Two Late Cretaceous A-type granites related to the Yingwuling W–Sn polymetallic mineralization in Guangdong province, South China: Implications for petrogenesis, geodynamic setting, and mineralization

Wei Zheng ^a, Jingwen Mao ^{a*}, Haijie Zhao ^{a*}, Caisheng Zhao ^b, Xiaofei Yu ^{c,d}

^a *Key Laboratory of Metallogeny and Mineral Assessment, Ministry of Land and Resources, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China*

^b *Technology and International Cooperation Department, Ministry of Land and Resources, Beijing 100812, China*

^c *Technology Guiding Center of Mineral Prospecting, Ministry of Land and Resources, Beijing 100120, China*

^d *Development Research Center, China Geological Survey, Beijing 100037, China*

*Corresponding author at:

Key Laboratory of Metallogeny and Mineral Assessment, Ministry of Land and Resources, Institute of Mineral Resources, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Street, Beijing 100037, China.

E-mail address: jingwenmao@263.net (J. Mao).

E-mail address: csal0714@126.com (H. Zhao).

ABSTRACT

Major and trace elements, whole rock Sr–Nd–Pb isotopes, LA–ICP–MS U–Pb zircon dating, zircon trace elements and Hf isotope data are reported for a suite of A-type granites from Yingwuling pluton in western Guangdong province, South China. Zircon U–Pb ages obtained by laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) show that biotite granite and alkali feldspar granite were emplaced in 81.3 ± 0.6 Ma and 80.6 ± 0.5 Ma, respectively. Both of the two suites have the petrographic and geochemical characteristics of A-type granite. These granitic rocks are metaluminous to weakly peraluminous and have pronounced contents of total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 7.80\text{--}8.84\%$), $\text{Fe}_2\text{O}_3^{\text{T}}/\text{MgO}$ and Ga/Al ratios. They exhibit low MgO, CaO and TiO_2 contents, enrichment in some LILEs and HFSEs (except for Zr, Eu and Y), depletion in Ba, Sr, P and Ti. They show A_2 subtype affinity and were probably formed at a temperature of $\sim 800^\circ\text{C}$. The Yingwuling biotite granite has relatively high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios of 0.70655 to 0.70928, low $\varepsilon_{\text{Nd}}(t)$ values of -5.8 to -4.2 and zircon $\varepsilon_{\text{Hf}}(t)$ values (-5.70–1.37). Whole-rock Nd isotopic and zircon Hf isotopic two-stages model ages mostly vary from 1057 to 1506 Ma. The alkali feldspar granite displays bulk rock $\varepsilon_{\text{Nd}}(t)$ values and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ ratios in the range of -6.6 to -6.1 and 0.70640 to 0.71077, respectively, and zircon $\varepsilon_{\text{Hf}}(t)$ values from -5.44 to 0.54, with Mesoproterozoic $T_{2\text{DM}}$ for both Nd and Hf isotopes. Geochemical and isotopic data indicate the Yingwuling A-type granitic magmas were derived from mantle–crust interaction. Zircon grains of Yingwuling granites have relatively low Eu/Eu^* and $\text{Ce}^{4+}/\text{Ce}^{3+}$ ratios, indicating low oxygen fugacity. The visible tetrad effect in the Yingwuling granites indicates that it experienced strong fractionation and is in close relationship to the W–Sn mineralization. Our new data together with previous published data indicate that Late Mesozoic A-type granitoids or alkaline intrusive rocks in South China can be grouped into four pulses: 195–180 Ma, 180–149 Ma, 136–116 Ma and 110–79 Ma. After 135 Ma, with a change in the polarity of the subduction

of paleo-Pacific plate, the crust and lithospheric mantle in eastern China became progressively thinned causing the upwelling of asthenosphere, which would have triggered crustal rocks to partially melt and generate Yingwuling A-type granitic magmas.

Keywords: Yingwuling A-type granites, Zircon U–Pb geochronology, Geochemistry, Late Cretaceous,
South China

1. Introduction

Since the term “A-type granite” defined by Loiselle and Wones (1979), numerous papers have discussed their petrographic and geochemical features, isotopic characteristics, petrogenesis and tectonic implications (Whalen et al., 1987; Eby, 1990, 1992; King et al., 1997, 2001). The original definition of A-type granite was alkaline, anhydrous and anorogenic (Loiselle and Wones, 1979). Wu et al. (2002) supposed that the generation of A-type granite might involve multiple processes, various tectonic settings and variable mantle/crust proportion in their sources. They are commonly associated with crustal extension features (Collins et al., 1982; Eby, 1992), formed in both post-orogenic and anorogenic settings (Whalen et al., 1987; Eby, 1992), and especially essential for their potential rare-metal mineralization (Bettencourt et al., 2005; Costi et al., 2009). Therefore, it is of great importance to study A-type granites, which can provide an crucial tectonic implication and prospecting evaluation (Loiselle and Wones, 1979; Whalen et al., 1987; Eby, 1992; Wu et al., 2002).

South China is renowned for widespread Middle-Late Mesozoic magmatism and mineralization, and particularly enriched in W, Sn, U, Nb–Ta, Cu, Pb, Zn and the REE, especially Sn and W ore deposits (Mao et al., 2013). Based on extensive geological investigations, it has been noted that there are many Middle-Late Jurassic A-type granitoids or alkaline intrusive rocks with small volume, occurring sporadically throughout the whole hinterland and are closely related to W–Sn mineralization, which have received wide attention by many researchers (Martin et al., 1994; Gilder et al., 1996; Chen and Jahn, 1998; Li et al., 2003). However, Late Cretaceous A-type granitic plutons related to W–Sn mineralization are rarely reported. This paper reports newly discovered Sn-related Late Cretaceous A-type granites in Yingwuling of western Guangdong Province in South China.

The Yingwuling granites are spatially associated with Yingwuling W–Sn polymetallic mineralization.

Because the Yingwuling deposit was discovered in recent years, information about this deposit is only limited to descriptions of the geological features, ore-forming age, and ore body morphology (Zheng et al., 2013), but the geochronology, petrogenesis, and magma sources of the intrusions in the Yingwuling area still remain unclear. In this study, we present precise zircon U–Pb ages of two granite bodies, together with geological and petrographic, whole rock geochemical, Sr–Nd–Pb isotopes, zircon trace elements and Hf isotope analyses in an attempt to better constrain the timing of magmatic activities, the petrogenesis of the intrusions and the implications for ore genesis. With our new data, we review and discuss the significance of Late Mesozoic A-type granites in the magmatic belt in order to better understand the Mesozoic magmatic evolution and geodynamic evolution of the South China.

2. Regional geology

The South China Block is bordered by the North China Craton and the Qinling–Dabie orogenic belts in the north, the Three River orogenic belts in the west, and the Indosinia Block in the southwest (Fig. 1a) (Mao et al., 2013). The South China block is composed of the Cathaysia Block in the SE and the Yangtze Block in the NW, which are separated by Shi–Hang Neoproterozoic suture (Fig. 1b; Yang et al., 2009). It is a complex continental plate resulting from multiple amalgamation, breakup and re-amalgamation of the Yangtze and Cathaysian blocks since the Proterozoic (Yang et al., 2009). The Mesozoic intrusive rocks in South China show a large variation in rock types, which include I-, S- and A-types, and most of the A-type granites were emplaced during the Yanshanian stage (Fig. 1b) (Wang et al. 2005), e.g. the Putuo, Yaokeng, Qingtian and Taohuadiao A-type granites in Zhejiang and the Wushan, Kuiqi, Xincun and Jingangshan A-type granites in Fujian along the Changle–Nan’ao fault zone (Martin et al. 1994), the distribution of the Beitou, Zhaibei and Keshubei A-type granites is constrained by the Shannan–Xunwu fault in South Hunan and South Jiangxi provinces (Chen et al., 1999), Xiangshan, Damaoshan, Baijuehuajian and Tongshan

A-type granites along the Gan–Hang Belt (Jiang et al., 2011; Wong et al., 2009), Nankunshan and Ejinao A-type granites in Guangdong along the Lianyang–Fogang–Xinfengjiang magma belt (Bao et al., 2000). South China is a world-class W–Sn province, with not only major granite-related Sn, W, and Sb deposits, but also porphyry Cu–Mo, vein-type Pb–Zn–Ag, and epithermal Au–Ag–(Cu) deposits (Mao et al., 2013), which can be divided into three pulses within the Mesozoic period of metallic mineralization, i.e., 230 to 210 Ma, 170 to 150 Ma and 134 to 80 Ma, and most of them are extensively located in pull-apart basins, volcano-sedimentary basins, and metamorphic core complexes.

In the Yangchun basin, a Cretaceous volcanic basin, porphyry Cu–Mo deposits, granite-related Sn deposits, and vein-type Pb–Zn–Ag deposits all be present. The Yangchun basin is located in the southwest of South China fold belt, at the junction of central Guangdong block and Yunkai block (Fig. 2). Bounded by Wuchuan–Sihui fault, the northwest of Yangchun basin is the Yunkai ancient uplift zone in which thick flysch and flyschoid sediments accumulated from Sinian to Cambrian, forming the basement of the region. Since the Caledonian, the Yangchun basin experienced several tectonic movements, related to Indo-China, Yanshan, Himalayan tectonics with dominant NE–NNE trending structures. Cai et al. (2002) proposed that the Mesozoic lithosphere in western Guangdong experienced three stages of tectonic evolution as follows: collision and compression (224–265 Ma), transition from compression to extension (154–163 Ma) and finally extension (80–120 Ma). The complex structural features in the area, provide suitable channel ways for the emplacement of magma and formation of polymetallic deposits. So far, more than 50 deposits have been found in the basin and surrounding areas, including the Shilu Cu–Mo deposit, the Potoumian Cu–Fe deposit, the Xishan W–Sn polymetallic deposit, the Tiantang Cu–Pb–Zn deposit, the Yingwuling W–Sn polymetallic deposit and so on. In the Yingwuling deposit, we recently recognised two A-type granites. Medium-fine grained biotite granite and alkali feldspar granite widely intruded the Devonian Maozifeng

formation as stocks (Fig. 3). The contact relationship among the granites is poorly constrained as there is no cross-cutting relationship for the two granites, and only limited drill hole are available.

