Palaeoproterozoic A-type magmatism in northern Wuyishan terrane, Southeast China: petrogenesis and tectonic implications

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ABSTRACT
In this article we present zircon U–Pb ages, Hf isotopes, and whole-rock geochemistry of the Longzhu rhyolite porphyry from the Cathaysia Block, Southeast China to constrain its petrogenesis and provide insights into the early Precambrian tectonic evolution of the Cathaysia Block. LA-ICP-MS zircon U–Pb dating of a representative sample yields a weighted mean 206Pb/238U age of 1819 ± 16 Ma, interpreted as the crystallization age of the Longzhu rhyolite porphyry. Zircons from this sample have εNd(t) values ranging from ~ 8.4 to ~ 2.2 and εHf(DM2) model ages from 2.76 to 2.46 Ga. The whole-rock Nd isotopic data from the Longzhu rhyolite porphyries yield εNd(t) values spanning ~ 6.3 to ~ 4.7 and εHf(DM2) model ages from 2.81 to 2.69 Ga. The rhyolite porphyries have geochemical features similar to those of the typical A-type granites (rhyolites), with high SiO2, total alkali contents and Fe2O3/MgO ratios, and low CaO and MgO contents. Additionally, the rhyolite porphyries have high total rare earth element concentrations (627 ~ 760 ppm), high (La/Yb)N values (14.5 ~ 26.9), strongly negative Eu anomalies (δEu = 0.28 ~ 0.41), and display enrichments of Rb, Ga, Th, and U and depletions of Sr, Nb, Ta, Eu, and Ti. The geochemical and Nd-Hf isotopic features suggest that the Palaeoproterozoic Longzhu rhyolite porphyries were generated by partial melting of source rocks similar to those of the Badu Complex in an intra-plate extensional setting. The results from this study, when combined with existing geochronological data, further demonstrate that the Palaeoproterozoic rocks of Wuyishan terrane probably represent a remnant of the Columbia supercontinent.

Introduction
South China is an important geological region in eastern Asia, comprising the Yangtze Block to the northwest and the Cathaysia Block to the southeast. It was formed through the assembly of the two blocks along the Shaoxing–Jiangshan–Pinging Fault during the Neoproterozoic (Li et al. 1995; Zhao and Cawood 1999; Wang et al. 2007a; Chen et al. 2009a, 2009b) (Figure 1). The term Cathaysia Block, named after the ‘Cathaysia old-land’ by Grabau (1924), is characterized by Precambrian metamorphic basement rocks which are unconformably overlain by the unmetamorphosed Lower Devonian sandstones (Shui 1988; Jahn et al. 1990; Hu et al. 1992; Gan et al. 1995; Chen and Jahn 1998; Li et al. 2000; Xu et al. 2007; Yu et al. 2009, 2012).

The oldest rocks in the Cathaysia Block mostly outcrop in southwest Zhejiang Province and northwest Fujian Province. It was commonly accepted that a unified Palaeoproterozoic and Mesoproterozoic crystalline basement existed in the Wuyishan terrane of Cathaysia Block, including the Palaeoproterozoic Badu, Tianjingping, and Mayuan groups, and the Mesoproterozoic Mamianshan, Wanquan, Longquan, and Chencai groups, based on conventional single- or multiple-grain zircon U–Pb methods or Sm–Nd isochron ages (Shui 1988; Hu et al. 1992; Gan et al. 1995, 1996; Zhuang et al. 2000). Recently, the application of advanced geochronological methods (SHRIMP and LA-ICP-MS) has been applied to the basement rocks, demonstrating that all these stratigraphic sequences formed in the Neoproterozoic or even later time, except for the Palaeoproterozoic Badu and Tianjingping groups in the Wuyishan terrane (Figure 2a) (Li et al. 2000; Wan et al. 2007; Yu et al. 2009). These basement rocks were intensively deformed and metamorphosed during the prolonged, multiple tectono-thermal events during the Neoproterozoic to Mesozoic (Li et al. 2005, 2010, 2011a; Wan et al. 2007; Wang et al. 2012).

