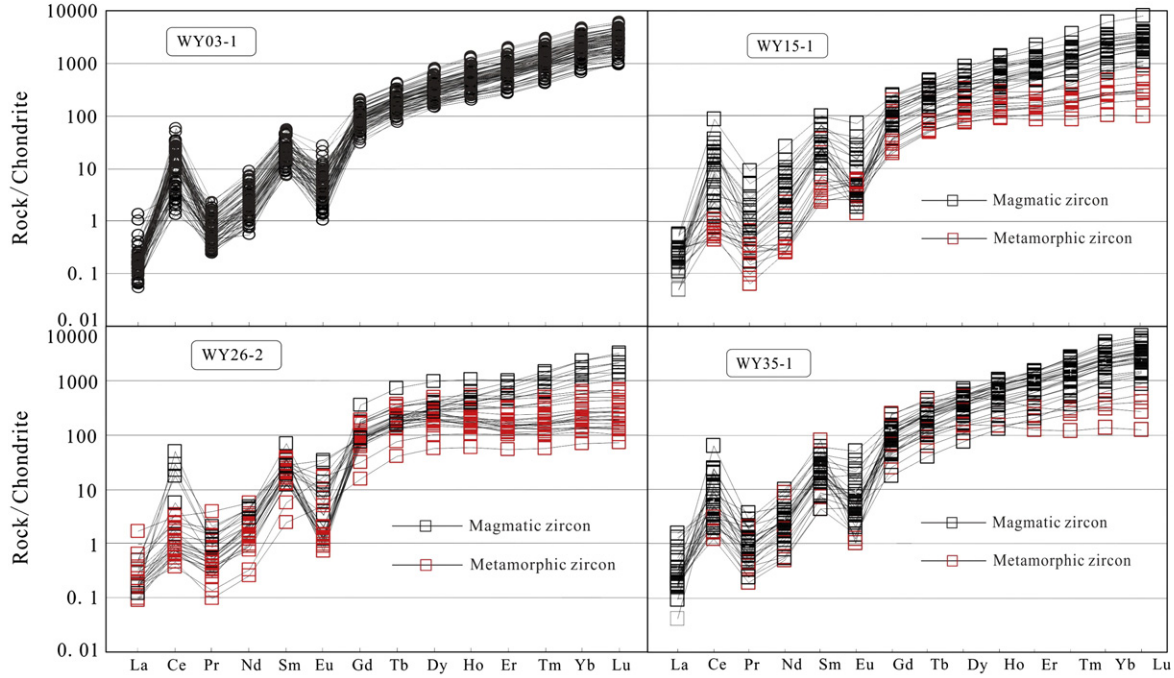

Fig. 7. REE patterns of zircons from the studied samples. REE normalization factors after Sun and McDonough (1989).

are mostly <0.1 and their chondrite normalized REE patterns show flat HREE, whereas only a few cores have Th/U ratios >0.1 and are enriched in HREE (Fig. 7).

Although most of the U–Pb results are discordant (concordance <90%), the data plot on a well-defined discordia with an upper intercept age of ~1860 Ma and a lower intercept age of ~250 Ma (Fig. 9). These

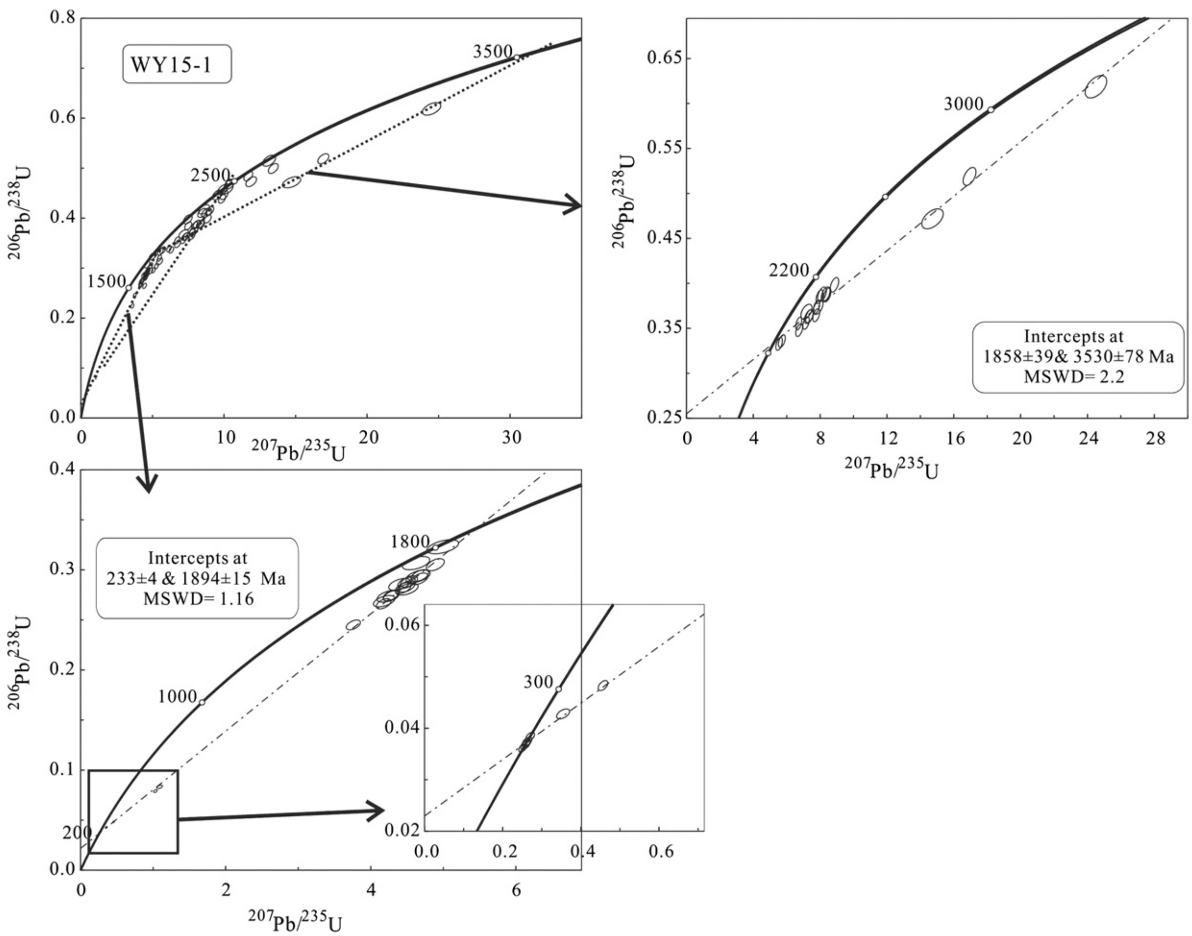

Fig. 8. Zircon U–Pb concordia diagrams for sample WY15 from the Badu Group.

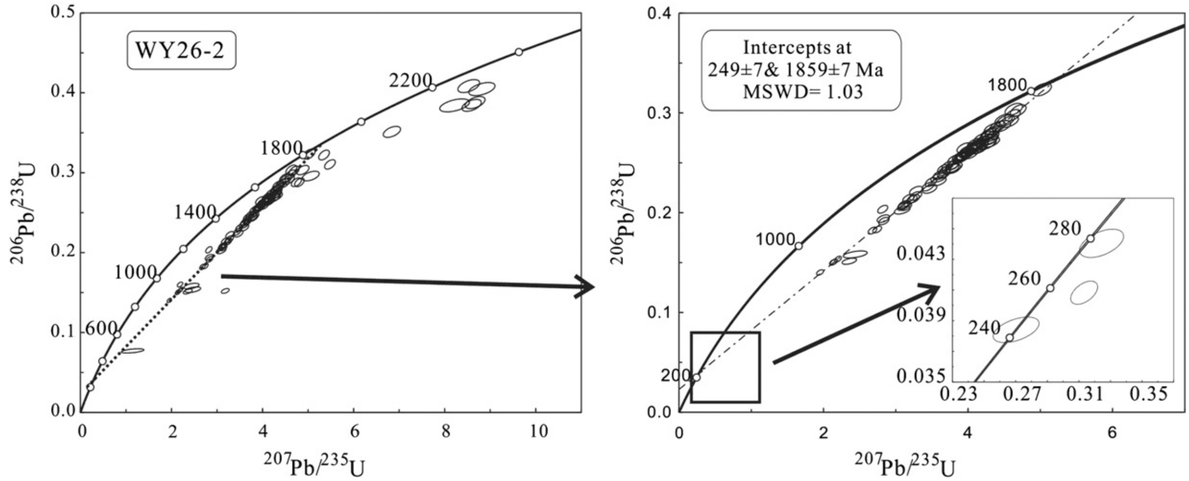

Fig. 9. Zircon U–Pb concordia diagrams for sample WY26 from the Mayuan Group.

two ages are consistent with the ages obtained from the Badu Group as shown above and as also reported in previous studies (Yu et al., 2009; J.-H. Yu et al., 2012; Xia et al., 2012; Zhao et al., 2014). The upper and lower intercept ages of this sample are also interpreted to represent two distinct tectonothermal events that took place in this region, similar to those recorded from sample above. None of the analyzed zircon cores that are of detrital origin gave concordant results.

