First discovery of a Palaeoproterozoic A-type granite in southern Wuyishan terrane, Cathaysia Block: evidence from geochronology, geochemistry, and Nd–Hf–O isotopes

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ABSTRACT

In this study, a combined study of zircon U–Pb and Hf–O isotopes, as well as whole-rock major and trace elements and Nd isotopes has been conducted for Yangjia gneissic granite from the southern Wuyishan terrane, Southeast China, to constrain its petrogenesis and provide a new window for investigating the tectonic evolution of the Cathaysia basement. U–Pb dating for magmatic zircons yields a 207Pb/206Pb age of ca. 1.80 Ga, interpreted as the emplacement age of the Yangjia granite. The granites have relatively high K2O, Rb, Ga, Zr, Nb, Y, and Ce contents and show low Al2O3, CaO, and Ba concentrations. Their 10,000*Ga/Al ratios range between 2.8 and 3.2. Zircons from the granite have εNd(t) values ranging from −13.2 to −7.2, corresponding to TDM2 model ages of 2.99 Ga to 2.72 Ga. The zircon δ18O values range between 6.7‰ and 9.1‰ with an average of 7.7‰. In addition, the whole-rock εNd(t) values of the granites range from −6.5 to −5.4 and the TDM2 model ages from 2.73 Ga to 2.82 Ga. All these geochemical and Nd–Hf–O isotopic signatures suggest an A-type affinity for the Yangjia granites, and they were likely generated by partial melting of Palaeoproterozoic parametamorphic rocks of the Wuyishan terrane in a post-collisional extensional setting. When our data is combined with existing geochronological data, it provides further evidence for the Palaeoproterozoic basement in the southern Wuyishan terrane, which records a rapid tectonic transition from post-collision to intraplate extension (1.80–1.77 Ga) related to the break-up of the supercontinent Columbia.

Introduction

Granitoids are one of the most abundant rock types in the Earth’s upper continental crust, and their petrogenesis is closely associated with tectonics and geodynamics. They have commonly been divided into I-, S-, M-, and A-types according to the nature of their protolith and genesis (Chappell and White 1974; Martin et al. 2005). The I- and S-type granites are considered to be derived from pre-existing intra-crustal igneous rocks and supra-crustal sedimentary rocks, respectively (Chappell and White 1974; Chappell et al. 1998; Chappell 1999). However, A-type granites are distinct from the common I-type and S-type granites. Loiselle and Wones (1979) first introduced the term ‘A-type granite’ into the geological community. Since then, A-type granites have drawn extensive attentions and enthused numerous articles dealing with their compositional features, petrogenesis, tectonic settings, and association with mineralization (Whalen et al. 1987; Eby 1990, 1992; Wu et al. 2002; Bonin 2007). A-type granites are generally derived from relative anhydrous and high-temperature magmas (Loiselle and Wones 1979). They are interpreted to have been formed in extensional tectonic regimes (i.e. rift zones, anorogenic settings, or post-collisional extensional settings). Therefore, the recognition of A-type granites can provide a diagnostic indicator of the extensional geodynamic environment and provide significant information on intraplate extensional or post-orogenic processes on a local or regional scale (Whalen et al. 1987; Eby 1992; Turner et al. 1992).

The Cathaysia Block is one of the largest Precambrian blocks in eastern China, which can be divided into the Wuyishan terrane to the northeast and the Nanling–Yunkai terrane to the southwest (Figure 1) (Yu et al. 2008, 2010). The Nanling–Yunkai terrane was originally a rifted sedimentary basin associated with break-up of the Rodinia supercontinent (Wang et al. 2007, 2010; Yu et al. 2008, 2010; Wan et al. 2010). The Precambrian basements of the Wuyishan terrane are composed of two main suites of metamorphic strata: the Badu...
(Palaeoproterozoic), Longquan, and Chencai Groups (Neoproterozoic) in Zhejiang Province; and the Tianjingping (Palaeoproterozoic), Mayuan, Miamianshan, Dikou, Jiaoxi, and Wanquan Groups (Neoproterozoic) in Fujian Province (Figure 2(a)) (Li 1997; Li et al. 2000, 2005; Wan et al. 2007; Wang et al. 2007, 2010; Yu et al. 2012; Zhao et al. 2014). New studies also show that a smaller part of the Mayuan Group is of Palaeoproterozoic age (Li et al. 2011b; Zhao et al. 2015). In this article, we first present detailed zircon U–Pb–Hf–O isotopic and whole-rock geochemical studies for a Palaeoproterozoic A-type granite body in south Wuyishan (Figure 2(b)) in an attempt to provide insights into the early Precambrian tectonic evolution history of the Cathaysia Block.