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complicating understanding of their temporal-spatial distribution and evolutionary histories (Shu 2006; Wan et al. 2007; Xu et al. 2007; Yu et al. 2007, 2010; Yao et al. 2011). Therefore, the scale or distribution of this Palaeoproterozoic basement is an intriguing question and still needs to be precisely defined. In this study, we undertake systematic field and experimental work to confirm a Palaeoproterozoic A-type rhyolite porphyry body in the northern Wuyishan region, and thus provide new and important insights into the early Precambrian tectonic evolution of the Cathaysia Block.

Geological background and samples

The Precambrian basement rocks of the Cathaysia Block are mainly exposed between the Shaoxing–Jiangshan–Pingxiang and Zhenghe–Dapu faults (Shu 2006), as sporadic tectonic windows largely covered by Mesozoic felsic volcanic rocks or intruded by Mesozoic granites (Yu et al. 2009). The basement rocks in the Cathaysia Block have been divided into two metamorphic sequences on the basis of lithologic and structural features and metamorphic grades (Li 1997). The lower sequence is termed the Mayuan Group in NW Fujian, and the Badu Group in SW Zhejiang, while the upper one is termed the Mamianshan Group in Fujian and the Longquan and Chencai groups in Zhejiang (Jin et al. 1992). Both the lower and upper sequences are characterized by amphibolite-facies metamorphism (Xiang et al. 2008; Zeng et al. 2008; Li et al. 2010, 2011b).

The Badu Group, also referred to as the Badu Complex (Yu et al. 2009, 2012; Xia et al. 2012), is widely distributed in the study area (Figure 2a), consisting of the Tangyuan, Qiantou, Zhangyan, Siyuan, and Dayanshan formations upwards (Hu et al. 1992). The Badu Complex mainly comprises graphitic mica schist, garnet sillimanite gneiss, marble, amphibolites, and migmatites. The typical metamorphic mineral assemblage of the metasedimentary rocks from the Badu Complex is composed of garnet + sillimanite + graphite (Zhao et al. 2015).
The Longzhu rhyolite porphyry is located in the northern Wuyishan terrane, with an outcrop area of approximately 0.12 km$^2$. It is in clear intrusive contact with the Badu Complex (Figure 2b). Jurassic volcanic rocks occur in the vicinity of the rhyolite porphyry body (Figure 2b). Four fresh samples were collected from the rhyolite porphyry in Longzhu region, Zhejiang Province. All rhyolite porphyry samples are pinkish, with gneissic structure and porphyritic texture. Quartz, plagioclase, and biotite are the main phenocrysts (10–15%) and are always present as corroded grains (Figure 3a, b, c, and d). The matrix is mainly composed of felsic minerals (85–90%) with a cryptocrystalline texture. Some of these contain variable concordant to nearly concordant felsic veins that are generally folded, indicating weak migmatization. Sample ZJ-11–1 was selected as a representative sample for zircon U–Pb dating and Lu–Hf isotope analysis because of its minimal migmatization. Major and trace element analyses were carried out for all samples.

**Analytical techniques**

Zircons were extracted using standard density and magnetic separation techniques. Selected zircon grains were hand-picked under a stereoscopic microscope and were
mounted in epoxy resin before being polished for analysis. Cathodoluminescence images were taken using a JXA-8800 R electron microprobe at the Institute of Mineral Resources in the Chinese Academy of Geological Sciences, Beijing.

Zircon dating was conducted by the LA-ICP-MS method at the School of Resources and Environmental Engineering at Hefei University of Technology, using an Agilent 7500a ICP-MS coupled with a 193 nm ComPex102-ArF laser-ablation system (Coherent Inc., USA). A spot size of 32 μm with a repetition rate of 6 Hz was applied in all analyses. The standard 91,500 and MT zircons were used as an external standard to normalize isotopic fractionation during isotope analysis, and we calibrated trace elements with an NIST610 as the external standard and 29Si as the internal standard. The detailed analytical procedures are described in Liu et al. (2008, 2010). U–Pb ages and U–Th contents of the zircon spots analysed were processed using the ICPMSDataCal program (Liu et al. 2010). Common Pb was corrected after Andersen (2002), and ISOPLOT software (Version 2.49) was used to calculate weighted zircon ages and depict a concordia plot (Ludwig 2001).