5.2.4. Grt-bearing Sil-Bt gneiss (WY35) of the Mayuan Group

Zircons in sample WY35 are mostly euhedral to subhedral, long prismatic with sizes and aspect ratios ranging from 50–100 × 100–300 μm and from 1:1 to 1:3, respectively. Some small, round and anhedral grains were also seen. In CL images, they show obvious core-rim structures and even core–mantle-rim structures suggesting at least two episodes of overgrowth (Fig. 5). The rims as well as some of the cores and

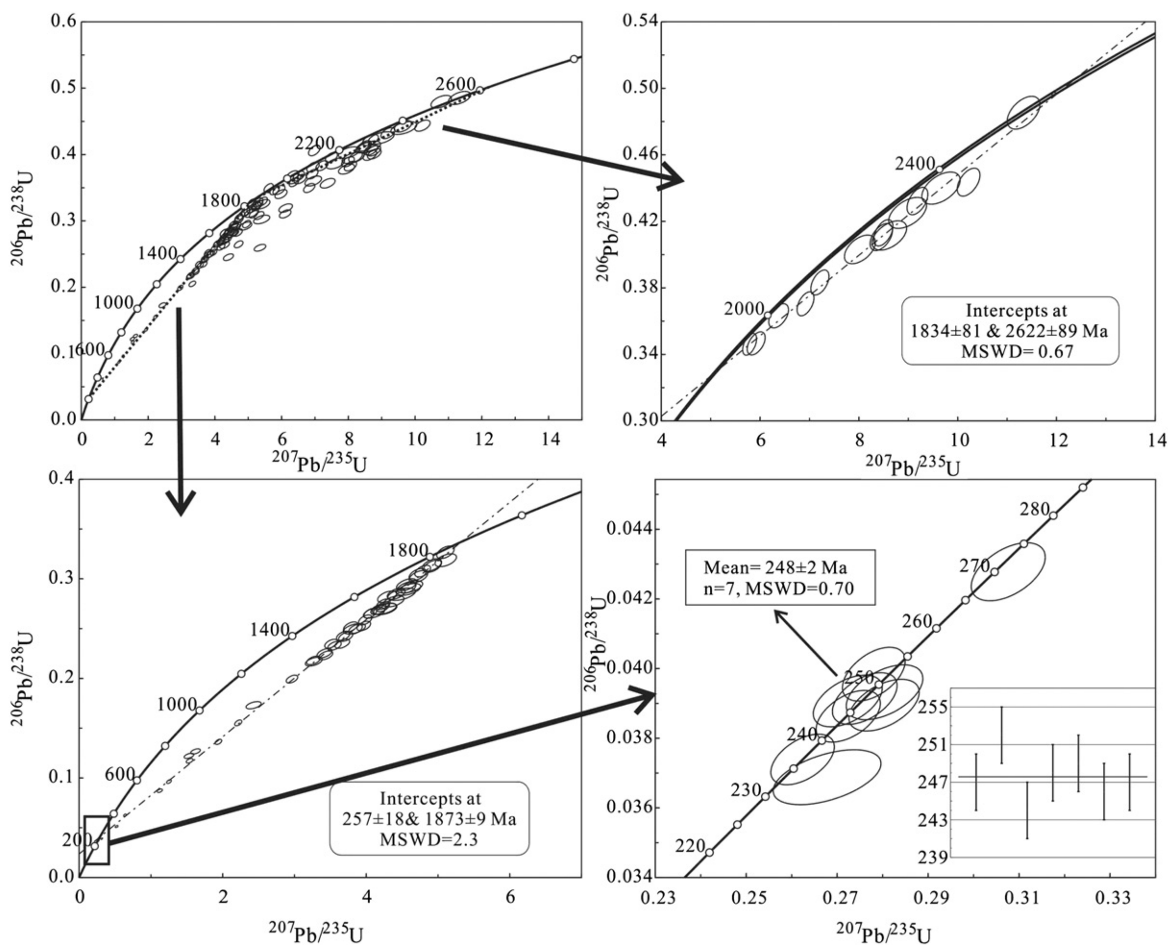

Fig. 10. Zircon U–Pb concordia diagrams for sample WY35 from the Mayuan Group.

mantles are unzoned. Many cores are irregular or angular and show weak oscillatory zones indicating their magmatic origin and mechanical abrasion and metamorphic alteration and overgrowth.

A total number of 120 grains were analyzed and U–Pb and trace element results are presented in Figs. 7, 10 and Appendix Table. Many of the analyzed spots were on zircon cores and their Th/U ratios are mostly >0.1 with their chondrite normalized REE patterns showing enriched HREE. Some of the spots were on zircon rims and mantles and the data show low Th/U ratios (<0.1) and flat HREE (Fig. 7). The zircon rims and some of the mantles are obviously of metamorphic origin because of their low Th/U ratios, flat HREE and internal structures as revealed by CL images (Vavra, 1990; Rubatto and Gebauer, 1996; Rubatto, 2002; Corfu et al., 2003). The cores might be of igneous origin and experienced partial dissolution and redeposition during two episodes of metamorphic overprinting resulting in the core–mantle–rim structures of zircons.

Most of the U–Pb results are discordant (Concordance <90%), however, they plot on a well-defined discordia and on a not so well-defined discordia. The upper and the lower intercept ages of the well-defined discordia are 1873 ± 9 Ma and 257 ± 18 Ma and these of the not so well-defined discordia are 2622 ± 89 Ma and 1834 ± 81 Ma, respectively. Seven of the most concordant results from the zircon rims have a weighted mean $^{206}Pb/^{238}U$ age of 248 ± 2 Ma. The two ages of ~1.85 Ga and ~250 Ma are interpreted to represent the two episodes of metamorphic overprinting as mentioned above. The ~2.6 Ga might suggest a Neoarchean source. The U–Pb results of this sample are consistent with those of the above three samples and with previously published results from rocks of the Badu Group (Yu et al., 2009; J.-H. Yu et al., 2012; Xia et al., 2012; Zhao et al., 2014). Also, the results are consistent with those from rocks of the Nanshan Formation in the Mayuan Group (Li et al., 2011a). Some of the zircon cores that are of detrital origin gave markedly concordant results (Concordance > 95%) with $^{207}Pb/^{206}Pb$ ages ranging from 1902 Ma to 2551 Ma.

5.3. Lu–Hf isotope analyses

Lu–Hf isotope analyses were done on the same domains where zircon U–Pb dating has been performed. Some zircon grains, however, are too small and were inadequate for Lu–Hf analyses, after their LA-SS-ICP-MS U–Pb dating. The analytical results are presented in Appendix Table, and shown in Fig. 11. The Lu/Hf ratios of zircons from all the samples are below 0.002, and therefore the accumulation of radiogenic Hf after the formation of zircons can be ignored. Due to significant analytical errors for zircon rims that were formed during Phanerozoic metamorphic overprinting, their Lu/Hf results will not be included.

The two obvious episodes of metamorphic overprinting have disturbed the U–Pb isotope system of most zircon grains. Even though

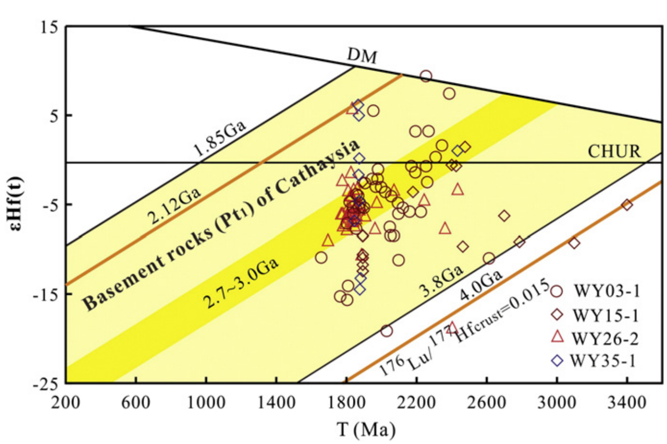

Fig. 11. Hf isotope compositions of the samples studied. Basement rocks (Pt_1) of Cathaysia are after Xu et al. (2007); J.-H. Yu et al. (2012); X. Yu et al. (2012) and Zhao et al. (2014).

$^{207}Pb/^{206}Pb$ ages could not be interpreted as the closest to crystallization ages in the cases where the zircon grains suffered ancient Pb loss, they are relatively closer than $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages to crystallization ages. Based on this, we used $^{207}Pb/^{206}Pb$ ages from each rock type for the calculation of $\varepsilon_{Hf}(t)$ values and crustal model ages ($T_{DM}^{C}(Hf)$) (Appendix Table). Zircons from all samples show $^{176}Lu/^{177}Hf$ ratios in the range of 0.00004–0.00190 and $^{176}Hf/^{177}Hf$ (c) ratios of 0.280553–0.281838. The $\varepsilon_{Hf}(t)$ of these zircons range from −19 to +11, mostly negative with a peak at about −5.5. The crustal model ages $T_{DM}^{C}(Hf)$ are 1.9–4.1 Ga with a peak at about 2.7–3.0 Ga.

6. Discussion

6.1. Lithostratigraphic ages of the Badu and Mayuan Groups

Considerable work has been done on the geochronology of the Badu Group rocks applying various analytical techniques including conventional single- or multigrain TIMS method (Hu et al., 1991; Wang et al., 1992; Gan et al., 1995), whole rock Sm–Nd and Rb–Sr method (Yang et al., 1994; Li et al., 1996), and in-situ LA-ICP-MS and SHRIMP zircon U–Pb methods (Li, 1997; Chen et al., 1998; Li et al., 1998; Yu et al., 2006, 2009; X. Wang et al., 2008; Xiang et al., 2008; Zeng et al., 2008; Li et al., 2009; Liu, 2009; Li et al., 2011a; Xia et al., 2012; J.-H. Yu et al., 2012; Zhao et al., 2014;). Although some of the techniques applied are not so precise, all the published ages show Paleoproterozoic ages from the Badu group. Zhao et al. (2014) reported ca. ~1.93 Ga leucogranite in the Badu Group and its detrital zircon ages, whole rock Sm–Nd and zircon Lu–Hf isotope characteristics greatly resemble these of the Badu sedimentary rocks. They proposed that the Badu sedimentary rocks or their equivalents at depth which underwent melting might be the source rocks of the leucogranite. Thus, it is quite likely that Badu Group is older than 1.93 Ga. Metamorphic ages of 1.84–1.89 Ga, similar to those obtained from zircons in sample WY15, were also reported in previous studies (J.-H. Yu et al., 2012; Zhao et al., 2014). In sample WY03 where the zircon overgrowth is not so obvious, no $^{207}Pb/^{206}Pb$ age younger than 1.90 Ga was found except for the discordant ones that plot on the discordia. Thus our results confirm that the Badu Group is a Paleoproterozoic lithostratigraphic unit.