**Geological background and samples**

South China consists of the Yangtze Block in the northwest and the Cathaysia Block in the southeast that were amalgamated along the Shaoxing–Jiangshan–Pingxiang Fault during the Neoproterozoic (Figure 1) (Li et al. 2008). The Precambrian basement rocks of the Cathaysia Block are mainly exposed in northwest Fujian and southwest Zhejiang provinces, as sporadic tectonic windows largely covered by Mesozoic felsic volcanic rocks or intruded by Mesozoic granites (Shu 2006; Yu et al. 2009). According to lithologic and geologic assessments, the basement rocks are divided into two metamorphic sequences. The lower sequence is named the Mayuan Group in the northwest Fujian Province and the Badu Group in the southwest Zhejiang Province, whereas the upper sequence is named the Miamianshan Group in Fujian and the Longquan and Chencai Groups in Zhejiang (Hu et al. 1992; Jin et al. 1992). Both the lower and upper sequences were characterized by amphibolite–granulite facies metamorphism (Xiang et al. 2008; Zeng et al. 2008; Li et al. 2011b).

The Mayuan Group is widespread in the study area (Figure 2(a)), consisting of the Dajinshan Formation and the Nanshan Formation from bottom to top (Zhuang et al. 2000). The Dajinshan Formation is composed predominantly of schist, gneiss, quartzite, marble, and amphibolite, whereas the Nanshan Formation is made up of strongly deformed gneiss and schist (Zhuang et al. 2000; Wan et al. 2007). The estimated peak P–T conditions of the Mayuan Group were 570–680°C at 4.3–7.0 kbar (Mei et al. 1993; Jin and Sun 1997) or 590–625°C at 4.2–4.5 kbar (Zhao and Cawood 1999).

The Yangjia gneissic granite body lies in NW Fujian Province, southern Wuyishan terrane, with an outcrop area of approximately 4 km². It was intruded by the
Mesozoic granite. The Dajinshan Formation is also exposed in the vicinity of the gneissic granite body (Figure 2(b)). All the studied samples from the Yangjia gneissic granite show a gneissic structure and are mainly composed of plagioclase (15–25%), K-feldspar (35–45%), quartz (20–25%), and biotite (5–10%), with minor amounts of garnet, zircon, apatite, and magnetite (Figure 3). K-feldspar occurs as subhedral tabular microcline perthite crystals. Plagioclase is partially sericitized subhedral crystals with polysynthetic twins. Biotite occurs as anhedral flaky mineral aggregates and is occasionally chloritized, and quartz usually occurs as elongate aggregates. Compositional bands of granular and flaky minerals are visible in both field outcrop and thin section (Figure 3).

Figure 2. (a) Sketch geological map of the Wuyishan terrane (modified from Hu et al. 1992; Zhuang et al. 2000; Chen et al. 2016). (b) Simplified geological map of the Yangjia granite. Reliable Palaeoproterozoic igneous rocks are from Li (1997), Li and Li (2007), Li et al. (2010, 2011b), Xiang et al. (2008), Liu et al. (2009, 2014), Yu et al. (2009), Xia et al. (2012), Chen and Xing (2013), Chen et al. (2016), and Zhao et al. (2014). Source data is listed in Table 1.

Figure 3. Representative field photo and microphotograph for the Yangjia granite in northwest Fujian. Mineral abbreviation: Qtz, quartz; Fs, feldspar; Kfs, K-feldspar; Pl, plagioclase; Bt, biotite.
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. CL images were taken using a JXA-8800R electron microprobe at the Institute of Mineral Resources in the Chinese Academy of Geological Sciences, Beijing.