3. Ore deposit geology

The Yingwuling W–Sn polymetallic deposit is situated in the Yangchun basin of western Guangdong Province, South China. The outcropping strata in this deposit consist of two Devonian formations and two Carboniferous formations (Fig. 3). The two Devonian formations include the Tianziling Formation and the Maozifeng Formation. The Devonian Tianziling Formation widely crops out in the ore district and consists of thinly bedded argillaceous limestones, which hosts the majority of the mineralization in the study area. The Maozifeng Formation is dominated by argillaceous siltstone and quartz siltstone. The two Carboniferous formations are the Menggong'ao Formation, consisting of argillaceous sandstone interbedded with siltstone and argillaceous shale, and the Ceshui Formation, consisting of argillaceous shale, carbonaceous shale, and quartz sandstone.

The structure of the Yingwuling deposit is dominated by the NWW trending Yingwuling anticline, which has a core that consists of the Tianziling Formation and limbs that are formed from the Maozifeng, Menggong'ao and Ceshui formations (Fig. 3). Several NNE, NW and NWW trending faults are present in the Yingwuling deposit, which controls both the outcrop of the granitoids and the location of the associated polymetallic mineralization within the deposit.

The granitoids associated with the Yingwuling deposit can be subdivided into biotite granite and alkali feldspar granite. The granitoids of the pluton mainly exhibit medium- and fine grained granitic texture and massive structure (Fig. 4). The biotite granite is light gray (Fig. 4A) and the major minerals (Fig. 4C, E) are alkali feldspar (30–40%), plagioclase (20–25%), quartz (25–30%) and biotite (10–15%), with accessory minerals including zircon, apatite, monazite, xenotime and thorite. The alkali feldspar grains are generally

subhedral and commonly display Carlsbad twins, with sizes varying from 0.5 mm to 7 mm. Plagioclase, sometimes altered to kaolinite and sericite, is preserved as subhedral to euhedral crystals. The quartz grains vary in size from 0.2 mm to 5 mm and exhibit clear undulatory extinction under a microscope. Quartz grains display subhedral to anhedral forms, and irregularly occur around the K-feldspars and plagioclase crystals. Biotites commonly occur as mineral aggregates and interstitial to both feldspar and quartz, and partly has been suffered from chloritization.

The alkali feldspar granite is red (Fig. 4B), which mainly consists of K-feldspar (50–60%), quartz (20–25%), plagioclase (10–15%) and biotite (3–5%) (Fig. 4D, F). K-feldspar is characterized by platy or anhedral granular textures and partly contains euhedral inclusions of plagioclase, biotite and quartz grains. Quartz is subhedral to anhedral and is mainly 0.5–2 mm in size, located between the K-feldspars and plagioclase. Plagioclase is slightly sericitized, and generally shows polysynthetic twins, and lacks oscillatory zoning. Biotite is locally altered to chlorite, and occurs either as individual crystals or as mineral aggregates. The accessory minerals mainly include magnetite, titanite and euhedral zircon.

Mineralization in the Yingwuling W-Sn polymetallic deposit mainly includes skarn types, but hydrothermal type is also present. The ore-bodies of the deposit occur in the inner- and outer-contact zones between the Yingwuling granites and limestones of the Tianziling Formation, hosted mainly by skarn. The ore-bodies in the deposit are mainly in stratiform and lentiform and minor of veins. The principal ore minerals are scheelite, cassiterite, molybdenite, magnetite, sphalerite, chalcopyrite, galena and pyrrhotite. Gangue minerals are garnet, diopside, epidote, chlorite, idocrase, quartz, calcite and fluorite.

4. Sampling and analytical techniques

The samples were collected from the fresh Yingwuling granitic plutons. Fourteen samples were collected from ten boreholes (ZK1902, ZK3204, ZK20, ZK10, ZK1202, ZK1601, ZK2803, ZK801 and

ZK3002) in the Yingwuling W–Sn polymetallic deposit for major and trace elements, and whole rock Sr–Nd–Pb isotopes analysis (Fig. 3). Biotite granite sample (ZK2805-Y-1) in the 234 m was collected from the borehole ZK2805, and alkali feldspar granite sample (ZK1902-Y-7) was collected from 214 m of the borehole ZK1902 for LA–ICP–MS U–Pb zircon dating, zircon trace elements and Hf isotope analysis.

4.1. Zircon U–Pb and trace element analyses

Zircon separation was carried out using conventional techniques, including crushing, sieving, and magnetic and heavy liquid separation methods. Zircon grains, handpicked under a binocular stereomicroscope, were mounted in epoxy resin, and then polished to expose their centres. All mounted zircon grains were studied petrographically with reflected- and transmitted light microscopy, as well as by cathodoluminescence (CL) imaging obtained using a JEOL-JXA-8800 micprobe to reveal their internal structures.

Zircon trace elements analyses were done using a Finnigan MAT ELEMENT II high-solution inductively coupled plasmas spectrometer (HR–ICP–MS) with high-performance interface in the National Research Center of Geoanalysis, at the Chinese Academy of Geological Sciences (CAGS), Beijing. The LA–ICP–MS analysis is coupled with a New-Wave UP-193nm Nd: YAG UV laser. Ablations material is carried out by He–Ar gas mixture (flow rate of 0.73 L He/min and 0.85 L Ar/min) and the resulting vapor was combined with argon before delivery into the ICP–MS. The analyses were conducted using a 35- μ m spot diameter (25- μ m for small crystals, Hongniu), a 10-Hz frequency, a 0.25-mJ/pulse power, during a 70-s analysis including 20 s measurement of gas blank, followed by ablation of sample for approximately 40 s by raster. Each group of 10 zircon analyses was bracketed by analysis of standard glass of NIST612, NIST 610 and K12g to correct for mass bias drift during the analysis. Calibration was carried out by normalizing count rates for each analysed elements with Si to obtain its concentration, assuming SiO₂ to

be stoichiometric in zircon (ZrSiO_4) with a concentration of ca. 32.8%.

U–Pb dating of zircons was conducted by laser ablation multicollector (MC) –ICP–MS at the Institute of Mineral Resources, CAGS, Beijing. Detailed operating conditions for the laser ablation system and the MC–ICP–MS instrument and data reduction were the same as described by Hou et al. (2009). Laser sampling was performed using a New-wave UP213 laser ablation system. Helium was used as the carrier gas to enhance the transport efficiency of the ablated material. Argon was used as the make-up gas and mixed with the carrier gas via a T-connector before entering the ICP–MS. A Thermo Finnigan Neptune MC–ICP–MS instrument was used to acquire ion-signal intensities.

Zircon GJ1 was used as external standard for U–Pb dating and was analyzed twice for every 5–10 analyses of zircon samples. Time-dependent drifts of U–Th–Pb isotopic ratios were corrected using a linear interpolation for every batch of bracketed analyses according to the variations in GJ1. U–Th–Pb isotopic ratios used for GJ1 are from Jackson et al. (2004). Uncertainties of preferred values for the external standard GJ1 were within the expected error range. In all analyzed zircon grains, the common Pb correction was not necessary due to the low signal of common ^{204}Pb and high $^{206}\text{Pb}/^{204}\text{Pb}$ ratio. U, Th, and Pb concentrations were determined using zircon M127 (U: 923 ppm; Th: 439ppm; Th/U: 0.475, Nasdala et al., 2008) as an external standard. Concordia diagrams and weighted mean calculations were made using Isoplot/Ex3.0. Uncertainty on individual analyses by laser ablation MC–ICP–MS is quoted at the 95 % (2σ) confidence level. The zircon Plesovice is dated as unknown samples and yielded weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 337 ± 2 Ma (2SD, $n = 12$), which is in good agreement with the recommended $^{206}\text{Pb}/^{238}\text{U}$ age of 337.13 ± 0.37 Ma (2SD) (Sláma et al., 2008).

4.2. Whole-rock major and trace element analyses

Major and trace elements were analyzed at the the Research Center for Geological Analysis, Institute

of Uranium Geology (GAIUG). Major elements were measured using X-ray fluorescence spectrometry (XRF) on fused glass beads, with a precision better than 1%. Trace elements were analyzed with inductively coupled plasma–mass spectrometry (ICP–MS), and the precision for minor element content is better than 5%, which is extremely low (Zheng et al., 2015).

4.3. Whole rock Sr–Nd–Pb isotopic analyses

Whole rock Sr–Nd–Pb isotopes were analyzed at the the Research Center for Geological Analysis, Institute of Uranium Geology (GAIUG). Sr–Nd isotopic tests used the ISOPROB-T thermalionization mass spectrometer, according to GB/T17672-1999 “Determinations for isotopes of lead, strontium and neodymium in rock samples”. The ICP–MS method measured Rb, Sr, Sm, Nd contents in order to calculate $^{87}\text{Rb}/^{87}\text{Sr}$ and $^{143}\text{Sm}/^{144}\text{Nd}$. Test precision of $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ is better than 2% and 0.5%, respectively. Pb was separated and purified by conventional anion-exchange technique (AG1 $\times$ 8, 200–400 resin) with diluted HBr. Pb isotopic ratios were measured using the MAT-261 mass spectrometer at the GAIUG. In-run analytical precision for $1\mu\text{g } ^{208}\text{Pb}/^{206}\text{Pb}$ is better than 0.005%. Repeated analyses of NBS981 yielded $^{204}\text{Pb}/^{206}\text{Pb} = 0.0591995 \pm 0.000013$, $^{207}\text{Pb}/^{206}\text{Pb} = 0.9145100 \pm 0.000056$ and $^{208}\text{Pb}/^{206}\text{Pb} = 2.1652465 \pm 0.000069$.

4.4. Zircon Hf isotopic analyses

The zircon Hf analyses were done on the same grains used for U–Pb dating (location shown on Fig. 5). Zircon Hf isotope analysis was carried out in situ using a Newwave UP213 laser-ablation microprobe attached to a Neptune multi-collector ICP–MS at the Institute of Mineral Resources, CAGS, Beijing. Instrumental conditions and data acquisition protocols were described by Wu et al. (2006). A stationary spot was used with a beam diameter of $\sim 55\text{ }\mu\text{m}$. He, mixed with Ar, was used as a carrier gas to transport the ablated compound from the laser-ablation cell to the ICP–MS torch via a mixing chamber. In order to

correct for the isobaric interferences of ^{176}Lu and ^{176}Yb on ^{176}Hf , $^{176}\text{Lu}/^{175}\text{Lu} = 0.02658$ and $^{176}\text{Yb}/^{173}\text{Yb} = 0.796218$ ratios were determined (Chu et al., 2002). For instrumental mass bias correction Yb isotope ratios were normalized to $^{172}\text{Yb}/^{173}\text{Yb} = 1.35274$ (Chu et al., 2002) and Hf isotope ratios to $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ using an exponential law. The mass bias behavior of Lu was assumed to follow that of Yb, the mass bias correction protocol was described by Wu et al. (2006). Zircon GJ1 was used as the reference standard during our analyses, and gave a weighted mean $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282017 ± 0.000017 (2σ , $n = 24$), indistinguishable from the weighted mean $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282000 ± 0.000005 (2σ) using a solution analysis method (Morel et al., 2008).