The age of the Mayuan Group has been a controversial issue. Some of the previous studies proposed that the Mayuan Group might be Neoproterozoic to Paleozoic (Wan et al., 2007; Xu et al., 2010). Li et al. (2011a) studied the Paleoproterozoic (1.85–1.86 Ga) orthogneiss that intruded into the Mayuan Group (Fig. 1) and suggested it to be the partial melting product of the paragneisses of the Mayuan Group or their deep equivalents thus inferring that the Mayuan Group might be Paleoproterozoic in age. We checked the samples studied by Wan et al. (2007) and found that the Neoproterozoic ages came from zircons in meta-volcanic rocks (sample no. FJ0115 in Wan et al., 2007 and Fig. 1) and these rocks have whole rock geochemistry and Sm–Nd isotopes indistinguishable from those of volcanic rocks of the Mamianshan Group (Pt_3) (Wan et al., 2007). However, in another sample (sample no. FJ0110 in Wan et al., 2007) which is a clastic sedimentary rock that experienced strong metamorphic overprinting during Paleozoic, no Neoproterozoic age was found. Since only a limited number of zircon grains were analyzed, Wan et al.'s (2007) data did not yield a well-defined discordia. But a discordia trend can still been seen with an upper intercept age not younger than 1.8 Ga.

Xu et al. (2010) reported LA-ICP-MS results of meta-clastic rocks from the Dajinshan Formation of the Mayuan Group. Unlike our results, all their analyzed spots in zircons yielded remarkably concordant results and all (except one) points plot on the concordia which is rather intriguing. Because all the formations of the Mayuan Group experienced high-grade metamorphism and strong deformation (Zhao and Cawood, 1999; Liu et al., 2008; Zeng et al., 2008; Liu et al., 2010), significant Pb loss must have occurred and discordant U–Pb data are reasonably expected. A more surprising feature is that their results show neither

Paleozoic nor Mesozoic metamorphic overprints, although these events are extensive in this area. Importantly, the CL images of zircons in Xu et al.'s (2010) study show clear overgrowths. The data from our study also show some 800–900 Ma $^{206}Pb/^{238}U$ ages, but are clearly discordant and cannot be considered to represent the crystallization ages of zircon grains. However, errors in counting time and the improper correction of common lead during the experiment, data processing processes can lead to discordant points plotting on the concordia. Therefore, we consider that our results are more precise and can better constrain the age of the Mayuan Group.

Two of our samples from the Dajinshan Formation of the Mayuan Group, WY26 and WY35, record similar Paleoproterozoic metamorphic overprint at 1859 ± 7 Ma and 1873 ± 9 Ma. The ages are similar taking into account the analytical errors, and are also consistent with the previous studies of the Badu Group which correlate the stratigraphic equivalent of the Mayuan Group in Zhejiang Province (Yu et al., 2009; J.-H. Yu et al., 2012; Xia et al., 2012; Zhao et al., 2014, among others). We therefore propose that the Dajinshan formation of the Mayuan Group is of Paleoproterozoic age (older than the metamorphic overprinting at 1.86–1.87 Ga and younger than the youngest concordant U–Pb results of detrital zircons at about 1.9 Ga).

Combined with previous geochronology data of the Nanshan Formation of the Mayuan Group reported by Li et al. (2011a), and also of the clastic sedimentary rocks belonging to the Dajinshan Formation reported by Wan et al. (2007), it is quite likely that at least part of the Mayuan Group is of Paleoproterozoic age. The other part that does not belong to the Paleoproterozoic group is composed of volcanic rocks which are relatively more mafic than the clastic components of the Mayuan Group (Wan et al., 2007). J.-H. Yu et al. (2012) also found some mafic components that are not Paleoproterozoic in the Badu Group. It is possible that these Neoproterozoic volcanic components found in the Mayuan and Badu Groups, which have similar geochemistry, U–Pb geochronology and Sm–Nd isotopic compositions with rocks from the Neoproterozoic Mamianshan and Longquan Groups, are not autochthonous. In other words, they might be components of Neoproterozoic Mamianshan and Longquan Groups adjacent to the Paleoproterozoic Mayuan and Badu Groups and all of these were subsequently deformed together during Paleozoic and Mesozoic tectonothermal events.

6.2. Episodic tectonothermal events and crustal growth of the Cathaysia block

The Cathaysia block has experienced several episodes of reworking related to episodic tectonothermal events, including the Paleoproterozoic magmatism and metamorphism (Hu et al., 1991; Gan et al., 1995; Li, 1997; Xiang et al., 2008; Liu et al., 2009; Yu et al., 2009; Li et al., 2011a; J.-H. Yu et al., 2012; Xia et al., 2012; Zhao et al., 2014), and the Paleozoic and Mesozoic deformation, magmatism and anatexis related to high-grade metamorphism (Wang et al., 2005; Y. Wang et al., 2010; Wang et al., 2011; Y. Wang et al., 2012; D. Wang et al., 2013; X.L. Wang et al., 2013; Y. Wang et al., 2013b; Y. Wang et al., 2013c; Xiao and He, 2005; Li et al., 2006, 2010; S. Li et al., 2012a; W.Y. Li et al., 2012; Li and Li, 2007; Lin et al., 2008; Shu et al., 2008; Faure et al., 2009; Chen et al., 2011; Mao et al., 2011, 2013; X. Yu et al., 2012; F. Zhang et al., 2012; Huang et al., 2013; Zhu et al., 2013; etc.). During Neoproterozoic, the Cathaysia block records significant crustal growth related to arc-accretion or mafic/bimodal magmatism (Chen and Jahn, 1998; Li et al., 2005; Wang et al., 2006; Li et al., 2008; L. Wang et al., 2008; Shu et al., 2011, 2013; Zhao et al., 2011; Cawood et al., 2013;). The Paleoproterozoic tectonothermal event is confined to the ancient basement rocks which outcrop mainly in the northeastern Cathaysia block, namely the Badu and Mayuan Groups. This episode of reworking has been well constrained by previous studies (Liu et al., 2009; Yu et al., 2009; Li et al., 2011a; J.-H. Yu et al., 2012; Xia et al., 2012; Zhao et al., 2014).

Published geochronological data related to Phanerozoic metamorphism in the study area and neighboring regions are shown in Fig. 12. The two episodes of Phanerozoic reworking related to high grade metamorphism in the Paleozoic and the Mesozoic (also called the Kwangsian and Indosinian by Wang et al., 2012), are generally believed to have affected the whole Cathaysia block (Li et al., 2006; Li and Li, 2007; Li et al., 2010; Y. Wang et al., 2010; 2012; 2013a; 2013c and references therein). However, after integrating the reliable geochronological data, which are closely related to high grade metamorphism, of the study area and neighboring areas on the geological map (Fig. 12), we can clearly identify two zones that show different extent of metamorphic reworking by the two episodes of tectonothermal events, the western Paleozoic metamorphic reworking zone and the eastern Mesozoic metamorphic reworking zone. Since the exact boundary between these two zones is not well defined, we have shown this as a dotted line in Fig. 12. In fact, part the eastern Mesozoic reworked zone has been pointed out by Zhao and Cawood (2012) and Cawood et al. (2013).

Three of the samples studied in this paper record both the Paleoproterozoic and the Mesozoic metamorphic reworking events and they show Paleoproterozoic and Mesozoic ages of 1894 ± 15 Ma and 236 ± 4 Ma (WY15); 1859 ± 7 Ma and 249 ± 7 Ma (WY26); 1873 ± 9 Ma and 248 ± 2 Ma, respectively. None of them show any evidence of Paleozoic metamorphic overprinting and all of them were sampled in the eastern Mesozoic reworked zone (Figs. 1 and 12). Based on our results and also in conjunction with those from previous studies discussed above, we propose three tectonothermal events which caused zircon overgrowth in different parts of northeastern Cathaysia block. The Paleoproterozoic episode of tectonothermal event is recorded by the ancient basement rocks belonging to the Badu and Mayuan Groups at about 1.8–1.9 Ga. The Paleozoic episode occurred at about 415–480 Ma with a peak at about 450 Ma and this episode of tectonothermal event is recorded by the Tianjingping Group, part of the Mayuan Group (Wan et al., 2007), as well as the Neoproterozoic sequences such as Tiaoxi Formation and the Zhoutan Group (Fig. 12). The western part of the northeastern Cathaysia block was more obviously reworked during this episode of metamorphism. The Mesozoic episode took place at about 230–250 Ma and the eastern part of the northeastern Cathaysia block was more obviously reworked during this tectonothermal event. Thus it seems that the Phanerozoic high grade metamorphism related to these episodes of tectonothermal events is not distributed all across the Cathaysia block, but it is quite likely that their distribution is regional and they form different reworked zones as shown in Fig. 12.