Zircon U–Pb isotopic dating was carried out at the School of Resources and Environmental Engineering, Hefei University of Technology. The zircons were dated on an Agilent 7500a ICP-MS equipped with a 193 nm ComPex102-ArF laser-ablation system (Coherent Inc, USA). Spot size was set to be 32 μm. Helium was used as the carrier gas. Zircon 91,500 was used as an external reference material for correcting mass bias and elemental fractionation, which was analysed twice every five analyses of zircon samples. The zircon standard Mud Tank (MT) (732 ± 5 Ma, Black and Gulson 1978) was analysed as a known sample to monitor the accuracy of the zircon age. Forty analyses yielded a weight mean 206Pb/238U age of 736 ± 8 Ma, identical within errors to the reported age of 732 ± 5 Ma (Black and Gulson 1978). Trace elements were calibrated with NIST610 as the external standard and 28Si as the internal standard (Yan et al. 2012). Offline selection and integration of background and analyte signals, and time-drift correction and quantitative calibration were conducted using an in-house software ICPMSDataCal program (Liu et al. 2008, 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 in situ Hf isotope analysis was carried out using a New-wave UP213 laser-ablation microprobe, attached to a Neptune multi-collector ICP-MS at Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing. The instrumental conditions and data acquisition were described by Hou et al. (2007). Zircon GJ-1 was used as the reference standard, with a weighted mean 176Hf/177Hf ratio of 0.282010 ± 0.000008 (2σ, n = 20) 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 and εHf(t) were calculated with reference to the chondritic reservoir of Bleichert-Toft and Albarède (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).

Zircon oxygen analysis was performed at the Beijing SHRIMP Center, Chinese Academy of Geological Science, Beijing, using the SHRIMP-IIe/MC. Detailed analytical procedure follows that described by Ickert et al. (2008). Instrument mass fractionation was corrected using the standard zircon BR266 (δ18O = 13.26‰ (Vienna Standard Mean Ocean Water, VSMOW)) (Ge et al. 2014). Corrected 18O/16O ratios are reported in δ18O notation, in per mil variations relative to VSMOW (18O/16O = 0.0020052). The internal precision of individual analyses was mostly <0.5‰, with an average of 0.32‰. Twenty-three analyses of BR266 yielded a spot-to-spot precision (reproductivity) of 0.52‰ (2σ) during the analytical session.

Whole-rock major-element analyses were performed by an X-ray fluorescence spectrometer (XRF) using Panalytical, Holland apparatus at Nanjing Institute of Geology and Mineral Resources, Nanjing. Analytical precisions as determined on the Chinese National standards GSR-1 and GSR-3 were generally around 1–5% (Chen and Xing 2013). Trace element abundances were measured using an Agilent 7500a ICP-MS at the State Key Laboratory of Continental Dynamics in Northwest University in Xi’an. The United States Geological Survey and the Chinese National standards (BCR-2, GSR-1, and GSR-3) were used for calibrating the element concentrations of the measured samples. In-run analytical precision for most elements was generally better than 5% (Liu et al. 2007).

Whole-rock Nd isotopic compositions were determined at the State Key Laboratory for Mineral Deposits Research at Nanjing University using a Finnigan Triton Tl thermal ionization mass spectrometer. The detailed chemical separation and isotopic measurement procedures used were described in Pu et al. (2005). For the present analyses, the Nd isotopic ratios were corrected for mass fractionation by normalizing to 146Nd/144Nd = 0.7219. During the analysis period, measurements of the Japan JNd–1 Nd standard yielded a 143Nd/144Nd ratio of 0.512072 ± 0.000010 (n = 12,2σ).

Results

U–Pb ages and trace elements of zircon grains

Two samples (WY-13 and WY-15) from the Yangjia pluton were selected for zircon U–Pb dating. The results are listed in Table S1 and plotted in Figure 5.

Zircon grains from sample WY-13 are prismatic with abraded edges and thin overgrowths. CL images show oscillatory and broadly zoned (Figure 4(a)) or homogeneous internal structures. Their Th and U concentrations range from 129 ppm to 528 ppm and from 258 ppm to 1024 ppm, respectively, with Th/U ratios of 0.26–0.95,
implying a magmatic origin. All the analyses define a well-defined discordia line with an upper intercept at 1800 ± 10 Ma (mean standard weighted deviation (MSWD) = 1.4; Figure 5(a)). Twenty concordant analyses fall in a group close to the upper intercept, yielding a weighted mean $^{207}$Pb/$^{206}$Pb age of 1796 ± 16 Ma (MSWD = 0.23). This weighted mean age is within errors of the upper intercept age.