Zircon Hf isotopic analysis was carried out in situ using a New-wave UP213 laser-ablation microprobe, attached to a Neptune multi-collector ICP-MS, with a spot size of 44 μm and a repetition rate of 8 Hz, at the Institute of Mineral Resources. Instrumental conditions and data acquisition are described by Wu et al. (2006) and Hou et al. (2007). Zircon GJ-1 was used as the reference standard, with a weighted mean 176Hf/177Hf ratio of 0.282010 ± 0.000010 (2σ, n = 10) during our routine analyses. In this work, we adopted the value of 1.865 × 10−11 year⁻¹ as the 176Lu decay constant (Scherer et al. 2001). Initial 176Hf/177Hf ratios εHf(t) were calculated with reference to the chondritic reservoir of Blichert-Toft and Albarede (1997). The depleted mantle Hf model age (TDM1) was calculated with present-day 176Hf/177Hf (0.28325) and 176Lu/177Lu (0.0384) (Griffin et al. 2000). Two-stage ‘crustal’ model ages (TDM2) were calculated assuming that the parental magma of the zircon was derived from a source with an average continental crust 176Lu/177Hf of 0.015 (Griffin et al. 2002).

Whole-rock major-element analyses were performed by X-ray fluorescence spectrometry (XRF) using Panalytical (Holland) apparatus at the Nanjing Institute of Geology and Mineral Resources, Nanjing. Analytical precision is generally better than 5% for all elements (Chen and Xing 2013). Trace element abundances were measured using an Agilent 7500a ICP-MS at the State Key Laboratory of Continental Dynamics at Northwest University, Xi’an. Analytical precision is better than 5–10% (Rudnick et al. 2004). Nd isotopic compositions were determined at the State Key Laboratory for Mineral Deposits Research at Nanjing University using a

Figure 3. Field photographs and microphotographs of rhyolite porphyries in the Longzhu region. (a) Field outcrop showing contact between the rhyolite porphyry and Badu Complex; (b) undulatory extinction of quartz phenocryst; (c) allanition of biotite phenocryst (plane polarized light); (d) felsitic texture and secondary enlargement of hyperthermal quartz phenocryst (perpendicular polarized light for (c)). Qtz, quartz; Bt, biotite; Pl, plagioclase.
Finnigan Triton TI TIMS, following the methods of Pu et al. (2005).

Results

\textbf{U–Pb ages and trace elements of zircon grains}

Twenty-five spot analyses were made on 25 zircon grains from sample ZJ-11–1. The analytical results are listed in Supplementary Table 1 (see http://dx.doi.org/10.1080/00206814.2015.1125808 for supplementary tables) and graphically illustrated in Figure 4. Most zircon grains have concentric, weak oscillatory zoning structures with thin metamorphic rims in CL images. They are 100–300 μm in length with elongation ratios of 2:1 to 3:1 (Figure 4a). The 23 spots have U and Th contents ranging from 77 to 433 ppm and 108 to 2024 ppm, respectively, with Th/U ratios of 0.25 to 1.62 that are typical of magmatic zircons (Koschek 1993). All the analyses show a well-defined discordia line with an upper intercept at 1844 ± 26 Ma (MSWD = 0.91; Figure 4b) and a lower intercept at 157 ± 650 Ma (not shown). Twenty-three concordant analyses fall within a group close to the upper intercept, yielding a weighted mean $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1819 ± 16 Ma (MSWD = 0.91, $n = 23$). This weighted mean age is within the error of the upper intercept age and is thus interpreted as the best estimate for the crystallization age of the Longzhu rhyolite porphyry. Two metamorphic zircons have $^{206}\text{Pb}/^{238}\text{U}$ ages of 238 and 240 Ma, and low Th/U ratios (0.08–0.09) with 12–15 ppm Th and 134–186 ppm U. The ca. 240 Ma age is considered to represent the timing of metamorphic overprint of the Longzhu rhyolite porphyry during the early Mesozoic.

Trace element analyses of magmatic zircons from sample ZJ-11–1 are presented in Supplementary Table 2. Zircons have Hf contents of 9178–14,587 ppm and Y of 334–3255 ppm. In the chondrite-normalized rare earth element (REE) patterns, most zircons are characterized by significant heavy HREE (HREE) enrichment, positive Ce anomalies, and prominent negative Eu anomalies (Figure 4c), features consistent with magmatic zircons (Belousova et al. 2002). The analysed zircons contain Ti in the range 16.1–41.2 ppm (Supplementary Table 2), yielding crystallization temperatures of 813–917°C (averaging 865°C) calculated using a Ti-in-zircon thermometer (Watson and Harrison 2005). Trace element data for two metamorphic zircons are not given because of unstable instrument status during LA-ICP-MS analysis.