Based on the above discussion, it seems that the two episodes of Phanerozoic tectonothermal events affected different parts of the northeastern Cathaysia block differently. As to the several Paleozoic metamorphic rocks in the Mesozoic metamorphic reworked zone in Fig. 12 (Chen et al., 2008; Y. Wang et al., 2012; Xia et al., 2014 and references therein), they might be allochthonous. Because while the Paleozoic rocks show few evidence for Mesozoic deformation and metamorphism, their country rocks all show very strong Mesozoic metamorphic reworking, clear foliation and lineation and metamorphic zircon overgrowth. However, there can also be other explanations of the spatial distribution of the Phanerozoic metamorphism. Chen et al. (2008) argued that the Paleozoic tectonothermal event did not affect the Paleoproterozoic basement rocks of the Cathaysia block that strongly like the Mesozoic tectonothermal event. Hsü et al. (1990) proposed that the Paleoproterozoic basement rocks, namely the Badu and Mayuan group rocks, might form a big antiform caused by the Mesozoic orogeny. So it is also a feasible explanation that in the area where the Badu and Mayuan group rocks outcrop, rocks in only the shallow crustal level were involved during the Paleozoic tectonothermal event if there were any. But during the Mesozoic tectonothermal event, rocks in the deeper crustal level, more precisely the rocks of the Badu and Mayuan group, were involved. Most of the Paleozoic metamorphic rocks have been subjected to uplift and erosion, and this resulting in the exhumation of the Mesozoic metamorphic rocks from deeper crustal levels.

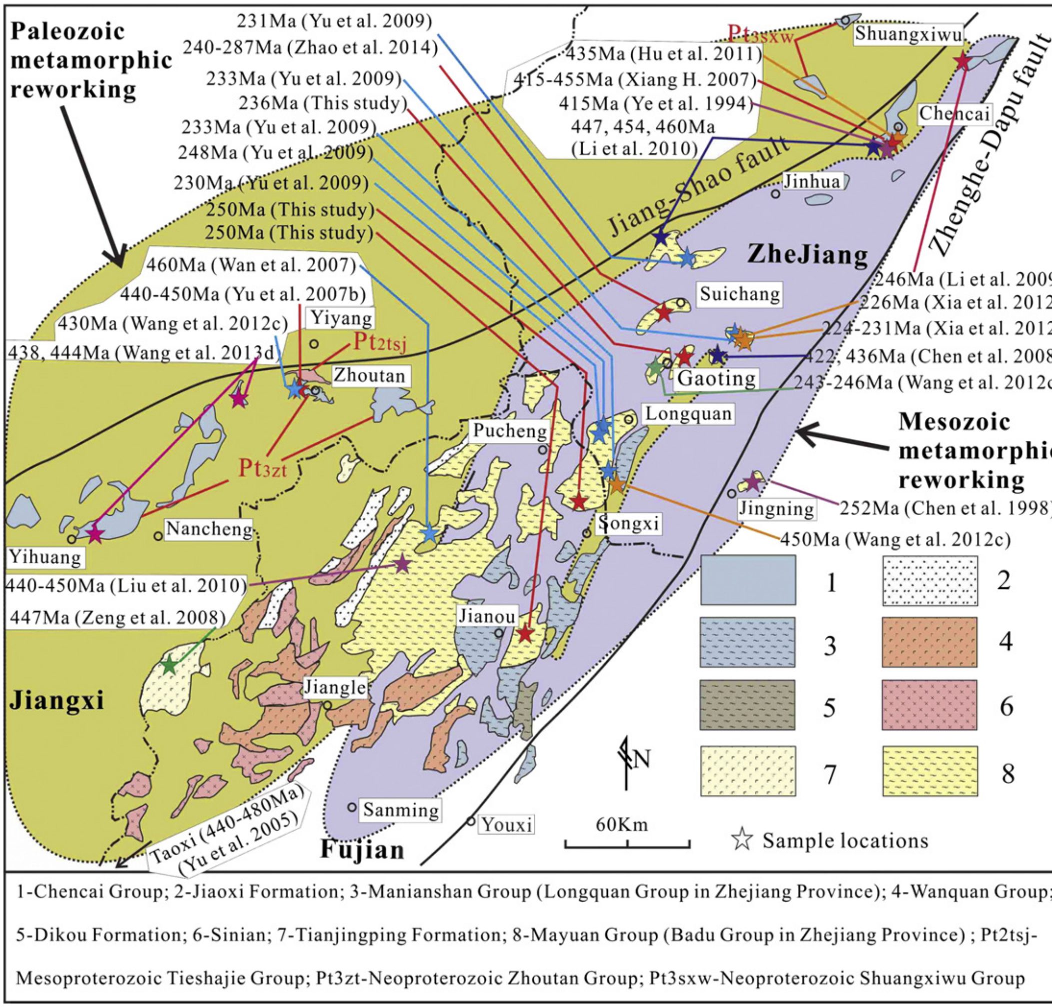

Fig. 12. Distribution of Phanerozoic tectonothermal events in the reworked zones of the Cathaysia block. Geochronological data are from Ye et al. (1994), Chen et al. (1998), Yu et al. (2005), Yu et al. (2007), Yu et al. (2009), Wan et al. (2007), Xiang (2008), Chen et al. (2008), Zeng et al. (2008), Li et al. (2010), Liu et al. (2010), Hu et al. (2011), Xia et al. (2012), Y. Wang et al. (2012), X.L. Wang et al. (2013), Zhao et al. (2014) and this study.

Yu et al. (2006) described the Cathaysia block as a young continent composed of ancient materials. Detrital zircons from across the block contain abundant Archaean to Paleoproterozoic record, with some rare evidence for Archaean rock inclusions within Phanerozoic intrusions (Fletcher et al., 2004; Xu, 2005; Xu et al., 2007; J. Yu et al., 2007; Yu et al., 2010; Wan et al., 2010; Zhao et al., 2010; Li et al., 2011b; Zheng et al., 2011; Xia et al., 2012; Cawood et al., 2013 and references therein). These studies mentioned proposed episodic crustal growth of the northeastern Cathaysia block at about 3.6 Ga, 2.9 Ga, 2.7 Ga, 1.85 Ga, 0.8–0.7 Ga. In the southwestern Cathaysia block, these events occurred at 3.6 Ga, 3.3 Ga, 2.5–2.6 Ga, 1.6 Ga, 1.0 Ga and 0.8–0.7 Ga. Lu–Hf isotopes of the samples in this study show a peak of T_{DM}^{C}(Hf) at about 2.7–3.0 Ga which is consistent with the previously proposed crustal growth time in the northeastern Cathaysia block. Our results confirm the possibility that Cathaysia block contains Archaean basement.

6.3. Tectonic significance

The Badu and Mayuan Groups are mainly composed of metapelites and metagreywackes, with a common mineral assemblage of sillimanite + garnet + biotite + plagioclase + quartz, as described in our study and also as reported in previous investigations by Fujian, BGMR (Bureau of Geology and Mineral Resources of Fujian Province) (1985), Hu et al. (1991), J.-H. Yu et al. (2012) and Zhao et al. (2014), typical of a continental shelf sequence. Some of the Paleoproterozoic S-type granites of the region (Yu et al., 2009; Li et al., 2011a; Zhao et al., 2014), are believed to be the partial melting products of these metasedimentary rocks or their deeper equivalents. Yu et al. (2009) proposed a Paleoproterozoic orogeny to explain the 1.85–1.89 Ga metamorphism and magmatism of the Badu region. However, Xia et al. (2012) argued that the 1.85–1.89 Ga metamorphism and magmatism might not be the result of an orogeny, but was caused by magma underplating in an extensional environment.

Zhao et al. (2014) discovered 1.93 Ga collision-related leucogranite in the Badu region, which also record the ~1.87 Ga metamorphism, and proposed that the collisional event took place at ~1.93 Ga with subsequent 1.85–1.89 Ga metamorphism and magmatism in an extensional environment caused by magma underplating. Samples of this study also recorded the Paleoproterozoic metamorphism at 1.86–1.89 Ga. Thus, it seems that the Paleoproterozoic metamorphism and magmatism not only occurred in the Badu region, but also took place in the Mayuan region. This extensive Paleoproterozoic thermal event is believed to represent the response of the Cathaysia block related to the assembly of the Columbia supercontinent (Rogers and Santosh, 2002, 2003; Zhao et al., 2002, 2003, 2004; Santosh et al., 2009, 2011; Meert, 2013; Robers, 2013; Nance et al., 2014).

The Paleozoic tectonothermal event in South China is generally believed to have occurred in an intraplate environment (Charvet et al., 2010; Li et al., 2010; Y. Wang et al., 2010; Wang et al., 2011; Y. Wang et al., 2013c), although the cause of this orogeny is still debated. Li et al. (2010) proposed possible causes like the far-field tectonic compression, and flat-slab subduction. Charvet et al. (2010) argued that this orogeny might be related to the underthrusting of the southern part of the South China Block beneath the northern part of this block which closed the pre-existing Nanhua rift. Y. Wang et al. (2010) and Wang et al. (2011) suggested that this (Kwangsian) orogenesis is probably the far-field response to the assembly of the Australian–Indian plate with the Cathaysia block.

The Mesozoic tectonothermal event, similar to that of the Paleozoic, is also a controversial issue. Hsü et al. (1988) proposed a southeastward subduction and final collision model to explain this event. John et al. (1990) suggested that this episode of reworking might be related to the collision of microcontinental blocks. Zhou et al. (2006) argued that it might be related to tectonic transition from continent–continent collision within the broad Tethyan oceanic domain to the subduction of Paleo-Pacific plate. Li and Li (2007) used the flat-slab subduction of the Paleo-Pacific plate underneath the southeastern Eurasia to explain this event. Y. Wang et al. (2013a) proposed a model that the progressive subduction and collision of the Indochina plate with the South China Block and also the contemporaneous interaction of the South China Block with the North China Craton might have all affected the Mesozoic intraplate reworking of the Cathaysia block.