Zircons in sample WY-15 are mostly euhedral and sharply prismatic. CL images show oscillatory zoning structures with thin metamorphic rims (Figure 4(b)), and they have Th and U contents ranging from 234 ppm to 677 ppm and from 356 ppm to 899 ppm, respectively, with Th/U ratios of 0.26–0.99, characteristic of a magmatic origin. Twenty analysed spots define a discordia line with the upper intercept at 1793 ± 26 Ma (MSWD = 0.27; Figure 5(b)). They have coherent $^{207}$Pb/$^{206}$Pb ages ranging from 1829 ± 46 to 1773 ± 30 Ma with a weighted average of 1795 ± 15 Ma (MSWD = 0.22, N = 20). This age is also identical within error to the age of sample WY-13, indicating that the Yangjia granite formed at ca. 1.80 Ga. Twenty trace element contents were simultaneously obtained for zircons from sample WY-15 during zircon U–Pb dating (Table S2). These zircons have Hf contents of 7078–13,599 ppm and Y contents of 722–2364 ppm. In the chondrite-normalized REE pattern, they show HREE enrichments, positive Ce anomalies, and moderate negative Eu anomalies (Figure 5(c)), features consistent with magmatic zircons (Belousova et al. 2002). Their Ti contents vary from 18.9 to 38.7 ppm (Table S2), which define the formation temperatures ranging from 798 to 876°C (average 838°C), by using the Ti-in-zircon thermometer (Watson and Harrison 2005).
**Hf–O isotopes**

Thirty-five zircon grains that were analysed for U–Pb dating were selected for Lu–Hf isotope analysis, and 20 zircons for O isotope analysis. The Hf–O analysed results are listed in Table S3. These zircons have variable $^{176}\text{Hf}/^{177}\text{Hf}$ ratios between 0.281298 and 0.281477 (Table S3), corresponding to $\varepsilon\text{Hf}(t = 1800 \text{ Ma})$ values of $-13.2$ to $-7.2$ and two-stage Hf model ages ($T_{\text{Hf}\text{DM2}}$) between 2.72 and 2.99 Ga. $\delta^{18}\text{O}$ values of the Palaeoproterozoic zircons range from 6.7‰ to 9.1‰, with an average of 7.7‰.

**Nd isotopes**

The whole-rock Nd isotope compositions are listed in Table S4. The four granite samples have relatively consistent $^{143}\text{Nd}/^{144}\text{Nd}$ ratios ranging from 0.511299 to 0.511325, corresponding to $\varepsilon\text{Nd}(t = 1800 \text{ Ma})$ values of $-6.5$ to $-5.4$. They yield two-stage Nd model ages ($T_{\text{Nd}\text{DM2}}$) ages of 2.82–2.73 Ga.

**Whole-rock geochemistry**

The major and trace element analyses are given in Table S5. These samples have high SiO$_2$ ranging from 68.1 to 72.4%, and high alkalis contents with K$_2$O of 6.21–7.26% and Na$_2$O of 2.05–2.83%. They are characterized by low TFe$_2$O$_3$ contents of 2.55–4.24%, CaO of 0.41–1.81%, MgO of 0.50–0.75%, TiO$_2$ of 0.25–0.42%, and P$_2$O$_5$ of 0.09–0.16%. All these samples are classified as shoshonitic series according to the K$_2$O versus SiO$_2$ diagram (not shown). Their A$_2$O$_3$ contents vary between 13.17% and 14.21%, exhibiting a metaluminous to slightly peraluminous feature (A/CNK ($\text{A}_2\text{O}_3$/($\text{CaO + Na}_2\text{O + K}_2\text{O}$) mole) = 0.99–1.08). In the normalized Q-A-P (quartz-orthoclase-plagioclase) classification diagram, the Yangjia granites plot in the field of syeno- and alk-granites (Figure 6).

All the samples show high REE contents and strong negative Eu anomalies (Table S2 and Figure 7(a)). They have moderate LREE enrichment ((La/Yb)$_N$ ratios of 5.3–8.4). In the normal mid-ocean-ridge basalt (N-MORB)-normalized trace element spidergram (Figure 7(b)), the samples exhibit high concentrations of Rb, Th, and Pb. They also show characteristics of negative anomalies of Ba, Sr, and Eu, which might be associated with the magmatic differentiation of plagioclase residual. In addition, the Yangjia granites and other Palaeoproterozoic A-type granites have REE patterns and trace element diagrams similar to the Palaeoproterozoic parametamorphic rocks in the Wuyishan terrane (Figure 7), suggesting the possibility that they were mainly derived from crustal materials.