5. Results

5.1. Zircon trace elements and $\text{Ce}^{4+}/\text{Ce}^{3+}$ ratios

Elemental concentrations of rare earth elements (REEs), U, Th, Ti and Hf in zircons are presented in Supplementary Table 1. Chondrite-normalized REE patterns of zircons are shown in Fig. 5. All zircons are depleted in LREE and enriched in HREE in chondrite normalized REE patterns. Zircons are commonly characterized by positive Ce and negative Eu anomalies on chondrite-normalized patterns because REEs in zircon are mainly trivalent except for Eu^{2+} and Ce^{4+} , which thus show different behaviors relative to other elements. Ce^{4+} easily substitutes Zr^{4+} of zircon under oxidizing conditions, and thus is compatible in zircon. In contrast, Ce^{3+} is incompatible in zircon. Therefore, the $\text{Ce}^{4+}/\text{Ce}^{3+}$ ratios of zircon can reflect the magmatic oxidation states (Pettke et al., 2005). Calculated zircon $\text{Ce}^{4+}/\text{Ce}^{3+}$ values are listed in Supplementary Table 1. Positive anomalies of Ce and negative anomalies of Eu are evident, zircons from biotite granite with mean values of Eu/Eu^* and $\text{Ce}^{4+}/\text{Ce}^{3+}$ varying from 0.14 to 0.23 and 8 to 58, respectively; while alkali feldspar granite zircons have relatively low $\text{Ce}^{4+}/\text{Ce}^{3+}$ and Eu/Eu^* mean ratios, indicating low oxygen fugacity, which is consistent with the occurrence of ilmenite in the Yingwuling

plutons.

5.2. U–Pb zircon chronology

Cathodoluminescence images of representative zircon grains from the Yingwuling plutons are shown in Fig. 6. The results of LA–ICP–MS zircon U–Pb isotopic analyses are given in Supplementary Table 2. $^{206}\text{Pb}/^{238}\text{U}$ ages are considered to be the most reliable for concordant Phanerozoic zircon, given that the low concentration on ^{207}Pb result in large statistical uncertainties and render the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios a less precise measure of age (Compston et al., 1992). The zircons chosen for this study are prismatic and euhedral (60 to 160 μm long), with length-to-width ratios of 1:1 to 4:1. Concentric zoning is common and no inherited cores were observed.

5.2.1. Biotite granite

Twenty-two zircons from biotite granite (ZK2805-Y-1) were chosen for dating analysis. The uranium and thorium contents in the zircons vary significantly (U, 44–3702 ppm; Th, 44–905 ppm). The Th/U ratios range from 0.24 to 1.17, which is consistent with a magmatic origin (Corfu et al., 2003). In the analyses of biotite granite sample, 22 spots yielded a weighted mean age of (81.3 ± 0.6) Ma, and MSWD = 0.85 (Fig. 7a), which is interpreted as the crystallization age of the medium-fine grained biotite granite.

5.2.2. Alkali feldspar granite

Thirteen analyses for zircons from the sample ZK1902-Y-7 were undertaken. The U concentration ranges from 103 to 4499 ppm and the Th concentration from 115 to 4755 ppm, with Th/U ratios ranging from 0.28 to 1.91. Thirteen zircon grains have ages ranging from 79.5 Ma to 82.5 Ma and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 80.6 ± 0.5 Ma (Fig. 7b), which is interpreted as the best estimation of the emplacement age of this intrusion. The results show that the biotite granite and the alkali feldspar granite were both emplaced in the Late Cretaceous.

5.3. Major and trace elements

Fourteen samples from the Yingwuling granites were analyzed for major and trace element compositions, including seven biotite granite and seven alkali feldspar granite samples. The major and trace element data are summarized in Supplementary Table 3.

5.3.1 Biotite granite

Biotite granite has high SiO_2 (75.1–76.42 wt.%), Na_2O (3.18–4 wt.%), K_2O (4.57–4.94 wt.%) contents and low TiO_2 (0.09–0.13 wt.%), Al_2O_3 (12.22–12.81 wt.%), $\text{Fe}_2\text{O}_3^{\text{T}}$ (1.93–2.83 wt.%), MgO (0.11–0.25 wt.%), CaO (0.73–0.82 wt.%) and P_2O_5 (0.01–0.03 wt.%) abundances. The $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios are 0.69–0.85, belong to high-K calc-alkaline granites (Fig. 8a). All the calculated A/CNK values (molar $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$) are from 0.96 to 1.05, indicating that these rocks are metaluminous-peraluminous as shown in Fig. 8b. The trace element spider diagrams of the samples (Fig. 9a) show the enrichment of large ion lithophile elements (LILE) such as Th, Rb, K and Pb and pronounced depletion of Nb, P, Ba, Ti, Zr, and Eu. Figure (9b) shows chondrite-normalized rare earth element (REE) distribution patterns (Boynton, 1984; Sun and McDonough, 1989). Biotite granite contains a total of REE ranging from 149.2 to 196.5 ppm, characterized by scarcely LREE/HREE fractionation (light REE/heavy REE; $(\text{La}/\text{Yb})_{\text{N}} = 1.3\text{--}3.3$) with clear negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.03\text{--}0.06$) (Supplementary Table 3; Fig. 9b).

5.3.2 Alkali feldspar granite

The Yingwuling alkali feldspar granite has also high SiO_2 (75.08–76.49 wt.%) coupled with high Al_2O_3 (12.32–12.68 wt.%), Na_2O (3.4–3.91 wt.%) as well as K_2O abundances (4.14–4.9 wt.%), yielding low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of 0.73–0.91. They are metaluminous to slightly peraluminous ($\text{A}/\text{CNK} = 0.90\text{--}1.05$) and belong to high-K calc-alkaline series (Fig. 8a). All samples have relatively low LOI (loss on ignition) values of 0.51–1.26 wt.%, consistent with the relative lack of late hydrothermal alteration. In the

primitive-mantle normalized multi-element diagram, the granite samples also show significant negative Ba, P, Sr, Nb and Ti anomalies and positive U, Th, Ta, Rb, K and Pb anomalies (Fig. 9a). The total REE concentrations are slightly higher than the biotite granite (Fig. 9b), with (La/Yb)_N ratios ranging from 0.9 to 4.5. The alkali feldspar granites have a lower Eu anomalies (Eu/Eu* = 0.01–0.04) and Mg[#] (0.10–0.19) compared to those of the biotite granite.

5.4. Sr–Nd–Pb isotopes

The Sr–Nd and Pb isotopic analyses for Yingwuling biotite granite and alkali feldspar granite are shown in Supplementary Table 4. Initial Sr–Nd isotopic compositions were calculated at $t = 81$ Ma. All of samples from biotite granite and alkali feldspar granite have low Sr contents with high Rb/Sr ratios. The biotite granite have higher (⁸⁷Sr/⁸⁶Sr)_i values (0.70655–0.70928) relative to the initial ⁸⁷Sr/⁸⁶Sr ratios (0.70640–0.71077) of the alkali feldspar granite samples. The age-corrected $\epsilon_{\text{Nd}}(t)$ values of Yingwuling biotite granite range from –5.8 to –4.2, and the T_{DM2} model ages are mostly between 1229 Ma and 1360 Ma. The alkali feldspar granite samples show slightly lower $\epsilon_{\text{Nd}}(t)$ values (–6.6 to –6.1), and the Nd model ages (T_{DM2} = 1380–1424 Ma) are also slightly older than that of the Yingwuling biotite granite.

The Pb isotopic ratios in the biotite granite are ²⁰⁶Pb/²⁰⁴Pb = 18.892–19.152, ²⁰⁷Pb/²⁰⁴Pb = 15.719–15.727 and ²⁰⁸Pb/²⁰⁴Pb = 39.279–39.444, respectively. The Pb content in alkali feldspar granite is essentially consistent with the Pb content in the biotite granite, i.e., the ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb are ranging from 19.023–19.254, 15.717–15.725 and 39.345–39.768, respectively.

5.5. Zircon Hf isotopic compositions

Zircons dated for U–Pb ages were also analyzed for Lu–Hf isotopes, with results given in Supplementary Table 5. Initial ¹⁷⁶Hf/¹⁷⁷Hf ratios, denoted as $\epsilon_{\text{Hf}}(t)$ values, and Hf model ages were also calculated based on crystallization ages from the U–Pb dating (Supplementary Table 5). All analyzed

zircons from the biotite granite have $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.000602–0.007467 and 0.282562–0.282772, respectively. The data indicates that the zircons have very low radiogenic Hf concentration. Therefore, the values obtained from $^{176}\text{Lu}/^{177}\text{Hf}$ analyses reflect the Hf isotope composition of the system during zircon formation (Amelin et al., 2000). Their $\varepsilon_{\text{Hf}}(t)$ values range from -5.70 to 1.37 (with an average of -1.96), and the two-stage Hf model ages ($T_{\text{DM}2}$) vary from 1057–1506 Ma (with an average of 1269 Ma).

The $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of analyzed spots on zircon from alkali feldspar granite sample (ZK1902-Y-7) range from 0.282570 to 0.282739 with $t = 81$ Ma, $\varepsilon_{\text{Hf}}(t)$ values of -5.44–0.54 (average at -2.3). Single-stage Hf model ages ($T_{\text{DM}1}$) range from 735 to 1014 Ma and two-stage Hf model ages ($T_{\text{DM}2}$) range from 1110 to 1489 Ma.

6. Discussion

6.1. Fractional crystallization process

It is significant to evaluate any effects of magmatic differentiation, assimilation, and/or contamination to fully understand magma petrogenesis and tectonic settings (Mao et al., 2014). The Yingwuling granites samples are metaluminous to slightly peraluminous and high in total alkalis ($\text{K}_2\text{O}+\text{Na}_2\text{O}$) due to strong fractionation. Harker diagrams for the Yingwuling granites show that SiO_2 have negative correlations with Na_2O , FeO^{T} , Al_2O_3 , TiO_2 , MgO and CaO (Fig. 10), suggesting that the granites are likely the result of fractional crystallization during their magmatic evolution. Trends of decreasing MgO , FeO^{T} , and CaO with increasing SiO_2 are consistent with the fractionation of mafic minerals, such as biotite, and calcium-rich minerals, such as plagioclase (Mao et al., 2014). Moreover, they display flat “V” shape in chondrite-normalized REE patterns and significant negative Eu anomalies, also indicating strong crystal fractionation (Li et al., 2014a).