\textbf{Whole-rock geochemistry}

The major and trace element analyses are listed in Supplementary Table 4. In general, these samples have...
high SiO$_2$ ranging from 67.2 to 72.1%, and high alkali contents with K$_2$O of 6.45–6.51% and Na$_2$O of 1.95–2.43%. They are characterized by low Fe$_2$O$_3$ contents of 0.66–1.36%, CaO of 0.96–1.65%, MgO of 0.18–0.43%, TiO$_2$ of 0.24–0.43%, and P$_2$O$_5$ of 0.09–0.24%. All these samples are classified as shoshonitic series according to the K$_2$O vs. SiO$_2$ diagram. Their Al$_2$O$_3$ contents vary between 13.19 and 13.97%, exhibiting an aluminous feature (A/CNK = 0.99–1.09). In Harker diagrams, the samples analysed display a negative correlation between some major elements (e.g. CaO, P$_2$O$_5$, and TFe$_2$O$_3$) and SiO$_2$, plotting in the fields of the Badu metasedimentary rocks, consistent with the trend of Palaeoproterozoic A-type granites in the Wuyishan terrane.

All the samples exhibit high REE contents, relative enrichment of light RREs (LREEs) ((La/Sm)$_N$ = 5.13–6.84, (La/Yb)$_N$ = 14.4–27.9), flat HREE patterns, and strong negative Eu anomalies (Supplementary patterns) and trace element spidergram (Figure 6b), all the samples show characteristic negative anomalies of Ba, Nb, Ta, Sr, P, Eu, and Ti. The negative Ba, Sr, and Eu anomalies may be associated with residues of plagioclase in the magma source, whereas the negative P and Ti anomalies are attributed to residues of apatite and ilmenite. In addition, the samples of the Longzhu rhyolite porphyries and Palaeoproterozoic A-type granites analysed from the Wuyishan terrane have REE patterns and trace element diagrams similar to Palaeoproterozoic Badu metasedimentary rocks (Figure 6), suggesting the possibility that they were mainly derived from crustal materials.

Figure 5. Harker diagrams of major-element compositions of the Longzhu rhyolite porphyries. Data source for Palaeoproterozoic A-type granites and Badu metasedimentary rocks in the Wuyishan terrane are from Yu et al. (2009, 2012), Xia et al. (2012), and Liu et al. (2009, 2014).

Figure 6. (a) Chondrite-normalized REE pattern and (b) N-MORB-normalized trace element spidergram of the Longzhu rhyolite porphyries. Chondrite and N-MORB values are from Sun and McDonough (1989). Data sources for Palaeoproterozoic A-type granites and Badu metasedimentary rocks in the Wuyishan terrane are Yu et al. (2009, 2012), Xia et al. (2012), and Liu et al. (2009, 2014).
**Hf isotopes**

Fifteen zircon grains analysed for U–Pb dating were selected for in situ Hf isotope analysis using LA-MC-ICP-MS, and the results are listed in Supplementary Table 3. These zircons have variable $^{176}$Hf/$^{177}$Hf ratios (0.281405–0.281588, Supplementary Table 3), corresponding to $\varepsilon_{\text{Hf}}(t)$ values of –8.1 to –2.2 and two-stage Hf model ages ($T_{\text{Hf DM2}}$) between 2.76 and 2.46 Ga.

**Nd isotopes**

The whole-rock Nd isotopic data of the Longzhu rhyolite porphyries are given in Supplementary Table 4. Four samples have similar Nd isotopic compositions, with $\varepsilon_{\text{Nd}}(t)$ values of −3.8 to −6.4 and $T_{\text{Nd DM2}}$ ages of 2.87–2.65 Ga, similar to the Hf model ages of the Palaeoproterozoic zircons in this study (2.76–2.46 Ga). These analyses are also similar to published Nd isotopic data for the metamorphic rocks from the Budu Complex, further documenting their petrogenetic relationship (Hu et al. 1992; Yu et al. 2009; Xia et al. 2012; Liu et al. 2014; Zhao et al. 2015).