**Figure 6.** Normalized Q-A-P classification diagram. Mineral abbreviation: Q, quartz; Or, orthoclase; Pl, plagioclase.

**Figure 7.** (a) Chondrite-normalized REE pattern and (b) N-MORB-normalized trace element spidergram of the Yangjia granites. Chondrite and N-MORB values are from Sun and McDonough (1989). Data source for Palaeoproterozoic A-type granites and parametamorphic rocks in the Wuyishan terrane are from Yu et al. (2009, 2012), Xia et al. (2012), Liu et al. (2009, 2014), Zhao et al. (2014, 2015), and Chen et al. (2016).
Discussion

Genetic type: an A-type affinity

The ‘A-type granite’ was named by Loiselle and Wones (1979) for the meaning of ‘alkaline’, ‘anhydrous’, and ‘anorogenic’. Further studies have demonstrated that the A-type granites are compositionally diverse. For example, they may be peralkaline and contain sodium-rich mafic minerals or be weakly peraluminous to metaluminous without sodium-rich mafic minerals (King et al. 1997; Kemp and Hawkesworth 2003). Nevertheless, A-type granites share the common geochemical characteristics of high K$_2$O, Fe/Mg contents, and incompatible elements such as REE (except Eu), Zr, and Hf, but low Al$_2$O$_3$, CaO, and Ba contents (Collins et al. 1982). They are characterized by high field strength element contents (Zr+Nb+Ce+Y > 350 ppm) and high 10,000*Ga/Al ratios (>2.6) (Whalen et al. 1987). In addition, A-type granites are also distinguished from other types of granites by their relatively high formation temperatures (Clemens et al. 1986; King et al. 1997, 2001).

The Yangjia granites resemble the features of A-type granite. They have high K$_2$O + Na$_2$O (up to 9.50%), high (Zr+Nb+Ce+Y > 440 ppm) contents, and Ga/Al ratios (10,000*Ga/Al = 2.8–3.2). In the discrimination diagrams of (K$_2$O+N$_2$O)/CaO versus (Zr+Nb+Ce+Y) and (Zr+Nb+Ce+Y) versus 10,000*Ga/Al (Figure 8), all the samples plot in the field of A-type granites. Although the Yangjia granites have an aluminous nature with A/CNK values of 0.99–1.08, they display a negative correlation between P$_2$O$_5$ and SiO$_2$ in the Harker diagram (not shown), which can be easily differentiated from S-type granites (King et al. 1997; Bonin 2007). Compared with high-evolved I-type granites at the same SiO$_2$ level, the Yangjia granites are comparatively enriched in Zr, Nb, Y, Ce, and Ga (Yang et al. 2006). In addition, the Yangjia granite has relatively high magma temperatures as revealed from the Ti-in-zircon formation temperatures of 798–876°C (average 838°C) (Table S2). These values are remarkably higher than temperatures of I-type granites, but similar to those of typical A-type granites worldwide (Clemens et al. 1986; King et al. 1997, 2001; Miller et al. 2003; Bonin 2007). Therefore, we consider that the Yangjia granites are aluminous A-type granites.

Petrogenesis of the Yangjia granite

Although a broad consensus has been reached concerning the tectonic setting and geochemical features of A-type granites, the origins of such granites are still quite controversial. Three main models have been proposed to explain the petrogenesis of A-type granites, which can be derived from crust (Collins et al. 1982; Clemens et al. 1986; Whalen et al. 1987; Creaser et al. 1991; King et al. 2001), mantle (Turner et al. 1992; Mushkin et al. 2003), and crust–mantle interactions (Anderson et al. 2003; Yang et al. 2006).

Mantle-derived A-type granites are generally associated with great amounts of mafic rocks (Turner et al. 1992) and show depleted Nd–Hf isotopic compositions (Kemp et al. 2006). These features are quite different from the Yangjia A-type granites, and thus preclude such a possibility. Crust–mantle interactions, including mantle-derived melts coupled with crustal assimilation and crystal fractionation (assimilation and fractional crystallization (AFC) process) (Anderson et al. 2003; Barboli and Bussy 2013) and magma mixing between mantle- and crust-derived melts (Yang et al. 2006; Haapala et al. 2007), have also been used to explain the formation of A-type granites. However, a remarkably large volume of basalts could only form even a small-scale felsic A-type granite through the AFC process.
Yangjia gneissic granites also imply little mantle material contribution in their genesis (Table S3 and Figure 9). Their relatively high magma temperatures indicate a possible underplating mantle heat input for their formation process. Taken together, we suggest the Yangjia A-type granite formed by the recycling of ancient crust in the high-temperature environment. The Yangjia granites have whole-rock Nd isotopic model ages of 2.82–2.73 Ga and zircon–Hf isotopic model ages of 2.99–2.72 Ga, consistent with those detrital zircons in the Dajinshan Formation reported by Zhao et al. (2015), and also similar to Palaeoproterozoic S- and A-type granites and parametamorphite in the Wuyishan terrane (Figure 10; Liu et al. 2009, 2014; Yu et al. 2009, 2012; Xia et al. 2012; Chen and Xing 2013; Zhao et al. 2014, 2015, 2016). In addition, the Yangjia A-type granites also have similar major-element compositions and REE patterns and trace element diagrams to the Palaeoproterozoic parametamorphic rocks in the Wuyishan terrane (Hu et al. 1992; Yu et al. 2009, 2012; Xia et al. 2012; Liu et al. 2014; Zhao et al. 2014, 2015; Chen et al. 2016). All of these further support the fact that the Yangjia A-type granites may be derived from the reworking of the Palaeoproterozoic metamorphic basement in the Wuyishan terrane. Anderson and Thomas (1985) and Whalen et al. (1987) pointed out that melting of previously dehydrated metasedimentary source rocks can also form A-type granites, which can explain their genetic affinity with S-type granites in the Palaeoproterozoic S- and A-type granites association of the northern Wuyishan terrane (Yu et al. 2009, 2012; Xia et al. 2012; Liu et al. 2014). We are unable to determine whether the Yangjia A-type granites in the southern Wuyishan terrane originated from partial melting of granulitic residues after the extraction of S-type magma. Our data can not provide a definitive solution because of lacking directly accompanied Palaeoproterozoic S-type granites in the study area, whereas this interpretation is partly supported by their higher magmas temperatures (average 838°C, see above) and younger ages of the Yangjia A-type granite compared with those of S-type granites in the Wuyishan terrane (Chen et al. 2016).