Pronounced depletion of P, Ti, Ba, Nb, Sr and Eu (Fig. 9a) further demonstrates that fractional crystallization occurred during the formation of the granites. The fractionation of plagioclase can result in negative Sr and Eu anomalies, and the fractionation of K-feldspar leads to negative Ba and Eu anomalies. Eu v.s. Sr and Eu v.s. Ba plots (Fig. 11) suggested that the evolution of the Yingwuling granites was controlled largely by plagioclase and alkali feldspar fractionation. In addition, the high Rb/Sr ratios of these granites also indicate high degrees of fractionation of plagioclase (EI Bouseilly and EI Sokkary, 1975).

Ilmenite, titanite and rutile are the main Ti enriched minerals, with ilmenite stable at low pressure and high temperature (Liou et al., 1998). Ilmenite usually has low Ta and Nb (Foley et al., 2002). In contrast, titanite and rutile usually have much higher contents of Ta and Nb (Cole and Stewart, 2009). Thus, crystallization of ilmenite brings Ti out of the magma, resulting in depletion of Ti in the granites, while without pronounced decreases of Ta and Nb (Li et al., 2012). Therefore, the Yingwuling granites with significant negative Ti anomalies and high Ta, Nb concentrations suggests crystallization of ilmenite and little influence of rutile or titanite. The Yingwuling granitic magmas underwent strong fractionation during crystallization processes are similar in composition, whereas the alkali feldspar granite has a slightly higher degree of fractionation.

6.2. Petrogenetic type: S-type, highly fractionated I-type granite or A-type?

The determination of petrogenetic type lies in the foundation of granitic researches. Since the introduction of the terms I- and S-type granites by Chappell and White (1974), granitic rocks have commonly been divided into I-, S-, M- and A-types according to the nature of their protolith (Pitcher, 1982), M-type granitic rocks are rarely reported, though. Various determination methods have been proposed by numbers of researchers (Chappell and White, 1974, 2001; Whalen et al., 1987; Chappell, 1999; Frost and Frost, 2011). Generally the presence of aluminous primary minerals, such as muscovite, cordierite,

tourmaline and garnet, are indicative of S-type granites, whereas alumina-deficient minerals, such as hornblende, represent I-type granites. Meanwhile, an alumina saturation index (A/CNK) and the P_2O_5 concentrations are also used to classify I- and S-type granites (Chappell and White, 1974; Chappell, 1999), because apatite reaches saturation in metaluminous and mildly peraluminous magmas but remains highly soluble in strongly peraluminous melts (Chappell, 1999). In general, typical A-type granitoids are characterized by enrichments of $Na_2O + K_2O$, Ce, REE, Y, Nb and Ga concentrations, high K_2O/Na_2O and Ga/Al ratios, low V, Ni, Cr, Ba, Sr and Eu contents, and flat HREE distribution patterns (Whalen et al., 1987; Collins et al., 1982; Yang et al., 2006; Wong et al., 2009). They also have high $FeO^T/(FeO^T+MgO)$ values, indicating that most of them are ferrous (Frost and Frost, 2011), although significant compositional overlap is also observed. Besides, various discrimination diagrams are also used to constrain the petrogenesis of granite (Whalen et al., 1987; Eby, 1990; King et al., 1997, 2001; Yang et al., 2006).

Generally, I- and most of A-type granites have lower A/CNK ratios (< 1.1) and P_2O_5 contents, higher Na_2O contents, and are more depleted in Sr, Ba and Eu relative to S-type granites (Chappell, 1999; Whalen et al., 1987). The Yingwuling granites have low P_2O_5 contents ($< 0.02\%$) and metaluminous to weakly peraluminous signatures, with A/CNK ratios of 0.90–1.05; these characteristics are distinctive from those of strongly peraluminous S-type granites. The extremely low Sr is important in discriminating A-type granites from calc-alkaline granites, as Sr contents in A-type granites are only about 33–50% of those in the calc-alkaline varieties at the same SiO_2 level (Douce, 1997). The Yingwuling granites mostly contain < 50 ppm Sr, which is significantly lower than typical calcalkaline I-type granites (Wong et al., 2009).

In addition, the Yingwuling granites are highly siliceous (mostly $SiO_2 > 72\%$), high $K_2O + Na_2O$ and FeO^T/MgO , low CaO, MgO, TiO_2 and P_2O_5 , and characterized by high contents of high field strength elements, element association $Nb + Zr + Ce + Y = 303 \times 10^{-6} - 418 \times 10^{-6}$, with an average of 351×10^{-6} ,

slightly higher than the minimum value of A-type granites (350×10^{-6}) (Whalen et al., 1987), which are traditionally thought to be the main characteristics distinguishing A-type granites from highly evolved I-type granites. Furthermore, in the discrimination diagrams of FeO^T/MgO , $(\text{K}_2\text{O}+\text{Na}_2\text{O})/\text{CaO}$, Ce and Nb vs. $10000\text{Ga}/\text{Al}$ (Fig. 12), they all plot in the A-type granite field as defined by Whalen et al. (1987).

A-type granites are high-temperature granites, and the temperature of magmatic crystallization is higher than those of S- and I-type granites (Skjerlie and Johnston, 1992), which facilitates the dissolution of accessory phases during the melting processes (King et al., 2001). Hence, it is a common feature that inherited zircons are rare in A-type granites (Williams, 1992). Previous studies have shown that the A-type granites should comprise accessory minerals such as apatite, zircon and titanite. The solubility of an accessory mineral in a melt depends on temperature, composition, solution kinetics and textural position (King et al., 2001). Zircon saturation thermometry provides a simple and effective way to estimate the magma temperature of granites (Watson and Harrison, 1983; King et al., 2001; Miller et al., 2003). Miller et al. (2003) indicate that zircon saturation temperatures calculated from whole-rock compositions provide minimum of magma temperature if the magma was undersaturated in Zr, but maxima if it was saturated. The Yingwuling granites have relatively low Zr contents (116–193 ppm), which lack inherited zircons and are likely undersaturated in Zr. Thus, the calculated T_{Zr} from bulk-rock compositions are likely to be a minimum estimate of their initial magma temperature. Using the saturation temperature calculation method proposed by Watson and Harrison (1983) and Boehnke et al. (2013), the zircon saturation temperatures of the Yingwuling granites were determined to be greater than the temperature (764 °C) of highly fractionated I-type granites (King et al., 1997). Taken together, both petrographic and geochemical features argue strongly that the Yingwuling granites are evolved A-type granites rather than highly fractionated I- or S-type granites.

6.3. Nature of magma source

The origins of A-type granites are still the subject of debate, mainly because numbers of compositional variations have been found, and there are some agreement for the origin of A-type and several petrogenetic schemes have been proposed for their origin: (1) high-temperature ($> 960\text{ }^{\circ}\text{C}$) melting of granulite-facies metasedimentary rocks (Huang et al., 2011; Sun et al., 2011); (2) direct fractionation products of mantle-derived alkaline basalts (Turner et al., 1992; Mushkin et al., 2003); (3) low degrees of partial melting of F- and/or Cl-enriched dry, lower crustal granulitic residue from which a granitoid melt was previously extracted (Collins et al., 1982; King et al., 1997); (4) low-pressure melting of calc-alkaline rocks at upper crustal levels (Skjerlie and Johnston, 1992; Patiño Douce, 1997) and (5) hybridization between anatectic granitic and mantle-derived mafic magmas (Kerr and Fryer, 1993; Yang et al., 2006, 2012).

The Yingwuling granites have low A/CNK values and no aluminous minerals, which are inconsistent with the metasedimentary-melting petrogenetic model (Chappell et al., 1987). Furthermore, sedimentary rocks are rare in this region and all the previously studied granitoids have demonstrated a igneous source in western Guangdong (Zheng et al., 2015; Huang et al., 2013).

For the Yingwuling granites, the ratios of Nd/Th range from 0.50 to 0.74, which are lower than those of crust-derived rocks (≈ 3) and significantly different from the mantle-derived rocks (> 15) (Bea et al., 2001), preclude their derivation directly from the mantle. Moreover, the high SiO_2 ($> 69\text{ wt.}\%$) and low MgO ($< 0.50\text{ wt.}\%$) contents indicate they could not have been directly generated by partial melting of mantle peridotites (Rapp and Watson, 1995). The Yingwuling biotite granite and alkali feldspar granite have strongly negative $\epsilon_{\text{Nd}}(t)$ values (-6.6 to -4.2) and zircon $\epsilon_{\text{Hf}}(t)$ values (-5.70 to 1.37), which implies that these granites were not directly derived from a mantle-derived mafic magma. If extensive fractionation of mafic magmas took place, large volumes of gabbroic and dioritic rocks might be expected, which is not

the case in the western Guangdong province during this period.

Although the “residual granulite melting” model can explain the lower water fugacity and high halogen content of some A-type granitoids, it cannot explain some geochemical characteristics (e.g. high $\text{FeO}^{\text{T}}/(\text{FeO}^{\text{T}}+\text{MgO})$) of A-type granitoids (Frost and Frost 1997). Experimental results indicate that partial melting of a wide range of crustal rocks would leave refractory granulitic residues, which are depleted in alkalis relative to Al, and depleted in TiO_2 relative to MgO (Douce, 1997). Remelting of these residues cannot produce granitic liquids with high TiO_2/MgO and $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$ ratios that are characteristics of A-type granites (Wong et al., 2009). The Yingwuling granites also have significantly high $\text{FeO}^{\text{T}}/(\text{FeO}^{\text{T}}+\text{MgO})$ value, therefore, this residual model cannot explain the formation of the Yingwuling granites.

Zircon $\varepsilon_{\text{Hf}}(t)$ values of the Yingwuling biotite granite and alkali feldspar granite vary from -5.70–1.37 and -5.44–0.54, respectively; and Mesoproterozoic $T_{2\text{DM}}$ ages ranging from 1057–1506 Ma and 1110–1489 Ma, respectively. As shown in the U–Pb zircon age versus $\varepsilon_{\text{Hf}}(t)$ diagram (Fig. 13a), zircons from these granites are all located above the evolution range of the Cathaysia crustal basement, which is consistent with diagram of Nd and Sr isotopic variation (Fig. 13b). The zircon Hf model ages and their Nd model ages are younger than the Paleo-proterozoic age of the Cathaysia crustal basement, which is deduced from the whole-rock Nd and zircon Hf model ages of the extensive intrusive granitoids, volcanic, metamorphic and sedimentary rocks from the Cathaysia Block (Chen and Jahn, 1998; Xu et al., 2007; He et al., 2010, 2012). This implies that the crust can be excluded as the unique source for the studied granites. Furthermore, zircons of these granites do not show any inherited components.