**Discussion**

**Genetic type of the Longzhu rhyolite porphyry: an A-type affinity**

Granitic rocks are generally divided into I-, S-, M-, and A-types, mainly according to geochemistry signatures (Whalen et al. 1987; Pitcher 1997). Relative to the well-known I- and S-type granites, A-type granites typically have chemical compositions with high SiO$_2$, (Na$_2$O + K$_2$O), Zr, Nb, Ta, Ga, Y, and REE (except Eu) contents, high Fe/Mg and Ga/Al ratios, and low concentrations of CaO, Ba, Sr, and Eu (Whalen et al. 1987; Eby 1990). A-type granites are also distinguished from other types by their relatively high temperature origin (Clemens et al. 1986; King et al. 1997, 2001).

The Longzhu rhyolite porphyries show high K$_2$O + Na$_2$O, Zr, Nb, and Ce contents, and high FeO/FeO$^\text{t}$ + MgO and Rb/Sr ratios, which share the geochemical features most common to A-type granites (Collins et al. 1982; Whalen et al. 1987; King et al. 1997, 2001). Their 10,000*Ga/Al ratios vary from 3.1 to 4.0 with an average of 3.6, close to the global average of 3.75 for A-type granites (Whalen et al. 1987), but higher than those of the aluminous A-type granites from southeastern China (Wu et al. 2002). In the discrimination diagrams of (K$_2$O + Na$_2$O) and FeO/FeO$^\text{t}$/MgO vs. 10,000*Ga/Al (Figure 7), they all plot in the field of A-type granites. The Longzhu rhyolite porphyries can easily be discriminated from S-type granites because the latter have much higher P$_2$O$_5$ contents, and are always peraluminous (King et al. 1997; Bonin 2007). Compared with highly evolved I-type granites at the same SiO$_2$ level, the Longzhu rhyolite porphyries are comparatively well enriched in Zr, Nb, Y, Ce, and Ga (Yang et al. 2006; Zhao et al. 2008; Peng et al. 2012; Lei et al. 2013). In addition, The Longzhu rhyolite porphyry has relatively high magma temperatures as shown by the Ti-in-zircon formation temperatures of 813–917°C (average 865°C) (Supplementary Table 2) and Zr saturation temperatures of 878–913°C (average 896°C) (Supplementary Table 4). These values are markedly higher than temperatures of I-type granites but similar to those of typical A-type granites worldwide (e.g. Clemens et al. 1986; King et al. 1997, 2001; Miller et al. 2003; Bonin 2007). High temperatures also account for the absence of inherited zircons in the Longzhu rhyolite porphyry. Taken together, we suggest that the Longzhu rhyolite porphyries are of A-type affinity.
Sources and petrogenesis

Many compositional variations have been found for A-type granites (rhyolites), and there is no consensus on the origin of A-type magma (Bonin 2007). Several petrogenetic schemes have been proposed for the origin of A-type granites: (1) direct fractionation of mantle-derived magmas or hybridization between anatectic granitic and mantle-derived mafic magmas (Eby 1990; Foland and Allen 1991; Turner et al. 1992; Kerr and Fray 1993; Bonin 2007; Sun et al. 2011); (2) low degrees of partial melting of lower-crustal granulites by extraction of previous granitic melt (Collins et al. 1982; Clemens et al. 1986; Whalen et al. 1987; King et al. 1997); (3) low-pressure melting of calc-alkaline rocks at upper crustal levels (Sylvester 1989; Creaser et al. 1991; Skjerlie and Johnston 1992; Patiño Douce 1997); and (4) partial melting of tholeiitic rocks newly derived from the mantle (Frost and Frost 1997; Dall’Agnol and de Oliveira 2007; Wang et al. 2010a). However, among these petrogenetic models above, interaction of mantle-derived magma with crustal rocks, and melting of deep continental crust, are considered the most important mechanism (Rämö and Haapala 1995; Bonin 1996).