Although our new findings on the spatial distribution of Phanerozoic metamorphism in northeastern Cathaysia block cannot provide definite solutions, they help to improve the understanding of the Phanerozoic evolution of the Cathaysia block.

7. Conclusion

(1) The metasedimentary units of the Badu and Mayuan Groups have similar mineral assemblages of garnet + sillimanite + biotite + plagioclase + quartz ± K-feldspar ± graphite as well as high contents of SiO_2 and Al_2O_3, which confirm that these rocks belong to the same lithostratigraphic unit.

(2) Zircon U–Pb results yield two discordia intercept ages of ~1990 Ma and ~2450 Ma in one sample from the Badu Group; zircons in another sample show intercept ages of ~3.5 Ga, 2.5 Ga, 1858 Ma and 233 Ma. Discordia intercept ages of 1859 Ma and 249 Ma are yielded by one sample from the Mayuan Group; another sample shows ages of ~2.6 Ga, 1873 Ma, 257 Ma and a weighted mean $^{206}Pb/^{238}U$ age of 248 Ma. Both the 1.86–1.87 Ga and 230–250 Ma ages are interpreted to represent the time of metamorphic reworking. The Paleoproterozoic metamorphic event is consistent with previous results and is considered to be the response to the assembly of the supercontinent Columbia in the Cathaysia block. These results confirm again that the Badu Group is a Paleoproterozoic lithostratigraphic unit and also suggest that at least part of the Mayuan Group is Paleoproterozoic. Rocks of this study also show that both lithostratigraphic preserve evidence for Mesozoic metamorphic reworking at about 230–250 Ma and they show no evidence of Paleozoic metamorphic reworking.

(3) Zircon Lu–Hf isotope results show εHf(t) values in the range of -19 to -11 with a peak of -5.5 and T_{DM}^{C}(Hf) ranging from 1.9 to 4.1 Ga with a peak at about 2.7–3.0 Ga suggesting that a major crustal growth took place during this time. This is consistent with previously suggested crustal growth peaks of ~2.7 Ga and ~2.9 Ga.

(4) A summary of the more precise geochronological data set from published works together with those of present study on the Phanerozoic metamorphic reworking of northeastern Cathaysia block shows that rocks were reworked during different Phanerozoic tectonothermal events in different zones. Rocks reworked by the Paleozoic tectonothermal event mainly outcrop in the western zone whereas those reworked during Mesozoic occur dominantly in the eastern zone. Previous models which propose uniform distribution of these rocks all across the northeastern Cathaysia block will have to be reconsidered.

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References

Andersen, T., 2002. Correction of common lead in U–Pb analysis that do not report ^{204}Pb. Chemical Geology 192, 59–79.

Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., Foudoulis, C., 2003. TEMORA 1: a new zircon standard for Phanerozoic U–Pb geochronology. Chemical Geology 200, 155–170.

Blichert Toft, J., Albarede, F., 1997. The Lu–Hf isotope geochemistry of chondrites and the evolution of the mantle–crust system. Earth and Planetary Science Letters 148, 243–258.

Cawood, P.A., Wang, Y., Xu, Y., Zhao, G., 2013. Locating South China in Rodinia and Gondwana: a fragment of greater India lithosphere? Geology 41, 903–906.

Charvet, J., Shu, L., Faure, M., Choulet, F., Wang, B., Lu, H., Breton, N.L., 2010. Structural development of the Lower Paleozoic belt of South China: genesis of an intracontinental orogen. Journal of Asian Earth Sciences 39, 309–330.

Chen, J., Jahn, B., 1998. Crustal evolution of southeastern China: Nd and Sr isotopic evidence. Tectonophysics 284, 101–133.

Chen, D.F., Li, X.H., Pan, J.M., Dong, W.Q., Chen, G.Q., Chen, X.P., 1998. Metamorphic newly produced zircons, SHRIMP Ion microprobe U–Pb age of the amphibolite of Hexi Group, Zhejiang and its implications. Acta Minerologica Sinica 4, 396–400 (In Chinese with English abstract).

Chen, C.H., Lee, C.Y., Hsieh, P.S., Zeng, W., Zhou, H.W., 2008. Approaching the age problem for some metamorphosed Precambrian basement rocks and Phanerozoic granitic bodies in the Wuyishan area: the application of EMP monazite age dating. Geological Journal of China Universities 14, 1–15 (In Chinese with English abstract).

Chen, C.H., Hsieh, P.S., Lee, C.Y., Zhou, H.W., 2011. Two episodes of the Indosinian thermal event on the South China Block: constraints from LA-ICPMS U–Pb zircon and electron microprobe monazite ages of the Darongshan S-type granitic suite. Gondwana Research 19, 1008–1023.

Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. Atlas of zircon textures. Reviews in Mineralogy and Geochemistry 53, 469–500.

Faure, M., Shu, L., Wang, B., Charvet, J., Choulet, F., Monie, P., 2009. Intracontinental subduction: a possible mechanism for the Early Palaeozoic Orogen of SE China. Terra Nova 21, 360–368.

Fletcher, C.J.N., Chan, L.S., Sewell, R.J., 2004. Basement heterogeneity in the Cathaysia crustal block, southeast China. In: Fletcher, Chris Jn, Chan, Lung S., Sewell, Roderick J., Diarmad, S., Campbell, G., Davis, Donald W., Zhu, Jieshou (Eds.), Aspects of the tectonic evolution of China, p. 145.

Fu, S.C., Chen, J.M., Lin, W.S., 1991. Geological characteristics of upper-Archaeazoic Tianjingping formation Ar_2t in western Jianning, Fujian Province. Geology of Fujian 2, 103–113 (In Chinese with English abstract).

Fujian, BGMR (Bureau of Geology and Mineral Resources of Fujian Province), 1985. Regional Geology of the Fujian Province. Geological Publishing House, Beijing pp. 1–610.

Gan, X.C., Li, H.M., Sun, D.Z., Zhuang, J.M., 1993. Geochronological study on the Precambrian metamorphic basement in northern Fujian. Geology of Fujian 12, 17–32 (In Chinese with English abstract).

Gan, X.C., Ji, H.M., Sun, D.Z., Jin, W.S., Zhao, F.Q., 1995. A geochronological study on early Proterozoic granitic rocks, southwestern Zhejiang. Acta Petrologica et Minerologica 14, 1–8 (In Chinese with English abstract).

Gao, S., Ling, W., Qiu, Y., Lian, Z., Hartmann, G., Simon, K., 1999. Contrasting geochemical and Sm–Nd isotopic compositions of Archean metasediments from the Kongling high-grade terrain of the Yangtze craton: evidence for cratonic evolution and redistribution of REE during crustal anatexis. Geochimica et Cosmochimica Acta 63, 2071–2088.

Gao, J., Klemd, R., Long, L., Xiong, X., Qian, Q., 2009. Adakitic signature formed by fractional crystallization: an interpretation for the Neo-Proterozoic meta-plagiogranites of the NE Jiangxi ophiolitic mélange belt, South China. Lithos 110, 277–293.

Grabau, A., 1924. Stratigraphy of China, part I, Paleozoic and Older. Geological Survey and Ministry of Agriculture and Commerce of China, Peking pp. 1–528.

Griffin, W., Wang, X., Jackson, S., Pearson, N., O'Reilly, S.Y., Xu, X., Zhou, X., 2002. Zircon chemistry and magma mixing, SE China: in-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. Lithos 61, 237–269.

Harley, S., Kelly, N., 2007. The impact of zircon–garnet REE distribution data on the interpretation of zircon U–Pb ages in complex high-grade terrains: an example from the Rauer Islands, East Antarctica. Chemical Geology 241, 62–87.

Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and metamorphic petrogenesis. Reviews in Mineralogy and Geochemistry 53, 27–62.

Hsü, K.J., Shu, S., Jiliang, L., Haihong, C., Haipo, P., Sengor, A., 1988. Mesozoic overthrust tectonics in south China. Geology 16, 418–421.

Hsü, K.J., Li, J., Chen, H., Wang, Q., Sun, S., Sengör, A., 1990. Tectonics of South China: key to understanding West Pacific geology. Tectonophysics 183, 9–39.

Hu, X., Xu, J., Tong, C., Chen, C., 1991. The Precambrian Geology of Southwestern Zhejiang Province. Geol. Publish. House, Beijing pp. 1–278.

Hu, Y.H., Gu, G.M., Xu, Y., Yu, S.Q., Wang, J.E., He, Y., 2011. The confirmation of the age of Caledonian Chencai Group in Zhuji area of Zhejiang Province and its geological significance. Geological Bulletin of China 30, 1661–1670 (In Chinese with English abstract).

Huang, J.Q., 1960. Preliminary summarization of geologic tectonics in China. Acta Geologica Sinica 1, 1–37 (In Chinese).

Huang, X.-L., Yu, Y., Li, J., Tong, L.-X., Chen, L.-L., 2013. Geochronology and petrogenesis of the early Paleozoic I-type granite in the Taishan area, South China: Middle-lower crustal melting during orogenic collapse. Lithos 177, 268–284.

John, B., Zhou, X., Li, J., 1990. Formation and tectonic evolution of southeastern China and Taiwan: isotopic and geochemical constraints. Tectonophysics 183, 145–160.

Kelly, N.M., Harley, S.L., Hinton, R.W., 2006. Zircon–garnet REE distribution events and processes in high grade terrains. Glodschmidt Conference Abstracts.

Li, X., 1997. Timing of the Cathaysia Block formation: constraints from SHRIMP U–Pb zircon geochronology. Episodes 20, 188–192.

Li, Z.X., Li, X.H., 2007. Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: a flat-slab subduction model. Geology 35, 179–182.