Magma mixing between mantle-derived mafic magmas and more felsic crustal melts has also been proposed to produce the I- and A-type granites (Griffin et al., 2002). The granitic rocks of this origin have

notable isotopic features, which vary in a wide range (Griffin et al., 2002). The zircon $\varepsilon_{\text{Hf}}(t)$ values of each samples in this study display a wide range of variation. Some $\varepsilon_{\text{Hf}}(t)$ values are positive and close to zero (Fig. 13a). These facts suggest that some juvenile mantle materials have contributed to the sources of the Yingwuling A-type granites, which are similar to Sanqingshan-Damaoshan A-type granites in Southeast China that are proposed to be derived mainly from partial melting of Paleo-Neoproterozoic crust with additions of juvenile mantle-derived magmas (Sun et al., 2015). In the $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ (Fig. 14a) and $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ model diagram (Fig. 14b), Yingwuling granites located between the marine sediments (or upper crust) and EM II evolutionary line, showing the Pb isotope of Yingwuling granites impacted by EM II type mantle end-member and the presence of mantle-crust interaction. In general, mantle-derived magmas are characterized by the low Lu/Yb ratios (0.14–0.15) (Sun and McDonough, 1989), whereas the continental crust has relatively higher Lu/Yb ratios (0.16–0.18). The low Lu/Yb ratios of 0.14–0.16 of the samples also suggest that Yingwuling A-type granites are likely to be the product of magma mixing. Mantle-derived magmas would provide not only sufficient heat energy for the melting of the lower crust by underplating into the crust–mantle interface, but also supply some juvenile mantle-derived materials by upwelling during the Cretaceous time. Therefore, the magma sources of Yingwuling granites are similar to Gejiu granites in South China proposed to be derived mainly from partial melting of Mesoproterozoic crust with additions of mantle-melts (Cheng and Mao, 2010), whereas are distinct from Kuiqi peralkaline granites originated from metasomatized mantle (Martin et al., 1994).

6.4. Implications on the mineralization process

Increasing numbers of granite plutons associated with tin mineralization have been classified as A-type granites in South China, which include the Qianlishan pluton hostings the Dongpo tin deposit, the Qitianling pluton which hosts the Furong and Huaxiangling tin deposits, the Bozhushan pluton which hosts

the Bainiuchang tin deposit, the Huashan–Guposhan pluton which hosts the Xinlu tin deposit, and the Jiuyishan–Jinjiling pluton which hosts the Daaio tin deposit (Wang et al., 2005; Jiang et al., 2008; Zhao et al., 2012; Chen et al., 2015). Generally, ore related granites in South China are mostly composite plutons, and fractional crystallization is a significant mechanism for the formation of W- and Sn-bearing granites. When fractional crystallization occurs in granitic melts, some minerals preferentially crystallize and separate with the dissipation of the magma heat and cause the granitic magma to develop and evolve along a rich direction of alkali, silica, volatile, Sn–W, and other rare elements (Li et al., 2014c). In the Yingwuling deposit, skarn rocks containing fluorite markedly developed around the granites, indicating the involvement of F-rich fluid (Yang et al., 2012). In addition, the intense hydrothermal alteration is probably coupled with the melt-fluid interaction between hydrothermal volatile-rich fluids and late stage magmatic liquids, which led to the formation of the REE tetrad effect (Jahn et al., 2001; Li et al., 2014c). The tetrad effect in REE also can be used as an effective way to distinguish mineralized granites from barren ones (Li et al., 2014c). The visible tetrad effect in the Yingwuling granites indicates its close relationship to the W–Sn mineralization in the Yingwuling deposit, which is a common feature for worldwide W–Sn mineralization (Lehmann, 1990, 1993). Mustard et al. (2006) pointed out that the W and Sn elements become more enriched during fractionation compared to the metals Zn, Pb, and Cu. All of these indicate that there is promising W–Sn prospecting potential related to the granites in the Yingwuling deposit. Our new zircon U–Pb ages show that the plutons formed in the Late Cretaceous. The molybdenite Re–Os isochron age of the Yingwuling W–Sn polymetallic deposits in the region determined by Zheng et al. (2013) is 83.0 ± 1.7 Ma is similar to the zircon U–Pb ages of the Yingwuling granites. This establishes a clear temporal link between the Yingwuling granitoids and the W–Sn polymetallic mineralization in the region.

Late Cretaceous granitoids (75–110 Ma, mostly 80–95 Ma) are widespread in South China, and these granitoids are related to W–Sn mineralization, such as the world-class Gejiu, Dachang, and Dulong deposits, which are part of Cretaceous tectono-magmatic-mineralization events (Chen et al., 2015; Zheng et al., 2016). Except for dense magmatism and mineralization in South China, Late Cretaceous granites have also recognized in the southern part of the Malay Peninsula and in Vietnam, and these granites are commonly related to Sn mineralization (Roger et al., 2012; Wang et al., 2014). And Morley (2012) and Chen et al. (2014) suggest that northeastern Vietnam is geologically part of the South China block. Along the eastern Asian continental margin, the north-most late Cretaceous tectono-magmatic activities also occurs in South Korea, southwest Japan and Russian Far East (Sonehara and Harayama, 2007; Zhang et al., 2012; Jahn et al., 2015). These all clearly suggest that the Late Cretaceous magmatism and mineralization activities are widespread along the continental margin of eastern Asia and are likely to be the products of the same geodynamic setting.

6.5. Tectonic implications

A-type granites may involve multiple processes, different tectonic settings and variable mantle/crust proportion in their sources. However, it appears that A-type granites can indicate a variety of extensional environments, such as back-arc, continental arc, post-collision and intra-plate, and they are commonly associated with crustal extension features (Collins et al., 1982; Whalen et al., 1987; Eby, 1992). Eby (1992) subdivided A-type granites into A₁ and A₂ groups. The A₁ group is mantle-derived and emplaced in an anorogenic setting such as continental rifts or other intra-plate environments; the A₂ group is derived from melting of underplated mafic crust or continental crust and emplaced in a variety of tectonic environments. Using the Rb/Nb-Y/Nb geochemical discriminant diagram of Eby (1990, 1992) (Fig. 15a and b), Yingwuling granites plotted in the A₂-type. Sun and McDonough (1989) proposed that it is distinctive for

La/Nb ratios from intra-plate and convergent margin magmatism, the former La/Nb <1.0, whereas La/Nb of the latter is higher, indicating Yingwuling granites formed in the WPG (within plate granites). We plotted our geochemical data on diagrams of Rb versus (Yb + Ta) and Ta vs. Yb diagrams (Fig. 15c and d) and all samples fall in WPG fields. It is, therefore, inferred that the Yingwuling A-type granite emplaced in an intra-plate tectonic setting.

6.6. Genetic model for Late Mesozoic A-type granitoids magmatism in South China

The intense magmatic activities in South China mainly occurred in two episodes, one in the Jurassic (Early Yanshanian) and the other in the Cretaceous (Late Yanshanian) (Zhou et al., 2006). Among these widespread granitoids, a number of A-type granites have been recognized: Wang et al. (2005) suggests that these intrusive rocks may be classified as three periods, 184–152 Ma, 139–123 Ma and 101–86 Ma; Yang et al. (2012) proposed four distinct episodes of A-type granitic rocks, 195–170 Ma, 170–150 Ma, 137–122 Ma and 110–90 Ma. By combining with previous published isotopic ages (Table 1), we propose that Late Mesozoic A-type granitoids or alkaline intrusive rocks in South China can be grouped into four pulses, i.e. 195–180 Ma, 180–149 Ma, 136–116 Ma and 110–79 Ma.

The earliest Yanshanian A-type granitoid magmatism was emplaced at around 195–190 Ma, as exemplified by the Keshubei A-type granites (189 Ma, Li and Li, 2007), the Wengong A-type granites (192 Ma, Zhu et al., 2010). These rocks formed in an intra-plate setting after the ca. 250–200 Ma South China Indosinian Orogeny (Zhou et al., 2006).

The predominant magmatic event of Period II (180–149 Ma) occurred at about ca. 160 Ma and most of these granitic rocks are distributed in the west of Zhenghe-Dapu fault along the southern inland area (Wang et al., 2005; Li and Li, 2007), such as Yangmei syenite (162 Ma, Li et al., 2004a), Tong'an syenite (163 Ma, Li et al., 2004a), Mashan monzonite (164 Ma, Li et al., 2004a), Qianlishan granite (152 Ma, Li et

al., 2004b), Nankunshan alkali syenite (158 Ma, Li et al., 2007), Zhaibei granite (172 Ma, Li et al., 2003), Tabei syenite (162 Ma, Li et al., 2003) and Quannan syenite (165 Ma, Li et al., 2003), which indicate the change from the Tethyan into Pacific tectonic domains and these A-type granitic rocks were formed in a continental arc related to the subduction of the Paleo-Pacific plate (Yang et al., 2012).

The Cretaceous magmatism occurred at 140–80 Ma, with two major phases at ca. 136–116 Ma and ca. 110–81 Ma. There appears to be two “magmatic quiescence” straddling at ca. 149–136 Ma (the Jurassic-Cretaceous boundary) and at ca. 116–110 Ma. The A-type granites of Period III (136–116 Ma) consist of the Xiangshan volcanic-intrusive complex (135–137 Ma, Yang et al., 2010), Sanqingshan alkali feldspar granite and syenogranite (130–131 Ma, Sun et al., 2015), Yangmeiwan granite (135 Ma, Yang et al., 2012), Daqiaowu granitic porphyry (133–136 Ma, Yang et al., 2012) and Tongshan granite (129 Ma, Jiang et al., 2011), Haiyang K-feldspar granite (117 Ma, Li et al., 2014b) and syenite (116 Ma, Li et al., 2014b), Huashan granite (125 Ma, Wang et al., 2005) and quartz syenite (126 Ma, Fan et al., 2008), Huangmeijian quartz syenite (125 Ma, Fan et al., 2008) and alkaline feldspar quartz syenite (127 Ma, Li et al., 2011), Ejinao alkaline syenite (128 Ma, Bao et al., 2000), Fanchang alkali feldspar granite (121 Ma, Su et al., 2013) and so on. They are mainly distributed inland area of the west of Zhenghe-Dapu fault, and do not exist on coastal area in Zhejiang and Fujian Provinces where contemporaneous calc-alkaline volcanics and intrusive rocks were greatly developed. Jiang et al. (2011) suggested that back-arc extension has developed or an intra-arc rift has been formed since the Early Cretaceous (~130 Ma); Wong et al. (2009) proposed a model of irregular and episodic rollback of the paleo-Pacific plate that led to localized extension; Wu et al. (2002) and Deng et al. (2004) pointed out that during such period the crust and lithospheric mantle became progressively thinned in eastern China, causing the upwelling of asthenosphere, which heated the

lithospheric mantle and triggered the partially melting of the crustal rocks and further re-activated the fault zone (Ren et al., 2002) that eventually generated the A-type granitic magmas at the extension of back-arc.