The high Rb/Sr ratios and significant negative $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values of the Longzhu rhyolite porphyry suggest that it cannot be originated from mantle-derived magmas. The lack of mafic enclaves in this porphyry argues against material involvement of mafic magma in the source. The Longzhu rhyolite porphyry has relatively high magma temperatures, indicating that the source rocks should have been underplated and heated by mantle-derived mafic magmas. Therefore, mantle input may have dominated as the heat source for the formation of the A-type Longzhu rhyolite porphyry. The identification of Palaeoproterozoic intra-plate rifting and mafic-ultramafic rocks in the neighbouring region also provides supportive evidence for the existence of underplating magmatism (Xiang et al. 2008).

Available geochronological and geochemical data suggest that Palaeoproterozoic S- and A-type granites in the northern Wuyishan terrane were mostly derived from the metamorphic rocks of the Badu Complex (Liu et al. 2009, 2014; Yu et al. 2009; Xia et al. 2012). The Badu metamorphic rocks have whole-rock Nd isotopic model ages of 2.87–2.65 Ga and zircon (most detrital grains) Hf isotopic model ages of 3.0–2.4 Ga, similar to zircons in those S- and A-type Palaeoproterozoic granites, suggesting similar sources (Yu et al. 2009, 2012; Xia et al. 2012; Liu et al. 2014). Likewise, the two-stage whole-rock Nd isotopic model ages (2.81–2.69 Ga) and zircon Hf isotopic model ages (2.76–2.46 Ga) of the Longzhu rhyolite porphyry are all consistent with those of the metamorphic rocks from the Badu Complex (Xu et al. 2007; Xiang et al. 2008; Liu et al. 2009, 2014; Yu et al. 2009, 2012; Xia et al. 2012; Zhao et al. 2015) (Figure 8). Regarding petrogenesis of Palaeoproterozoic A-type granites in the Wuyishan terrane, Yu et al. (2009) further proposed three possible models to explain their formation: (1) melting of a source residual after extraction of S-type granitic melts; (2) partial melting of meta-igneous rocks; and (3) mixing of majority sedimentary source with low proportions of mafic materials. However, to date, such felsic orthometamorphic rocks and amphibolites in the Badu Complex still lack systematic reliable geochemical studies and precise dating. Thus, here we were unable to estimate these last two schemes. In fact, the enriched Nd-Hf isotopic compositions of the Longzhu rhyolite porphyries also imply little mantle material contribution in their genesis. Notably, the studied rhyolite porphyries have similar major-element compositions to the Badu metasedimentary rocks (Figure 5). In addition, the Longzhu rhyolite porphyries also have similar REE patterns and trace element diagrams to metasedimentary rocks of the Badu Complex (Figure 6). Considering these results in the context of the regional geology, we are inclined to conclude that the Palaeoproterozoic Longzhu rhyolite porphyries were derived from metasedimentary rocks similar to those of the Badu Complex. We are unable to determine whether they originated from partial melting of granulitic residues after extraction of S-type granitic melts. Our geochemical data cannot provide a definitive solution, whereas this inference is partly supported by their higher magma temperatures (>813°C, see above) and younger ages of A-type
Longzhu rhyolite porphyry compared with those of S-type granites.

**Tectonic significance**

Late Palaeoproterozoic collisional orogenic events have been increasingly recognized in Precambrian cratons worldwide, and may have ultimately resulted in the formation of the supercontinent Columbia (e.g. Rogers and Santosh 2002; Zhao et al. 2002, 2004, 2009; Santosh et al. 2007). In the last two decades, Palaeoproterozoic tectonothermal events have also been recognized in the Cathaysia Block (Li 1997; Li and Li 2007; Wang et al. 2008; Liu et al. 2009, 2014; Yu et al. 2009, 2012; Li et al. 2010, 2011b; Xia et al. 2012; Chen and Xing 2013). Available precise ages and geochemical affinity are compiled in Table 1 and Figure 9; it appears that the I-type granites were generated at 1.91–1.89 Ga in the Proterozoic.