Li, S.G., Chen, Y.Z., Ge, N.J., Hu, X.J., Liu, D.L., 1996. Isotopic ages of metavolcanic rocks and metacryst mylonite in the Badu Group in southwestern Zhejiang Province and their implications for tectonics. Acta Petrologica Sinica 12, 79–87 (In Chinese with English abstract).

Li, J., Wang, G., Zheng, T., Liang, S., Li, C., 1997. Study on the Multiple Classification and Correlation of the Strata in Fujian Province. China University of Geosciences Publishing House pp. 1–216 (In Chinese).

Li, X.H., Wang, Y.X., Zhao, Z.H., Chen, D.F., Zhang, H., 1998. SHRIMP U–Pb zircon geochronology for amphibolite from the Precambrian basement in SW Zhejiang and NW Fujian Provinces. Geochimica 27, 327–334 (In Chinese with English abstract).

Li, X., Li, Z.X., Zhou, H., Liu, Y., Kinny, P.D., 2002. U–Pb zircon geochronology, geochemistry and Nd isotopic study of Neoproterozoic bimodal volcanic rocks in the Kangdian Rift of South China: implications for the initial rifting of Rodinia. Precambrian Research 113, 135–154.

Li, W., Li, X.H., Li, Z., 2005. Neoproterozoic bimodal magmatism in the Cathaysia Block of South China and its tectonic significance. Precambrian Research 136, 51–66.

Li, X.H., Li, Z.X., Li, W.X., Wang, Y., 2006. Initiation of the Indosinian orogeny in South China: evidence for a Permian magmatic arc on Hainan Island. The Journal of Geology 114, 341–353.

Li, X.-H., Li, W.-X., Li, Z.-X., Liu, Y., 2008. 850–790 Ma bimodal volcanic and intrusive rocks in northern Zhejiang, South China: a major episode of continental rift magmatism during the breakup of Rodinia. Lithos 102, 341–357.

Li, X.H., Li, W.X., Li, Z.X., Lo, C.H., Wang, J., Ye, M.F., Yang, Y.H., 2009. Amalgamation between the Yangtze and Cathaysia Blocks in South China: constraints from SHRIMP U–Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu volcanic rocks. Precambrian Research 174, 117–128.

Li, Z.X., Li, X.H., Wartho, J.A., Clark, C., Li, W.X., Zhang, C.L., Bao, C., 2010. Magmatic and metamorphic events during the early Paleozoic Wuyi-Yunkai orogeny, southeastern South China: new age constraints and pressure–temperature conditions. Geological Society of America Bulletin 122, 772–793.

Li, L.-M., Sun, M., Wang, Y., Xing, G., Zhao, G., Cai, K., Zhang, Y., 2011a. Geochronological and Geochemical study of Palaeoproterozoic gneissic granites and clinopyroxenite xenoliths from NW Fujian, SE China: implications for the crustal evolution of the Cathaysia Block. Journal of Asian Earth Sciences 41, 204–212.

Li, L.-M., Sun, M., Wang, Y., Xing, G., Zhao, G., He, Y., He, K., Zhang, A., 2011b. U–Pb and Hf isotopic study of detrital zircons from the meta-sedimentary rocks in central Jiangxi Province, South China: implications for the Neoproterozoic tectonic evolution of South China Block. Journal of Asian Earth Sciences 41, 44–55.

Li, S., Santosh, M., Zhao, G., Zhang, G., Jin, C., 2012a. Intracontinental deformation in a frontier of super-convergence: a perspective on the tectonic milieu of the South China Block. Journal of Asian Earth Sciences 49, 313–329.

Li, W.Y., Ma, C.Q., Liu, Y.Y., Robinson, P.T., 2012b. Discovery of the Indosinian aluminum A-type granite in Zhejiang Province and its geological significance. Science China Earth Sciences 55, 13–25.

Li, L., Lin, S., Xing, G., Davis, D.W., Davis, W.J., Xiao, W., Yin, C., 2013. Geochronology and geochemistry of volcanic rocks from the Shaojiwa Formation and Xingzi Group, Lushan area, SE China: implications for Neoproterozoic back-arc basin in the Yangtze Block. Precambrian Research 238, 1–17.

Lin, W., Wang, Q., Chen, K., 2008. Phanerozoic tectonics of south China block: new insights from the polyphase deformation in the Yunkai massif. Tectonics 27, 1–16.

Liu, R., 2009. Pre-Hercynian Crustal Anatexis in the Cathaysia Block: A Case Study from Zhejiang and Fujian Provinces. Chinese University of Geosciences pp. 1–81 (Doctoral dissertation, (In Chinese with English abtract)).

Liu, R., Zhang, L., Zhou, H.W., Zhong, Z.Q., Zeng, W., Xiang, H., Jin, S., Lv, X.Q., Li, C.Z., 2008. Petrogenesis of Caledonian migmatites and related granites in northwestern Fujian Province, south China: syn-deformational anatexis. Acta Petrologica Sinica 24, 1205–1222 (In Chinese with English abstract).

Liu, R., Zhou, H., Zhang, L., Zhong, Z., Zeng, W., Xiang, H., Jin, S., Lu, X., Li, C., 2009. Paleoproterozoic reworking of ancient crust in the Cathaysia Block, South China: evidence from zircon trace elements, U–Pb and Lu–Hf isotopes. Chinese Science Bulletin 54, 1543–1554.

Liu, R., Zhou, H., Zhang, L., Zhong, Z., Zeng, W., Xiang, H., Jin, S., Lu, X., Li, C., 2010. Zircon U–Pb ages and Hf isotope compositions of the Mayuan migmatite complex, NW Fujian Province, Southeast China: constraints on the timing and nature of a regional tectonothermal event associated with the Caledonian orogeny. Lithos 119, 163–180.

Ludwig, K., 2003. User's Manual for Isoplot/Ex version 3.00—A Geochronology Toolkit for Microsoft Excel, No. 4. Berkeley Geochronological Center, Special Publication.

Mao, J., Takahashi, Y., Kee, W.-S., Li, Z., Ye, H., Zhao, X., Liu, K., Zhou, J., 2011. Characteristics and geodynamic evolution of Indosinian magmatism in South China: a case study of the Guikeng pluton. Lithos 127, 535–551.

Mao, J., Ye, H., Liu, K., Li, Z., Takahashi, Y., Zhao, X., Kee, W.-S., 2013. The Indosinian collision-extension event between the South China Block and the Palaeo-Pacific plate: evidence from Indosinian alkaline granitic rocks in Dashuang, eastern Zhejiang, South China. Lithos 172–173, 81–97.

Meert, J.G., 2013. What's in a name? The Columbia (Palleopangaea/Nuna) supercontinent. Geoscience Frontiers 21, 987–993.

Nance, R.D., Murphy, J.B., Santosh, M., 2014. The supercontinent cycle: a retrospective essay. Gondwana Research 25, 4–29.

Qiu, Y.M., Gao, S., McNaughton, N.J., Groves, D.I., Ling, W., 2000. First evidence of >3.2 Ga continental crust in the Yangtze craton of south China and its implications for Archean crustal evolution and Phanerozoic tectonics. Geology 28, 11–14.

Robers, N.M.W., 2013. The boring billion? Lid tectonics, continental growth and environmental change associated with the Columbia supercontinent. Geoscience Frontiers 4, 681–691.

Rogers, J.J.W., Santosh, M., 2002. Configuration of Columbia, a Mesoproterozoic supercontinent. Gondwana Research 5, 5–22.

Rogers, J.J.W., Santosh, M., 2003. Supercontinents in Earth history. Gondwana Research 6, 357–368.

Rubatto, D., 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U–Pb ages and metamorphism. Chemical Geology 184, 123–138.

Rubatto, D., Gebauer, D., 1996. Use of cathodoluminescence for U–Pb zircon dating by ion microprobe (SHRIMP): some examples from high-pressure rocks of the Western Alps. pp. 131–132.

Santosh, M., Maruyama, S., Yamamoto, S., 2009. The making and breaking of supercontinents: some speculations based on superplumes, super downwelling and the role of tectosphere. Gondwana Research 15, 324–341.

Santosh, M., Kusky, T., Wang, L., 2011. Supercontinent cycles, extreme metamorphic processes, and changing fluid regimes. International Geology Review 53, 1403–1423.

Schaltegger, U., Fanning, C., Günther, D., Maurin, J., Schulmann, K., Gebauer, D., 1999. Growth, annealing and recrystallization of zircon and preservation of monazite in high-grade metamorphism: conventional and in-situ U–Pb isotope, cathodoluminescence and microchemical evidence. Contributions to Mineralogy and Petrology 134, 186–201.

Shu, L., Charvet, J., 1996. Kinematics and geochronology of the Proterozoic Dongxiang–Shexian ductile shear zone: with HP metamorphism and ophiolitic melange (Jiangnan region, south China). Tectonophysics 267, 291–302.

Shu, L., Faure, M., Wang, B., Zhou, X., Song, B., 2008. Late Palaeozoic–Early Mesozoic geological features of south China: response to the Indosinian collision events in southeast Asia. Comptes Rendus Geosciences 340, 151–165.

Shu, X.-J., Wang, X.-L., Sun, T., Xu, X., Dai, M.-N., 2011. Trace elements, U–Pb ages and Hf isotopes of zircons from Mesozoic granites in the western Nanling Range, South China: implications for petrogenesis and W–Sn mineralization. Lithos 127, 468–482.

Shu, X.-J., Wang, X.-L., Sun, T., Chen, W.-F., Shen, W.-Z., 2013. Crustal formation in the Nanling Range, South China Block: Hf isotope evidence of zircons from Phanerozoic granitoids. Journal of Asian Earth Sciences 74, 210–224.