### Tectonic significances

A series of global collisional orogenic events have been documented in many large continental cratons during the Palaeoproterozoic and they are generally considered to have resulted in the formation of the supercontinent Columbia (e.g. Rogers and Santosh 2002; Zhao et al. 2002, 2004, 2009; Santosh et al. 2007). Some Palaeoproterozoic tectonothermal events in the Cathaysia Block have also been found (Gan et al. 1995; Barboni and Bussy 2013). Therefore, the lack of mafic rocks and mafic enclaves in this study does not favour the AFC model. Magma mixing is a common cause for the generation of A-type granites, which is difficult to discriminate using the whole-rock geochemical compositions for they might be homogenized in granite pluton. However, zircon Hf–O isotopic compositions are susceptible to magma mixing and are thus usually used to reconstruct such processes (Zhou et al. 2015). It has been documented that magma mixing processes would yield large variations in Hf–O isotope compositions (Yang et al. 2006; Bonin 2007). Thus, a narrow range of zircon $\varepsilon_{Hf}(t)$ and $\delta^{18}O$ values of the Yangjia A-type granites (Table S3 and Figure 9) suggests that magma mixing could be excluded in their genesis. In fact, the enriched Nd–Hf–O isotopic compositions of the Yangjia granites also suggest magma mixing processes (Zhou et al. 2015).
Li 1997; Li et al. 2000, 2010, 2011b; Li and Li 2007; Liu et al. 2009, 2014; Yu et al. 2009, 2012; Xia et al. 2012; Chen and Xing 2013; Zhao et al. 2014, 2015, 2016. Based on the ages and geochemistry of the Palaeoproterozoic igneous rocks in the Wuyishan terrane, Liu et al. (2014) subdivided three main magmatic events related to a late Palaeoproterozoic orogeny: 1.91–1.88 Ga I- and S-type granitic magmatism (syn-orogenic), 1.88–1.83 Ga A-type granitic magmatism (post-orogenic), and 1.78–1.77 Ga mafic magmatism (anorogenic). However, Zhao et al. (2014) recognized the 1.93 Ga syn-collisional leucogranite and the 1.89–1.85 Ga post-collisional A-type granites in the Badu Group. Xiang et al. (2008) reported rift-related mafic-ultramafic dikes (ca. 1.85 Ga) in the Danzhu area of SW Zhejiang. Xia et al. (2012) found Palaeoproterozoic (1.89–1.85 Ga) intraplate rifting S- and A-type granite associations in north Wuyishan. Therefore, timing of this collisional cycle remains an issue of controversy. Nevertheless, the strong orogenic event (1.89–1.85 Ga high-pressure metamorphism) has been newly identified from the Badu and Mayuan Groups (Yu et al. 2012; Zhao et al. 2014, 2015). This implies that at least post-collisional and intraplate extension in the Wuyishan terrane began after ca. 1.85 Ga. In this article, our zircon dating data clearly define a formation age of the Yangjia granites at ca. 1.80 Ga, implying an important Palaeoproterozoic magmatic event in the southern Wuyishan. This presently obtained U–Pb age also supports the widespread Palaeoproterozoic basement in the Wuyishan terrane, representing an important part of the Columbia supercontinent.