In situ zircon U–Pb dating results indicate that these A-type granitic rocks (Period IV) have a relatively long duration from 110 to 79 Ma, including Yingwuling granites (80–81 Ma, this study), Baishishan alkali feldspar granite and subordinate granite (91–92 Ma, Zhao et al., 2015), Damaoshan alkali feldspar granite and syenogranite (109–110 Ma, Jiang et al., 2011), Bozhushan granite (86 Ma, Chen et al., 2015), Qingtian alkaline granite (101 Ma, Qiu et al., 1999), Kuiqi alkaline granite (94 Ma, Martin et al., 1994), occur along the coastal area in Zhejiang and Fujian Provinces and inland area of South China, suggesting the peak of extension in South China. Sun et al. (2007) proposed an abrupt change in the drift direction ($\sim 80^\circ$) of the Pacific Plate at 125–122 Ma. Gilder et al. (1996) argues a change in velocity and dip of paleo-Pacific subduction is mainly responsible for the Late Yanshanian tectonic transition from compression to extension in SE China. Mao et al. (2013) suggests that the movement direction of the Paleo-Pacific plate changes from oblique subduction to parallel to the continental margin after 135 Ma. He et al. (2012) proposed the early stage (140–110 Ma) in response to the compressional environment and the late stage (110–85 Ma) in response to the extensional environment, corresponding to the forward and rollback subduction of the paleo-Pacific plate, respectively. Whether the “magmatic quiescence” at ca. 149–136 Ma and ca. 116–110 Ma related to such changes in plate motion needs further investigation. Evidently, an associated large-scale lithospheric extension of South China occurred linked to the subduction of the Izanagi plate during the Late Yanshanian (Mao et al., 2011), which led to intensive underplating of mantle-derived magma and a high degree of crustal melting, thereby producing strong magma mixing and hybrid granitoids in a largely extensional tectonic setting.

7. Conclusions

The geological, geochronological, geochemical, and Sr–Nd–Pb–Hf isotopic evidence presented here leads to the following conclusions:

- (1) LA–ICP–MS U–Pb zircon dating indicate that Yingwuling biotite granite and alkali feldspar granite were emplaced in 81.3 ± 0.6 Ma and 80.6 ± 0.5 Ma, respectively, which are closely related to the W–Sn mineralization.
- (2) Geochemical data indicate that Yingwuling biotite granite and alkali feldspar granite have pronounced contents of total alkalis, $\text{Fe}_2\text{O}_3^{\text{T}}/\text{MgO}$ and Ga/Al ratios. They display low MgO, CaO and TiO_2 contents, enrichment in some LILEs and HFSEs (except for Zr, Eu and Y), depletion in Ba, Sr, P and Ti. They show typical geochemical signatures of A-type granites and exhibit an A_2 subtype affinity.
- (3) Geochemical and Sr–Nd–Pb–Hf isotopic studies show that Yingwuling granites were generated by partial melting of Mesoproterozoic crust rocks in the Cathaysia Block. They were formed at a high temperature of $\sim 800^\circ\text{C}$ and low oxygen fugacity, with a possible input of mantle-derived materials and followed by subsequent fractional crystallization.
- (4) Our new data together with previous published data suggest that Late Mesozoic A-type granitoids or alkaline intrusive rocks in South China can be divided into four pulses: 195–180 Ma, 180–149 Ma, 136–116 Ma and 110–79 Ma. With a change in the subduction direction of paleo-Pacific plate, the upwelling of asthenosphere triggered Mesoproterozoic crustal rocks to partially melt and generate Yingwuling A-type granitic magmas.

Supplementary materials associated with this article can be found online at

Acknowledgments

We would like to thank associate Professor Kejun Hou and Chunli Guo from the Chinese Academy of Geological Sciences for their assistance during LA–ICP–MS zircon U–Pb dating and Hf isotope analyses. We are grateful to Dr. Linhao Zhao for helping with zircon trace elements analyses, and Senior Engineer Mu Liu for helping during Sr–Nd–Pb isotope analyses. We thank Dr. Yanbo Cheng and Jia Sun from the Chinese Academy of Geological Sciences, Maocheng Luo and Fangge Chen from the China University of Geosciences (Beijing) for their help to improve the manuscript. Prof. Nelson Eby and two anonymous reviewers provide valuable comments and suggestion which helped in the improvement of this manuscript. The work was financially supported by the National Science Foundation of China (Grant No. 41430314) and the excellent doctorate Research Program of Beijing (Grant No. 519002650744).

References

- Amelin, Y., Lee, D.C., Halliday, A.N., 2000. Early-middle Archaean crustal evolution deduced from Lu–Hf and U–Pb isotopic studies of single zircon grains. *Geochimica et Cosmochimica Acta* 64, 4205–4225.
- Bea, F., Arzamastsev, A., Montero, P., Arzamastseva, L., 2001. Anomalous alkaline rocks of Soustov, Kola: Evidence of mantle-derived metasomatic fluids affecting crustal materials. *Contributions to Mineralogy and Petrology* 140, 554–566.
- Bettencourt, J.S., Leite, W.B., Goraieb, C.L., Sparrenberger, I., Bello, R.M.S., Payolla, B.L., 2005. Sn-polymetallic greisen type deposits associated with late stage rapakivi granites, Brazil: fluid inclusion and stable isotope characteristics. *Lithos* 80, 363–386.
- Boehnke, P., Watson, E.B., Trail, D., Harrison, T.M., Schmitt, A.K., 2013. Zircon saturation re-revisited.

- Chemical Geology 351, 324–334.
- Boynton, W.V., 1984. Geochemistry of the rare earth elements: meteorite studies. In: Henderson, P. (Ed.), *Rare Earth Element Chemistry*. Elsevier, Amsterdam, pp. 63–114.
- Cai, M.H., Zhan, M.G., Peng, S.B., Meng, X.J., Liu, G.Q., 2002. Study of Mesozoic metallogenic geological setting and dynamic mechanism in Yunkai area. *Mineral Deposit* 21, 254–269 (in Chinese with English abstract).
- Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. *Pacific Geology* 8, 173–174.
- Chappell, B.W., 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* 46, 535–551.
- Chappell, B.W., White, A.J.R., 2001. Two contrasting granite type: 25 years later. *Australian Journal of Earth Science* 48, 489–499.
- Chen, J.F., Zhou, T.X., Yin, C.S., Foland, K.A., 1991. ^{40}Ar - ^{39}Ar dating of several Mesozoic plutons in southeastern Zhejiang province. *Acta Geologica Sinica* 7, 37–44 (in Chinese with English abstract).
- Chen, J.F., Jahn, B. M., 1998. Crustal evolution of southeastern China: evidence from Sr, Nd and Pb isotopic compositions of granitoids and sedimentary rocks. *Tectonophysics* 284, 101–133.
- Chen, P.R., Kong, X.G., Wang, Y.X., 1999. Rb–Sr isotopic dating and significance of early Yanshanian bimodal volcanic intrusive complex from south Jiangxi Province. *Geological Journal of China Universities* 5, 378–383 (in Chinese with English abstract).
- Chen, X.C., Hu, R.Z., Bi, X.W., Zhong, H., Lan, J.B., Zhao, C.H., Zhu, J.J., 2015. Zircon U–Pb ages and Hf–O isotopes, and whole-rock Sr–Nd isotopes of the Bozhushan granite, Yunnan province, SW China: Constraints on petrogenesis and tectonic setting. *Journal of Asian Earth Sciences* 99, 57–71.

- Chen, Z.C., Lin, W., Faure, M., Lepvier, C., Nguyen, V.V., Tich, V.V., 2014. Geochronology and isotope analysis of the Late Paleozoic to Mesozoic granitoids from northeastern Vietnam and implications for the evolution of the South China block. *Journal of Asian Earth Sciences* 86, 131–150.
- Cheng, Y.B., Mao, J.W., 2010. Age and geochemistry of granites in Gejiu area, Yunnan province, SW China: constraints on their petrogenesis and corresponding tectonic setting. *Lithos* 120, 258–276.
- Chu, N.C., Taylor, R.N., Chavagnac, V., Nesbitt, R.W., Boella, R.M., Milton, J.A., German, C.R., Bayon, G., Burton, K., 2002. Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: an evaluation of isobaric interference corrections. *Journal of Analytical Atomic Spectrometry* 17, 1567–1574.
- Cole, R.B., Stewart, B.W., 2009. Continental margin volcanism at sites of spreading ridge subduction: examples from southern Alaska and western California. *Tectonophysics* 464, 118–136.
- Collins, W.J., Beams, S.D., White, A.J.R., Chappell, B.W., 1982. Nature and origin of A-type granites with particular reference to Southeastern Australia. *Contributions to Mineralogy and Petrology* 80, 189–200.
- Compston, W., Williams, I.S., Kirschvink, J.L., Zhang, Z.C., Ma, G.G., 1992. Zircon U–Pb ages for the Early Cambrian time-scale. *Journal of the Geological Society* 149, 171–184.
- Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P., 2003. Atlas of zircon textures. *Reviews in Mineralogy and Geochemistry* 53, 469–495.
- Costi, H.T., Dall'Agnol, R., Pichavant, M., Rämö, O.T., 2009. The peralkaline tin-mineralized Madeira cryolite albite-rich granite of Pitinga, Amazonian Craton, Brazil: petrography, mineralogy, and crystallization processes. *The Canadian Mineralogist* 47, 1301–1327.
- Deng, J.F., Mo, X.X., Zhou, H.L., Wu, Z.X., Luo, Z.H., Su, S.G., 2004. A new model for the dynamic

- evolution of Chinese lithosphere: continental roots-plume tectonics. *Earth Science Reviews* 65, 223–275.
- Douce, A.E.P., 1997. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. *Geology* 25, 743–746.
- Eby, G.N., 1990. The A-type granitoids: A review of their occurrence and chemical characteristics and speculations on their petrogenesis. *Lithos* 26, 115–134.
- Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. *Geology* 20, 641–644.
- EI Bouseilly, A.M., EI Sokkary, A.A., 1975. The relation between Rb, Ba and Sr in granitic rocks. *Chemical Geology* 16, 207–219.
- Fan, Y., Zhou, T.F., Yuan, F., Qian, C.C., Lu, S.M., Cooke, D., 2008. LA–ICP–MS zircon U–Pb ages of the A-type granites in the Lu-Zong (Lujiang–Zongyang) area and their geological significances. *Acta Petrologica Sinica* 24, 1715–1724 (in Chinese with English abstract).
- Foley, S., Tiepolo, M., Vannucci, R., 2002. Growth of early continental crust controlled by melting of amphibolite in subduction zones. *Nature* 417 (6891), 837–840.
- Frost, C.D., Frost, B.R., 1997. Reduced rapakivi-type granites: the tholeiite connection. *Geology* 25, 647–650.
- Frost, C.D., Frost, B.R., 2011. On ferroan (A-type) granitoids: Their compositional variability and modes of origin. *Journal of Petrology* 52, 39–53.
- Fu, J.M., Ma, C.Q., Xie, C.F., Zhang, Y.M., Peng, S.B., 2005. Ascertainment of the Jinjiling aluminous A-type granite, Hunan Province and its tectonic settings. *Geochimica* 34, 215–226 (in Chinese with English abstract).