**Table 1.** A complication of precise zircon U–Pb ages of different types of Palaeoproterozoic rocks in the Wuyishan terrane.

| Location       | Lithology     | Geochemical affinity | Age (Ma) | Low intercept | Metamorphic | Dating method       | Data source         |
|----------------|---------------|----------------------|----------|---------------|-------------|---------------------|---------------------|
| Zhuji          | Chencai meta-gabbro | A-type               | 1781 ± 21 | 197           | SHRIMP zircon U-Pb | Li et al. (2010)    |
| Suichang       | Tianhou granodiorite | A-type               | 1856 ± 10 | 230           | SHRIMP zircon U-Pb | Yu et al. (2009)    |
| Songyang       | Lizhuang granite | S-type               | 1875 ± 9  | 233           | LA-ICP-MS zircon U-Pb | Yu et al. (2009)    |
|                | Jingju granite | A-type               | 1861 ± 35 | 226           | LA-ICP-MS zircon U-Pb | Xia et al. (2012)   |
|                | Jingju granite | A-type               | 1849 ± 30 | 231           | LA-ICP-MS zircon U-Pb | Xia et al. (2012)   |
|                | Jinluohou granite | A-type             | 1877 ± 10 | 224           | LA-ICP-MS zircon U-Pb | Xia et al. (2012)   |
|                | Jinluohou granite | S-type             | 1878 ± 28 | 18            | LA-ICP-MS zircon U-Pb | Xia et al. (2012)   |
| Longquan       | Danzhu granite | A-type               | 1832 ± 6  | 243           | SHRIMP zircon U-Pb | Li and Li (2007)    |
|                | Danzhu granodiorite | A-type           | 1875 ± 33 | 209           | LA-ICP-MS zircon U-Pb | Wang et al. (2008)  |
|                | Danzhu monzogranite | A-type          | 1855 ± 8  | 228           | LA-ICP-MS zircon U-Pb | Yu et al. (2009)    |
|                | Danzhu granite | A-type               | 1867 ± 8  | 230           | LA-ICP-MS zircon U-Pb | Yu et al. (2009)    |
|                | Huaqiao granitoid | A-type            | 1859 ± 21 | 18            | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Danzhu meta-mafic rocks | A-type       | 1850 ± 9  | 260–230       | LA-ICP-MS zircon U-Pb | Liu et al. (2009)   |
|                | Badu Complex  | A-type               | 1886–1882 |              | LA-ICP-MS zircon U-Pb | Yu et al. (2012)    |
|                | Longzhu rhyolite porphyry | A-type       | 1819 ± 16 Ma | 157           | 240–238     | LA-ICP-MS zircon U-Pb | This study          |
| Jingning       | Sanzhishu granite | A-type             | 1860 ± 13 Ma | 238          | 114–108     | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Chimushan granite | I-type             | 1887 ± 19 | 185           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Chimushan granite | S-type             | 1876 ± 18 | 319           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Xiaocu granite | I-type               | 1912 ± 51 | 238           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Xiaocu granite | S-type               | 1882 ± 21 | 250           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Xiaocu granitoid | A-type             | 1869 ± 24 | 220           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Wongkeng granite | S-type             | 1884 ± 14 | 229           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
|                | Wongkeng granitoid | A-type          | 1878 ± 20 | 192           | LA-ICP-MS zircon U-Pb | Liu et al. (2014)   |
| Qingyuan       | Xiaji granite  | S-type               | 1887 ± 7  | 233           | LA-ICP-MS zircon U-Pb | Yu et al. (2009)    |
| Pucheng        | Qiuyuan granite | S-type              | 1851 ± 21 | 234           | LA-ICP-MS zircon U-Pb | Li et al. (2011b)   |
|                | Qiuyuan granite | S-type              | 1857 ± 29 |              | LA-ICP-MS zircon U-Pb | Li et al. (2011b)   |
|                | Xiaochuan      | S-type              | 1839 ± 16 |              | LA-ICP-MS zircon U-Pb | Chen et al. (2013)  |
| Jianning       | Tianjingping meta-mafic rocks | A-type | 1766 ± 19 |              | LA-ICP-MS zircon U-Pb | Li (1997)           |
Wuyishan terrane, whereas the A- and S-type granites were more or less synchronously generated at 1.88–1.82 Ga. Moreover, the Palaeoproterozoic granulite facies metamorphism (ca. 1.89 Ga, Yu et al. 2012) is almost earlier than that of A-type magmatism (1.88–1.82 Ga), indicating such a collisional orogen to intra-plate extensional setting may be more likely to explain Palaeoproterozoic tectonic evolution. This strong collisional event has been identified from the Badu Complex, as marked by 1.89 Ga high-pressure metamorphism (Yu et al. 2012). Subsequent extension occurred during the 1.88–1.76 Ga interval, as manifested by A-type granites and rift-related mafic rocks in the Wuyishan terrane (Li 1997; Li et al. 2000; Liu et al. 2009, 2014; Yu et al. 2009, 2014; Yu et al. 2009; Xia et al. 2012). In this study, zircon U–Pb dating constrains the formation of the Longzhu rhyolite porphyry at ca. 1.82 Ga, indicating an important Palaeoproterozoic tectonothermal event in the northern Wuyishan. This newly obtained U–Pb age also substantiates the existence of Palaeoproterozoic basement rocks in northern Wuyishan, represented by remnants of the Columbia supercontinent.