Söderlund, U., Patchett, P.J., Vervoort, J.D., Isachsen, C.E., 2004. The 176Lu decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. Earth and Planetary Science Letters 219, 311–324.

Song, S., Niu, Y., Wei, C., Ji, J., Su, L., 2010. Metamorphism, anatexis, zircon ages and tectonic evolution of the Gongshan block in the northern Indochina continent—an eastern extension of the Lhasa Block. Lithos 120, 327–346.

Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geological Society, London, Special Publications 42, 313–345.

Vavra, G., 1990. On the kinematics of zircon growth and its petrogenetic significance: a cathodoluminescence study. Contributions to Mineralogy and Petrology 106, 90–99.

Wan, Y., Liu, D., Xu, M., Zhuang, J., Song, B., Shi, Y., Du, L., 2007. SHRIMP U–Pb zircon geochronology and geochemistry of metavolcanic and metasedimentary rocks in Northwestern Fujian, Cathaysia block, China: tectonic implications and the need to redefine lithostratigraphic units. Gondwana Research 12, 166–183.

Wan, Y., Liu, D., Wilde, S., Cao, J., Chen, B., Dong, C., Song, B., Du, L., 2010. Evolution of the Yunkai Terrane, South China: evidence from SHRIMP zircon U–Pb dating, geochemistry and Nd isotope. Journal of Asian Earth Sciences 37, 140–153.

Wang, Y.X., Yang, J.D., Guo, L.Z., Shi, Y.S., Hu, X.J., Wang, X., 1992. The discovery of the lower Proterozoic granite in Longquan, Zhejiang Province, and the age of the basement. Geological Review 38, 525–531 (In Chinese with English abstract).

Wang, Y., Zhang, Y., Fan, W., Peng, T., 2005. Structural signatures and $^{40}Ar/^{39}Ar$ geochronology of the Indosinian Xuefengshan tectonic belt, South China Block. Journal of Structural Geology 27, 985–998.

Wang, X.-L., Zhou, J.-C., Qiu, J.-S., Zhang, W.-L., Liu, X.-M., Zhang, G.-L., 2006. LA-ICP-MS U–Pb zircon geochronology of the Neoproterozoic igneous rocks from Northern Guangxi, South China: implications for tectonic evolution. Precambrian Research 145, 111–130.

Wang, L., Yu, J., O'Reilly, S.Y., Griffin, W.L., Sun, T., Wei, Z., Jiang, S., Shu, L., 2008a. Grenvillian orogeny in the Southern Cathaysia Block: constraints from U–Pb ages and Lu–Hf isotopes in zircon from metamorphic basement. Chinese Science Bulletin 53, 3037–3050.

Wang, X., Chen, J., Luo, D., 2008b. Study on petrogenesis of zircons from the Danzhu granodiorite and its geological implications. Geological Review 54, 387–398 (In Chinese with English abstract).

Wang, Q., Wyman, D.A., Li, Z.-X., Bao, Z.-W., Zhao, Z.-H., Wang, Y.-X., Jian, P., Yang, Y.-H., Chen, L.-L., 2010a. Petrology, geochronology and geochemistry of ca. 780 Ma A-type granites in South China: petrogenesis and implications for crustal growth during the breakup of the supercontinent Rodinia. Precambrian Research 178, 185–208.

Wang, Y., Zhang, F., Fan, W., Zhang, G., Chen, S., Cawood, P.A., Zhang, A., 2010b. Tectonic setting of the South China Block in the early Paleozoic: resolving intracontinental and ocean closure models from detrital zircon U–Pb geochronology. Tectonics 29, 1–16.

Wang, Y., Zhang, A., Fan, W., Zhao, G., Zhang, G., Zhang, Y., Zhang, F., Li, S., 2011. Kwangsian crustal anatexis within the eastern South China Block: geochemical, zircon U–Pb geochronological and Hf isotopic fingerprints from the gneissoid granites of Wugong and Wuyi-Yunkai Domains. Lithos 127, 239–260.

Wang, W., Zhou, M.-F., Yan, D.-P., Li, J.-W., 2012a. Depositional age, provenance, and tectonic setting of the Neoproterozoic Sibao Group, southeastern Yangtze Block, South China. Precambrian Research 192–195, 107–124.

Wang, X.-L., Shu, L.-S., Xing, G.-F., Zhou, J.-C., Tang, M., Shu, X.-J., Qi, L., Hu, Y.-H., 2012b. Post-orogenic extension in the eastern part of the Jiangnan orogen: evidence from ca 800–760 Ma volcanic rocks. Precambrian Research 222–223, 404–423.

Wang, Y., Wu, C., Zhang, A., Fan, W., Zhang, Y., Zhang, Y., Peng, T., Yin, C., 2012c. Kwangsian and Indosinian reworking of the eastern South China Block: constraints on zircon U–Pb geochronology and metamorphism of amphibolites and granulites. Lithos 150, 227–242.

Wang, Z., Wang, J., Du, Q., Deng, Q., Yang, F., 2013a. The evolution of the Central Yangtze Block during early Neoarchean time: evidence from geochronology and geochemistry. Journal of Asian Earth Sciences 77, 31–44.

Wang, Y., Fan, W., Zhang, G., Zhang, Y., 2013b. Phanerozoic tectonics of the South China Block: key observations and controversies. Gondwana Research 23, 1273–1305.

Wang, D., Zheng, J., Ma, Q., Griffin, W.L., Zhao, H., Wong, J., 2013c. Early Paleozoic crustal anatexis in the intraplate Wuyi-Yunkai orogen, South China. Lithos 175–176, 124–145.

Wang, W., Zhou, M.-F., Yan, D.-P., Li, L., Malpas, J., 2013d. Detrital zircon record of Neoproterozoic active-margin sedimentation in the eastern Jiangnan Orogen, South China. Precambrian Research 235, 1–19.

Wang, X.L., Yu, J.H., Shu, X.J., Tang, C.H., Xing, G.F., 2013e. U–Pb geochronology of detrital zirocns from the parametamorphic rocks of the Zhoutan Group, central Jiangxi Province. Acta Petrologica Sinica 29, 801–811 (In Chinese with English abstract).

Wang, D., Wang, X.-L., Zhou, J.-C., Shu, X.-J., 2013f. Unraveling the Precambrian crustal evolution by Neoproterozoic conglomerates, Jiangnan orogen: U–Pb and Hf isotopes of detrital zircons. Precambrian Research 233, 223–236.

Wang, Y., Xing, X., Cawood, P.A., Lai, S., Xia, X., Fan, W., Liu, H., Zhang, F., 2013g. Petrogenesis of early Paleozoic peraluminous granite in the Sibumasu Block of SW Yunnan and diachronous accretionary orogenesis along the northern margin of Gondwana. Lithos 182–183, 67–85.

Wang, Y., Zhang, A., Fan, W., Zhang, Y., Zhang, Y., 2013h. Origin of paleosubduction-modified mantle for Silurian gabbro in the Cathaysia Block: geochronological and geochemical evidence. Lithos 160–161, 37–54.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W., Meier, M., Oberli, F., Quadt, A.v, Roddick, J., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards Newsletter 19, 1–23.

Woodhead, J.D., Hergt, J.M., 2005. A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. Geostandards and Geoanalytical Research 29, 183–195.

Wu, F.Y., Yang, Y.H., Xie, L.W., Yang, J.H., Xu, P., 2006. Hf isotopic compositions of the standard zircons and baddeleyites used in U–Pb geochronology. Chemical Geology 234, 105–126.

Xia, Y., Xu, X.-S., Zhu, K.-Y., 2012. Paleoproterozoic S- and A-type granites in southwestern Zhejiang: magmatism, metamorphism and implications for the crustal evolution of the Cathaysia basement. Precambrian Research 216–219, 177–207.

Xia, Y., Xu, X., Zou, H., Liu, L., 2014. Early Paleozoic crust–mantle interaction and lithosphere delamination in South China Block: Evidence from geochronology, geochemistry, and Sr–Nd–Hf isotopes of granites. Lithos 184–187, 416–435.

Xiang, H., 2008. Phanerozoic metamorphism of Precambrian metamorphic basement in southwestern Zhejiang. Dissertation submitted to China University of Geoseiences for the Master's Degree of ScienceChina University of Geosciences, Wuhan pp. 1–50 (In Chinese with English abtract).

Xiang, H., Zhang, L., Zhou, H., Zhong, Z., Zeng, W., Liu, R., Jin, S., 2008. U–Pb zircon geochronology and Hf isotope study of metamorphosed basic–ultrabasic rocks from metamorphic basement in southwestern Zhejiang: the response of the Cathaysia Block to Indosinian orogenic event. Science in China Series D: Earth Sciences 51, 788–800.

Xiao, W., He, H., 2005. Early Mesozoic thrust tectonics of the northwest Zhejiang region (Southeast China). Geological Society of America Bulletin 117, 945–961.

Xie, L., Zhang, Y., Zhang, H., Sun, J., Wu, F., 2008. In situ simultaneous determination of trace elements, U–Pb and Lu–Hf isotopes in zircon and baddeleyite. Chinese Science Bulletin 53, 1565–1573.

Xu, X., 2005. Relict Proterozoic basement in the Nanling Mountains (SE China) and its tectonothermal overprinting. Tectonics 24.

Xu, X., O'Reilly, S.Y., Griffin, W.L., Wang, X., Pearson, N.J., He, Z., 2007. The crust of Cathaysia: age, assembly and reworking of two terranes. Precambrian Research 158, 51–78.

Xu, X.B., Zhang, Y.Q., Shu, L.S., Jia, D., Wang, R.R., Xu, H.Z., 2010. Precambrian geochronology and stratigraphy in the Wuyishan area, South China. Journal of Stratigraphy 3, 254–267 (In Chinese with English abstract).