- Griffin, W.L., Wang, X., Jackson, S.E., Pearson, N.J.O., Reilly, S.Y., Xu, X.S., Zhou, X.M., 2002. Zircon chemistry and magma mixing, SE China: *in-situ* analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* 61, 237–269.
- Hart, S.R., 1984. A large-scale isotope anomaly in the southern hemisphere mantle. *Nature* 309, 753–757.
- He, Z.Y., Xu, X.S., Niu, Y.L., 2010. Petrogenesis and tectonic significance of a Mesozoic granite-syenite-gabbro association from inland South China. *Lithos* 119, 621–641.
- He, Z.Y., Xu, X.S., 2012. Petrogenesis of the Late Yanshanian mantle-derived intrusions in southeastern China: Response to the geodynamics of paleo-Pacific plate subduction. *Chemical Geology* 328, 208–221.
- Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and metamorphic petrogenesis. In: Hanchar, J.M., Hoskin, P.W.O. (Eds.), *Zircon: Reviews in Mineralogy and Geochemistry* 53, pp. 27–62.
- Huang, H.Q., Li, X.H., Li, W.X., Li, Z.X., 2011. Formation of high ^{18}O fayalite-bearing A-type granite by high-temperature melting of granulitic metasedimentary rocks, southern China. *Geology* 39, 903–906.
- Huang, H.Y., Li, X.H., Li, Z.X., Li, X.W., 2013. Intraplate crustal remelting as the genesis of Jurassic high-K granites in the coastal region of the Guangdong Province, SE China. *Journal of Asian Earth Sciences* 74, 280–302.
- Hou, K.J., Li, Y.H., Tian, Y.Y., 2009. *In situ* U–Pb zircon dating using laser ablation-multi ion counting-ICP-MS. *Mineral Deposits* 28, 481–492 (in Chinese with English abstract).
- Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometer (LA–ICP–MS) to *in situ* U–Pb zircon

- geochronology. *Chemical Geology* 211, 47–69.
- Jahn, B.M., Wu, F.Y., Capdevila, R., Martineau, F., Zhao, Z.H., Wang, Y.X., 2001. Highly evolved juvenile granites with tetrad REE patterns: the Woduhe and Baerzhe granites from the Great Xing'an Mountains in NE China. *Lithos* 59, 171–198.
- Jahn, B.M., Valui, G., Kruk, N., Gonevchuk, V., Usuki, M., Wu, J.T.J., 2015. Emplacement ages, geochemical and Sr–Nd–Hf isotopic characterization of Mesozoic to early Cenozoic granitoids of the Sikhote-Alin Orogenic Belt, Russian Far East: Crustal growth and regional tectonic evolution. *Journal of Asian Earth Sciences* 111, 872–918.
- Jiang, S.Y., Zhao, K.D., Jiang, Y.H., Dai, B.Z., 2008. Characteristics and genesis of Mesozoic A-type granites and associated mineral deposits in the Southern Hunan and Northern Guangxi provinces along the Shi–Hang belt, South China. *Geological Journal of China Universities* 14, 496–509 (in Chinese with English abstract).
- Jiang, Y.H., Zhao, P., Zhou, Q., Liao, S.Y., Jin, G.D., 2011. Petrogenesis and tectonic implications of Early Cretaceous S- and A-type granites in the northwest of the Gan–Hang rift, SE China. *Lithos* 121, 55–73.
- Kerr, A., Fryer, B.J., 1993. Nd isotope evidence for crust-mantle interaction in the generation of A-type granitoid suites in Labrador, Canada. *Chemical Geology* 104, 39–60.
- King, P.L., White, A.J.R., Chappell, B.W., Allen, C.M., 1997. Characterization and origin of aluminous A-type granites from the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* 38, 371–391.
- King, P.L., Chappell, B.W., Allen, C.M., White, A.J.R., 2001. Are A-type granites the high-temperature felsic granites? Evidence from fractionated granites of the Wangrah Suite. *Australian Journal of Earth*

Sciences 48, 501–514.

Lehmann, B., 1990. Metallogeny of tin. Springer, Berlin/Heidelberg/New York, pp. 211.

Lehmann, B., 1993. Metallogeny of granite-related rare-metal mineralization. *Resource Geology*, Special Issue 15, 385–392.

Li, X.H., Chen, Z.G., Liu, D.Y., Li, W.X., 2003. Jurassic gabbro-granite-syenite suites from southern Jiangxi Province, SE China: Age, origin and tectonic significance. *International Geology Review* 45, 898–921.

Li, X.H., Chung, S.L., Zhou, H.W., Lo, C.H., Liu, Y., Chen, C.H., 2004a. Jurassic intra-plate magmatism in southeastern Hunan-eastern Guangxi: $^{40}\text{Ar}/^{39}\text{Ar}$ dating, geochemistry, Sr–Nd isotopes, and implications for tectonic evolution of SE China, Geological Society of London Special Publication 226, 193–215.

Li, X.H., Liu, D.Y., Sun, M., Liang, X.R., Liu, Y., 2004b. Precise Sm–Nd and U–Pb isotopic dating of the supergiant Shizhuyuan polymetallic deposit and its host granite, SE China. *Geological Magazine* 141, 225–231.

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

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

Li, X.H., Li, Z.X., Li, W.X., Liu, Y., Yuan, C., Wei, G.J., Qi, C.S., 2007. U–Pb zircon, geochemical and Sr–Nd–Hf isotopic constraints on age and origin of Jurassic I- and A-type granites from central Guangdong, SE China: a major igneous event in response to foundering of a subducted flat-slab? *Lithos* 96, 186–204.

Li, H., Zhang, H., Ling, M.X., Wang, F.Y., Ding, X., Zhou, J.B., Yang, X.Y., Tu, X.L., Sun, W.D., 2011.

Geochemical and zircon U-Pb study of the Huangmeijian A-type granite: implications for geological evolution of the Lower Yangtze River belt. *International Geology Review* 53, 499–525.

Li, H., Ling, M.X., Li, C.Y., Zhang, H., Ding, X., Yang, X.Y., Fan, W.M., Li, Y.L., Sun, W.D., 2012.

A-type granite belts of two chemical subgroups in central eastern China: indication of ridge subduction. *Lithos* 150, 26–36.

Li, Z., Qiu, J.S., Yang, X.M., 2014a. A review of the geochronology and geochemistry of Late Yanshanian

(Cretaceous) plutons along the Fujian coastal area of southeastern China: Implications for magma evolution related to slab break-off and rollback in the Cretaceous. *Earth Science Review* 128, 232–248.

Li, H., Ling, M.X., Ding, X., Zhang, H., Li, C.Y., Liu, D.Y., Sun, W.D., 2014b. The geochemical

characteristics of Haiyang A-type granite complex in Shandong, eastern China. *Lithos* 200–201, 142–156.

Li, H., Watanabe, K., Yonezu, K., 2014c. Geochemistry of A-type granites in the Huangshaping

polymetallic deposit (South Hunan, China): Implications for granite evolution and associated mineralization. *Journal of Asian Earth Sciences* 8, 149–167.

Liou, J.G., Zhang, R.Y., Ernst, W.G., Liu, J., McLimans, R., 1998. Mineral parageneses in the Piampaludo

eclogitic body, Gru ppo di Voltri, Western Ligurian Alps. *Schweizerische Mineralogische Und Petrographische Mitteilungen* 78, 317–335.

Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. *Geological Society*

of America Abstracts with Programs 11, 468.

Mao, J.W., Zhang, J.D., Pirajno, F., Ishiyama, D., Su, H.M., Guo, C.L., Chen, Y.C., 2011. Porphyry

- Cu–Au–Mo–epithermal Ag–Pb–Zn–distal hydrothermal Au deposits in the Dexing area, Jiangxi province, East China—a linked ore system. *Ore Geology Reviews* 43, 203–216.
- Mao, J.W., Cheng, Y.B., Chen, M.H., Pirajno, F., 2013. Major types and time–space distribution of Mesozoic ore deposits in South China and their geodynamic settings. *Mineralium Deposita* 48, 267–294.
- Mao, Z.H., Liu, J.J., Mao, J.W., Deng, J., Zhang, F., Meng, X.Y., Xiong, B.K., Xiang, X.K., Luo, X.H., 2015. Geochronology and geochemistry of granitoids related to the giant Dahutang tungsten deposit, middle Yangtze River region, China: Implications for petrogenesis, geodynamic setting, and mineralization. *Gondwana Research* 28, 816–836.
- Martin, H., Bonin, B., Capdevila, R., Jahn, B.M., Lameyre, J., Wang, Y., 1994. The Kuiqi peralkaline granitic complex (SE China): petrology and geochemistry. *Journal of Petrology* 35, 983–1015.
- McDonough, W.F., Sun, S.S., 1995. The composition of the Earth. *Chemical Geology* 120, 223–253.
- Miller, C.F., McDowell, S.M., Mapes, R.W., 2003. Hot and cold granites? Implications of zircon saturation temperatures and preservation of inheritance. *Geology* 31, 529–532.
- Morel, M.L.A., Nebel, O., Nebel-Jacobsen, Y.J., Miller, J.S., Vroon, P.Z., 2008. Hafnium isotope characterization of the GJ-1 zircon reference material by solution and laser-ablation MC-ICPMS. *Chemical Geology* 255, 231–235.
- Morley, C.K., 2012. Late Cretaceous–Early Palaeogene tectonic development of SE Asia. *Earth-Science Reviews* 115, 37–75.
- Mushkin, A., Navon, O., Halica, L., Hartmann, C., Stein, M., 2003. The petrogenesis of A-type magmas from the Amram Massif, southern Israel. *Journal of Petrology* 44, 815–832.