The Longzhu rhyolite porphyry in northern Wuyishan has an A-type affinity and was likely produced by reworking of the Palaeoproterozoic Badu Complex. A-type granites (rhyolites) have been traditionally considered to form in intra-plate extensional tectonic environment, regardless of the origin of the magma source (Whalen et al. 1987; Eby 1992; Pitcher 1997). The Longzhu rhyolite porphyry has relatively high magma temperatures, suggesting mantle input (heat) in their petrogenesis (see above). These formation temperatures for the Longzhu rhyolite porphyry are comparable to values of A-type granites in the northern Wuyishan (Yu et al. 2009; Xia et al. 2012; Liu et al. 2014), indicating that they were all generated in an intra-plate extensional tectonic setting. Indeed, the Palaeoproterozoic Longzhu A-type rhyolite porphyries in southwestern Zhejiang mainly fall into the within-plate field in the tectonic discrimination diagram (Figure 10). Intra-plate extension could easily have facilitated upwelling and decompression melting of the mantle asthenosphere to produce mafic magmas that provided heat energy, inducing crustal anatexis to form the A-type granitic magmatism represented by the Longzhu rhyolite porphyry. Taking into account all geochronological and geochemical data on Palaeoproterozoic (1.88–1.82 Ga) A-type rocks of the Wuyishan terrane (Table 1, Figure 9) (Liu et al. 2009, 2014; Yu et al. 2009; Xia et al. 2012), we suggest initiation of intra-plate extension after 1.89 Ga, perhaps at 1.88–1.82 Ga in the Cathaysia Block. Subsequent enhanced extension at 1.78–1.77 Ga resulted in the eruption of minor volumes of rift-related mafic magmas (Li et al. 2000, 2010), signalling the cessation of the whole Palaeoproterozoic tectonic evolutionary cycle in the Wuyishan terrane (Liu et al. 2014).

The early Mesozoic metamorphic event was identified in this study area, and is recorded in the Longzhu rhyolite porphyry sample (ZJ-11–1) with a $^{206}$Pb/$^{238}$U age of ca. 240 Ma. Recent studies suggest that the Palaeoproterozoic Badu Complex and S- and A-type granites also underwent early Mesozoic metamorphism, probably having reached amphibolite-granulite facies (Xiang et al. 2008; Yu et al. 2009, 2012; Xia et al. 2012; Liu et al. 2014; Zhao et al. 2015). Metamorphism led not only to Pb loss in Palaeoproterozoic zircons and older (Archean) inherited cores, but also resulted in overgrowth or recrystallization of rims on earlier zircons in those of Palaeoproterozoic rocks (Xiang et al. 2008; Yu et al. 2009, 2012; Xia et al. 2012; Liu et al. 2014; Zhao et al. 2015). In fact, early Mesozoic tectono-magmatic events are well known in Southeast China and are characterized by an intensely compressional tectonic setting related to the Indosinian Orogeny. This collisional orogenic event might have affected Mesozoic intra-plate reworking of the Cathaysia Block (Zhao et al. 2015).

**Conclusions**

1. LA-ICP-MS zircon U–Pb ages indicate that the Longzhu rhyolite porphyry was formed at ca. 1.82 Ga and suffered metamorphic overprinting in early Mesozoic (ca. 240 Ma).
(2) The geochemical data and zircon Hf isotopic compositions of the Longzhu rhyolite porphyry suggest that they have A-type affinity and were probably produced by reworking of source rocks similar to those of the Badu Complex in an intra-plate extensional setting.

(3) Palaeoproterozoic basement rocks in northern Wuyishan terrane may represent remnants of the Columbia supercontinent.

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