As mentioned above, the Yangjia granites have an A-type affinity and were likely produced by the reworking of Palaeoproterozoic metasedimentary rocks in the Wuyishan terrane. A-type granites have been traditionally considered to form in an extensional tectonic environment (Whalen et al. 1987; Eby 1992; Pitcher 1997). Eby (1992) further subdivided A-type granites into A1 and A2 groups. The A1 group represents the differentiation of magmas derived from ocean island basalt-like sources and emplaced in an anorogenic setting, such as continental rift or intraplate environments, whereas the A2 group is derived from the melting of continental crust or underplated mafic crust and emplaced in post-collisional or post-orogenic environments. The A1 and A2 groups can be differentiated by using the Y–Nd–Ce geochemical discriminating diagram (Eby 1992). The studied samples from the Yangjia granite are mostly plotted into the A2 group (Figure 11), and are all plotted in the post-collisional field (Figure 11), well consistent with their crustal origin. Therefore, it is inferred that the Yangjia A-type granites formed in a post-collisional tectonic setting. Taking into account all Palaeoproterozoic magmatism and high-pressure metamorphism in the Wuyishan terrane (Table 1, Figure 12), we suggest the beginning of syn-orogen at ca. 1.93 Ga, perhaps at the time of ca. 1.93–1.85 Ga in the Wuyishan terrane. Subsequent post-collisional and intraplate extension resulted in the formation of the later A- and S-type granitic and basaltic rocks (1.85–1.77 Ga). When our new findings of Palaeoproterozoic Yangjia granites (ca. 1.80 Ga) are combined with the existing intraplate rifting meta-mafic rocks (Tianjingping Group) (ca. 1.77 Ga) (Figures 2 and 12), it demonstrates a potential tectonic transition from post-collision to intraplate extension at about 1.80–1.77 Ga in the southern Wuyishan terrane, which might be related to the break-up of the Palaeoproterozoic supercontinent Columbia. This whole Palaeoproterozoic orogeny in the Wuyishan terrane from 1.93 Ga to 1.77 Ga, with a time span of ~ 160 million years, is in agreement with other typical global orogenies (Liu et al. 2014), such as the Grenville orogenic cycle (ca. 1.35–1.00 Ga, McLelland et al. 1996) related to the amalgamation of...
Table 1. Precise geochronological data for the Palaeoproterozoic rocks in the Wuyishan terrane.