Yang, J.D., Xu, S.J., Wang, Y.X., Hu, X.J., 1994. Determination on the Sm–Nd and Rb–Sr ages of amphibolite from Badu Group in Longquan, Zhejiang Province, and its geological implications. Geochimica 25–31 (In Chinese with English abstract).

Yao, J., Shu, L., Santosh, M., Li, J., 2013. Geochronology and Hf isotope of detrital zircons from Precambrian sequences in the eastern Jiangnan Orogen: constraining the assembly of Yangtze and Cathaysia Blocks in South China. Journal of Asian Earth Sciences 74, 225–243.

Ye, Y., Lan, Y.Q., Chen, Y.S., Farrar, E., 1994. ^{40}Ar–^{39}Ar chronology and metamorphic age of Chencai Group, Zhejiang Province, China. Acta Petrologica Sinica 2, 193–201 (In Chinese with English abstract).

Yin, C., Lin, S., Davis, D.W., Xing, G., Davis, W.J., Cheng, G., Xiao, W., Li, L., 2013. Tectonic evolution of the southeastern margin of the Yangtze Block: Constraints from SHRIMP U–Pb and LA-ICP-MS Hf isotopic studies of zircon from the eastern Jiangnan Orogenic Belt and implications for the tectonic interpretation of South China. Precambrian Research 236, 145–156.

Yu, J., Zhou, X., O'Reilly, Y., Zhao, L., Griffin, W., Wang, R., Wang, L., Chen, X., 2005. Formation history and protolith characteristics of granulite facies metamorphic rock in Central Cathaysia deduced from U–Pb and Lu–Hf isotopic studies of single zircon grains. Chinese Science Bulletin 50, 2080–2089.

Yu, J.H., Wei, Z.Y., Wang, L.J., Shu, L.S., Sun, T., 2006. Cathaysia block: a young continent composed of ancient materials. Geological Journal of China Universities 4, 440–447 (In Chinese with English abstract).

Yu, J., O'Reilly, Y.S., Wang, L., Griffin, W.L., Jiang, S., Wang, R., Xu, X., 2007a. Finding of ancient materials in Cathaysia and implication for the formation of Precambrian crust. Chinese Science Bulletin 52, 13–22.

Yu, J.H., Wang, L.J., Wei, Z.Y., Sun, T., Shu, L.S., 2007b. Phanerozoic metamorphic episodes and characteristics of Cathaysia block. Geological Journal of China Universities 3, 474–483 (In Chinese with English abstract).

Yu, J.H., Wang, L., O'Reilly, S., Griffin, W., Zhang, M., Li, C., Shu, L., 2009. A Paleoproterozoic orogeny recorded in a long-lived cratonic remnant (Wuyishan terrane), eastern Cathaysia Block, China. Precambrian Research 174, 347–363.

Yu, J.-H., O'Reilly, S.Y., Wang, L., Griffin, W.L., Zhou, M.-F., Zhang, M., Shu, L., 2010. Components and episodic growth of Precambrian crust in the Cathaysia Block, South China: evidence from U–Pb ages and Hf isotopes of zircons in Neoproterozoic sediments. Precambrian Research 181, 97–114.

Yu, J.-H., O'Reilly, S.Y., Zhou, M.-F., Griffin, W.L., Wang, L., 2012a. U–Pb geochronology and Hf–Nd isotopic geochemistry of the Badu Complex, Southeastern China: implications for the Precambrian crustal evolution and paleogeography of the Cathaysia Block. Precambrian Research 222–223, 424–449.

Yu, X., Wu, G., Zhao, X., Zhang, D., Di, Y., Qiu, J., Dai, Y., Li, C., 2012b. New geochronological data from the Paleozoic and Mesozoic nappe structures, igneous rocks, and molybdenite in the North Wuyi area, Southeast China. Gondwana Research 22, 519–533.

Zeh, A., Gerdes, A., Klemd, R., Barton, J.M., 2007. Archaean to Proterozoic crustal evolution in the central zone of the Limpopo belt (South Africa–Botswana): constraints from combined U–Pb and Lu–Hf isotope analyses of zircon. Journal of Petrology 48, 1605–1639.

Zeng, W., Zhang, L., Zhou, H., Zhong, Z., Xiang, H., Liu, R., Jin, S., Lü, X., Li, C., 2008. Caledonian reworking of Paleoproterozoic basement in the Cathaysia Block: constraints from zircon U–Pb dating, Hf isotopes and trace elements. Chinese Science Bulletin 53, 895–904.

Zhai, M., 2013. The main old lands in China and assembly of Chinese unified continent. Science China Earth Sciences 56, 1829–1852.

Zhang, S.-B., Zheng, Y.-F., Wu, Y.-B., Zhao, Z.-F., Gao, S., Wu, F.-Y., 2006. Zircon isotope evidence for ≥3.5 Ga continental crust in the Yangtze craton of China. Precambrian Research 146, 16–34.

Zhang, A., Wang, Y., Fan, W., Zhang, Y., Yang, J., 2012a. Earliest Neoproterozoic (ca. 1.0 Ga) arc-back-arc basin nature along the northern Yunkai Domain of the Cathaysia Block: geochronological and geochemical evidence from the metabasite. Precambrian Research 220–221, 217–233.

Zhang, F., Wang, Y., Zhang, A., Fan, W., Zhang, Y., Zi, J., 2012b. Geochronological and geochemical constraints on the petrogenesis of Middle Paleozoic (Kwangsian) massive granites in the eastern South China Block. Lithos 150, 188–208.

Zhang, S.-B., Wu, R.-X., Zheng, Y.-F., 2012c. Neoproterozoic continental accretion in South China: geochemical evidence from the Fuchuan ophiolite in the Jiangnan orogen. Precambrian Research 220–221, 45–64.

Zhang, Y., Wang, Y., Fan, W., Zhang, A., Ma, L., 2012d. Geochronological and geochemical constraints on the metasomatised source for the Neoproterozoic (~825 Ma) high-mg volcanic rocks from the Cangshuipu area (Hunan Province) along the Jiangnan domain and their tectonic implications. Precambrian Research 220–221, 139–157.

Zhang, C.-L., Santosh, M., Zou, H.-B., Li, H.-K., Huang, W.-C., 2013a. The Fuchuan ophiolite in Jiangnan Orogen: geochemistry, zircon U–Pb geochronology, Hf isotope and implications for the Neoproterozoic assembly of South China. Lithos 179, 263–274.

Zhang, Y., Wang, Y., Geng, H., Zhang, Y., Fan, W., Zhong, H., 2013b. Early Neoproterozoic (~850 Ma) back-arc basin in the Central Jiangnan Orogen (Eastern South China): geochronological and petrogenetic constraints from meta-basalts. Precambrian Research 231, 325–342.

Zhao, G., Cawood, P., 1999. Tectonothermal evolution of the Mayuan Assemblage in the Cathaysia Block; implications for Neoproterozoic collision-related assembly of the South China Craton. American Journal of Science 299, 309–339.
Zhao, G., Cawood, P.A., 2012. Precambrian geology of China. Precambrian Research 222–223, 13–54.
Zhao, L., Zhou, X., 2012. The metamorphic evolution and pT path of pelitic granulite from the Badu Group in Southwestern Zhejiang Province. Acta Petrologica et Minerologica 31, 61–71 (In Chinese with English abstract).
Zhao, G., Cawood, P.A., Wilde, S.A., Sun, M., 2002. Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth-Science Reviews 59, 125–162.
Zhao, G., Sun, M., Wilde, S.A., Li, S., 2003. Assembly, accretion and breakup of the Paleo-Mesoproterozoic Columbia supercontinent: records in the North China Craton. Gondwana Research 6, 417–434.
Zhao, G., Sun, M., Wilde, S.A., Li, S., 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth-Science Reviews 67, 91–123.
Zhao, L., Guo, F., Fan, W., Li, C., Qin, X., Li, H., 2010. Crustal evolution of the Shiwandashan area in South China: Zircon U–Pb–Hf isotopic records from granulite enclaves in Indo-Sinian granites. Chinese Science Bulletin 55, 2028–2038.
Zhao, J.-H., Zhou, M.-F., Yan, D.-P., Zheng, J.-P., Li, J.-W., 2011. Reappraisal of the ages of Neoproterozoic strata in South China: no connection with the Grenvillian orogeny. Geology 39, 299–302.
Zhao, L., Zhou, X., Zhai, M., Santosh, M., Ma, X., Shan, H., Cui, X., 2014. Paleoproterozoic tectonic transition from collision to extension in the eastern Cathaysia Block, South China: evidence from geochemistry, zircon U–Pb geochronology and Nd–Hf isotopes of a granite–charnockite suite in southwestern Zhejiang. Lithos 184–187, 259–280.
Zheng, J.P., Griffin, W.L., Li, L.S., O'Reilly, S.Y., Pearson, N.J., Tang, H.Y., Liu, G.L., Zhao, J.H., Yu, C.M., Su, Y.P., 2011. Highly evolved Archean basement beneath the western Cathaysia Block, South China. Geochimica et Cosmochimica Acta 75, 242–255.
Zheng, Y.-F., Xiao, W.-J., Zhao, G., 2013. Introduction to tectonics of China. Gondwana Research 23, 1189–1206.
Zhou, X., Sun, T., Shen, W., Shu, L., Niu, Y., 2006. Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: a response to tectonic evolution. Episodes 29, 26.
Zhu, K.-Y., Li, Z.-X., Xu, X.-S., Wilde, S.A., 2013. Late Triassic melting of a thickened crust in southeastern China: evidence for flat-slab subduction of the Paleo-Pacific plate. Journal of Asian Earth Sciences 74, 265–279.