| Locations | Lithology | La | Geochronological age (Ma) | Geochronological age (Ma) | Crystallization | Low intercept | Metamorphic | Dating method | Data source |
|-----------|-----------|----|--------------------------|--------------------------|-----------------|---------------|-------------|--------------|-------------|
| Zhuji     | Chencai meta-gabbro |   | 1781 ± 21                |                          |                 |               |             | SHRIMP zircon U-Pb | Li et al. (2010) |
| Suichang  | Dazhe granites | S-type | 1929 ± 15                | 1872 ± 34                |                 |               |             | LA-ICP-MS zircon U-Pb | Zhao et al. (2014) |
|           | Dazhe granodiorite | A-type | 1886 ± 16                | LA-ICP-MS zircon U-Pb    |                 |               |             | LA-ICP-MS zircon U-Pb | Zhao et al. (2014) |
|           | Dazhe charnockite | A-type | 1858 ± 7                 | LA-ICP-MS zircon U-Pb    |                 |               |             | LA-ICP-MS zircon U-Pb | Zhao et al. (2014) |
|           | Dazhe charnockite | A-type | 1848 ± 11                | LA-ICP-MS zircon U-Pb    |                 |               |             | LA-ICP-MS zircon U-Pb | Zhao et al. (2014) |
|           | Tianhou granodiorite | A-type | 1856 ± 10                | 197                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Yu et al. (2009) |
| Songyang  | Lihuang granite | S-type | 1875 ± 9                 | 233                      | 232             | LA-ICP-MS zircon U-Pb |             | LA-ICP-MS zircon U-Pb | Yu et al. (2009) |
|           | Jingu granite | A-type | 1861 ± 35                | 226                      | SHRIMP zircon U-Pb |                 |             | SHRIMP zircon U-Pb | Xie et al. (2012) |
|           | Jingu granite | A-type | 1849 ± 30                | 231                      | SHRIMP zircon U-Pb |                 |             | SHRIMP zircon U-Pb | Xie et al. (2012) |
|           | Jinluohou granite | A-type | 1877 ± 10                | 224                      | SHRIMP zircon U-Pb |                 |             | SHRIMP zircon U-Pb | Xie et al. (2012) |
|           | Jinluohou granite | S-type | 1878 ± 28                | 18                       | SHRIMP zircon U-Pb |                 |             | SHRIMP zircon U-Pb | Xie et al. (2012) |
| Longquan  | Danzhu granite | A-type | 1832 ± 6                 | 243                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Li and Li (2007) |
|           | Danzhu granodiorite | A-type | 1875 ± 33                | 209                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Wang et al. (2008) |
|           | Danzhu monzogranite | A-type | 1855 ± 8                 | 228                      | 248             | LA-ICP-MS zircon U-Pb |             | LA-ICP-MS zircon U-Pb | Yu et al. (2009) |
|           | Danzhu granite | A-type | 1867 ± 8                 | 230                      | 230             | LA-ICP-MS zircon U-Pb |             | LA-ICP-MS zircon U-Pb | Yu et al. (2009) |
|           | Huaqiao granitoid | A-type | 1859 ± 21                | 212                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Danzhu meta-mafic rocks | A-type | 1850 ± 9                 | 233                      | 260–230         | LA-ICP-MS zircon U-Pb |             | Xiang et al. (2008) |
|           | Longzhu rhyolite porphyry | A-type | 1844 ± 26                | 157                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Chen et al. (2016) |
|           | Badu Complex |  | 1886–1882                | 1894–1850                | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Zhao et al. (2015) |
|           | Jinling |  |  |  |  |  |  |  |  |  |
|           | Sanzhihu granitic | A-type | 1860 ± 13 Ma              | 209                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2009) |
|           | Chimushan granite | I-type | 1867 ± 19                | 185                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Chimushan granite | S-type | 1876 ± 18                | 319                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Xiaocui granite | I-type | 1912 ± 51                | 238                      | 114–108         | LA-ICP-MS zircon U-Pb |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Xiaocui granite | S-type | 1882 ± 21                | 250                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Xiaocui granite | S-type | 1869 ± 24                | 220                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Wongkeng granite | S-type | 1884 ± 14                | 229                      | 239             | LA-ICP-MS zircon U-Pb |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
|           | Wongkeng granitoid | A-type | 1878 ± 20                | 192                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Liu et al. (2014) |
| Qingyuan  | Xinji granite | S-type | 1887 ± 7                 | 233                      | 234             | LA-ICP-MS zircon U-Pb |             | LA-ICP-MS zircon U-Pb | Yu et al. (2009) |
|           | Qiuyuan granite | S-type | 1857 ± 29                | 234                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Li et al. (2011b) |
|           | Xiaoquan granite | A-type | 1839 ± 16                | 16                      | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Chen and Xing (2013) |
| Jianou    | Dajinshan Formation |  | 1859–1873                | 1894–1850                | LA-ICP-MS zircon U-Pb |                 |             | LA-ICP-MS zircon U-Pb | Zhao et al. (2015) |

Figure 12. Age histogram of precise Palaeoproterozoic magmatism and metamorphism in the Wuyishan terrane. Data source is listed in Table 1 and references therein.

the Rodinia supercontinent, the Pan-African orogenic cycle from 0.65 Ga to 0.50 Ga (Cordani et al. 2003) associated with the configuration of the Gondwana supercontinent, the ca. 0.50–0.35 Ga Caledonian orogeny in Europe (Grade et al. 2003), and the Hercynian orogenic cycle that resulted in the Pangea supercontinent (ca. 0.43–0.30 Ga) (Kroner and Romer 2013).

Conclusions

(1) The Yangjia granite was emplaced at ca. 1.80 Ga, which is obviously younger than the ca. 1.89–1.85 Ga collisional event in the Cathaysia Block.

(2) Identification of the Yangjia granite further provides evidence for the existence of the Palaeoproterozoic basement in the southern Wuyishan terrane, representing an important part of the Columbia supercontinent.

(3) The Yangjia granites are typical A2-type granites and formed by reworking the Palaeoproterozoic parametamorphic rocks in a post-collisional tectonic setting.
(4) The geodynamic setting switched from post-collision to intraplate extension during the time of 1.80–1.77 Ga in the southern terrane, which might be related to the break-up of the Palaeoproterozoic supercontinent Columbia.

Acknowledgements

The authors thank Dr Quan-Zhong Li for their assistance with LA-ICP-MS zircon U–Pb dating.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was financially supported by the National Natural Science Foundation of China (41202141), the Distinguished Young Scholar Programme of the Chinese Ministry of Land and Resources (201302071), and the China Geological Survey (12120113069100).

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