- Mustard, R., Ulrich, T., Kamenetsky, S., Mernagh, T., 2006. Gold and metal enrichment in natural granitic melts during fractional crystallization. *Geology* 34, 85–88.
- Nasdala, L., Hofmeister, W., Norberg, N., Mattinson, J.M., Corfu, F., Dörr, W., Kamo, S.L., Kennedy, A.K., Kronz, A., Reiners, P.W., Frei, D., Kosler, J., Wan, Y., Götze, J., Häger, T., Kröner, A., Valley, J.W., 2008. Zircon M257-a homogeneous natural reference material for the ion microprobe U–Pb analysis of zircon. *Geostandards and Geoanalytical Research* 32, 247–265.
- Patiño Douce, A.E.P., 1997. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. *Geology* 25, 743–746.
- Peng, S.B., Jin, Z.M., Fu, J.M., Liu, Y.H., He, L.Q., Cai, M.H., 2006. Geochemical characteristics of basic intrusive rocks in the Yunkai uplift, Guangdong–Guangxi, China, and their tectonic significance. *Geological Bulletin of China* 25, 434–441 (in Chinese with English abstract).
- Pettke, T., Audétat, A., Schaltegger, U., Heinrich, C.A., 2005. Magmatic-to-hydrothermal crystallization in the W–Sn mineralized Mole Granite (NSW, Australia): Part II: Evolving zircon and thorite trace element chemistry. *Chemical Geology* 220, 191–213.
- Pitcher, W.S., 1982. Granite type and tectonic environment. In: Hsu, K.J. (Ed.), *Mountain Building Processes*.
- Qiu, J.S., Wang, D.Z., McInnes, B.I.A., 1999. Geochemistry and petrogenesis of the I- and A-type composite granite masses in the coastal area of Zhejiang and Fujian province. *Acta Petrologica Sinica* 15, 237–246 (in Chinese with English abstract).
- Rapp, R.P., Watson, E.B., 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust-mantle recycling. *Journal of Petrology* 36, 891–931.

- Ren, J.Y., Tamaki, K., Li, S.T., Zhang, J.X., 2002. Late Mesozoic and Cenozoic rifting and its dynamic setting in Eastern China and adjacent areas. *Tectonophysics* 344, 175–205.
- Rickwood, P.C., 1989. Boundary lines within petrologic diagrams which use oxides of major and minor elements. *Lithos* 22, 247–263.
- Roger, F., Maluski, H., Lepvrier, C., Van, T.V., Paquette, J.L., 2012. LA-ICPMS zircons U/Pb dating of Permo-Triassic and Cretaceous magmatisms in Northern Vietnam—Geodynamical implications. *Journal of Asian Earth Sciences* 48, 72–82.
- Shen, W.Z., Wang, D.Z., Liu, C.S., 1995. Isotope geochemical characteristics and material sources of tin-bearing porphyries in South China. *Acta Geologica Sinica* 69, 349–359 (in Chinese with English abstract).
- Shu, X.J., Wang, X.L., Sun, T., Xu, X.S., 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.
- Skjerlie, K.P., Johnston, A.D., 1992. Vapor-absent melting at 10 kbar of a biotite-and amphibole-bearing tonalitic gneiss: implications for the generation of A-type granites. *Geology* 20, 263–266.
- Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plesovice zircon—a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology* 249, 1–35.
- Sonehara, T., Harayama, S., 2007. Petrology of the Nohi Rhyolite and its related granitoids: a Late Cretaceous large silicic igneous field in central Japan. *Journal of Volcanology and Geothermal Research* 167, 57–80.

- Su, Y.P., Zheng, J.P., Griffin, W.L., Zhao, J.H., O'Reilly, S.Y., Tang, H., Ping, X.Q., Xiong, Q., 2013. Petrogenesis and geochronology of Cretaceous adakitic, I-and A-type granitoids in the NE Yangtze block: constraints on the eastern subsurface boundary between the North and South China blocks. *Lithos* 175–176, 333–350.
- Sun, F.J., Xu, X.S., Zou, H.B., Xia, Y., 2015. Petrogenesis and magmatic evolution of ~130 Ma A-type granites in Southeast China. *Journal of Asian Earth Sciences* 98, 209–224.
- Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implication for mantle composition and process. In: Saunders, A.D., Norry, M.J. (Eds), *Magmatism in the Ocean Basin*. Geological Society Special Publication 42, pp. 313–345.
- Sun, W.D., Ding, X., Hu, Y.H., Li, X.H., 2007. The golden transformation of the Cretaceous plate subduction in the west Pacific. *Earth and Planetary Science Letters* 262, 533–542.
- Sun, Y., Ma, C.Q., Liu, Y.Y., She, Z.B., 2011. Geochronological and geochemical constraints on the petrogenesis of late Triassic aluminous A-type granites in southeast China. *Journal of Asian Earth Sciences* 42, 1117–1131.
- Turner, S.P., Foden, J.D., Morrison, R.G., 1992. Derivation of some A-type magmas by fractionation of basaltic magma: An example from the Padthaway Ridge, South Australia. *Lithos* 28, 151–179.
- Wang, C., Deng, J., Carranza, E.J.M., Santosh, M., 2014. Tin metallogenesis associated with granitoids in the southwestern Sanjiang Tethyan Domain: nature, deposit types, and tectonic setting. *Gondwana Research* 26, 576–593.
- Wang, Q., Zhao, Z.H., Jian, P., Xiong, X.L., Bao, Z.W., Dai, T.M., Xu, J.F., Ma, J.L., 2005. Geochronology of Cretaceous A-type granitoids or alkaline intrusive rocks in the hinterland, South

- China: constraints for late-Mesozoic tectonic evolution. *Acta Petrologica Sinica* 21, 795–808 (in Chinese with English abstract).
- Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* 64, 295–304.
- Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* 95, 407–419.
- Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M., 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature* 409, 175–178.
- Williams, I.S., 1992. Some observations on the use of zircon U–Pb geochronology in the study of granitic-rocks. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 83, 447–458.
- Wong, J., Sun, M., Xing, G.F., Li, X.H., Zhao, G.C., Wong, K., Yuan, C., Xia, X.P., Li, L.M., Wu, F.Y., 2009. Geochemical and zircon U–Pb and Hf isotopic study of the Baijuehuajian metaluminous A-type granite: Extension at 125–100 Ma and its tectonic significance for South China. *Lithos* 112, 289–305.
- Wu, F.Y., Sun, D.Y., Li, H., Jahn, B.M., Wilde, S., 2002. A-type granites in northeastern China: age and geochemical constraints on their petrogenesis. *Chemical Geology* 187, 143–173.
- Wu, F.Y., Yang, Y.H., Xie, L.W., Yang, J.H., Ping, X., 2006. Hf isotopic compositions of the standard zircons and baddeleyites used in U–Pb geochronology. *Chemical Geology* 234, 105–126.
- Xu, X.S., O'Reilly, S.Y., Griffin, W.L., Wang, X.L., Pearson, N.J., He, Z.Y., 2007. The crust of Cathaysia: age, assembly and reworking of two Terranes. *Precambrian Research* 158, 51–78.
- Yang, J.H., Wu, F.Y., Chuang, S.L., Wilde, S.A., Chu, M.F., 2006. A hybrid origin for the Qianshan A-type granite, northeast China: geochemical and Sr–Nd–Hf isotopic evidence. *Lithos* 89, 89–106.

- Yang, M.G., Huang, S.B., Lu, F.S., Tang, W.X., Mao, S.B., 2009. Major types and time-space distribution of Mesozoic ore deposits in South China: implications for geodynamic settings. *Geology in China* 36, 528–543 (in Chinese with English abstract).
- Yang, S.Y., Jiang, S.Y., Jiang, Y.H., Zhao, K.D., Fan, H.H., 2010. Zircon U–Pb geochronology, Hf isotopic composition and geological implications of the rhyodacite and rhyodacitic porphyry in the Xiangshan uranium ore field, Jiangxi Province, China. *Science China Earth Sciences* 53, 1411–1426.
- Yang, S.Y., Jiang, S.Y., Zhao, K.D., Jiang, Y.H., Ling, H.F., Li, Luo., 2012. Geochronology, geochemistry and tectonic significance of two Early Cretaceous A-type granites in the Gan–Hang Belt, Southeast China. *Lithos* 150, 155–170.
- Yang, X.A., Liu, J.J., Li, D.P., Zhai, D.G., Yang, L.B., Han, S.Y., Wang, H., 2012. Zircon U–Pb dating and geochemistry of the linong granitoid and its relationship to Cu mineralization in the Yangla Copper Deposit, Yunnan, China. *Resource Geology* 63, 224–238.
- Zhang, Y.B., Zhai, M., Hou, Q.L., Li, T.S., Liu, F., Hu, B., 2012. Late Cretaceous volcanic rocks and associated granites in Gyeongsang Basin, SE Korea: their chronological ages and tectonic implications for cratonic destruction of the North China Craton. *Journal of Asian Earth Sciences* 47, 252–264.
- Zhao, J.L., Qiu, J.S., Liu, L., Wang, R.Q., 2015. Geochronological, geochemical and Nd–Hf isotopic constraints on the petrogenesis of Late Cretaceous A-type granites from the southeastern coast of Fujian Province, South China. *Journal of Asian Earth Sciences* 105, 338–359.
- Zhao, K.D., Jiang, S.Y., Yang, S.Y., Dai, B.Z., Lu, J.J., 2012. Mineral chemistry, trace elements and Sr–Nd–Hf isotope geochemistry and petrogenesis of Cailing and Furong granites and mafic enclaves from the Qitianling batholith in the Shi–Hang zone, South China. *Gondwana Research* 22, 310–324.

- Zheng, W., Zhao, H.J., Chen, M.H., Xu, L.G., Liu, J.X., Luo, D.L., Hu, Y.G., 2013. Re–Os isotopic dating of molybdenites from the Yingwuling polymetallic deposit in Guangdong Province and its geological. *Journal of Mineralogy and Petrology* 33, 38–46 (in Chinese with English abstract).
- Zheng, W., Mao, J.W., Pirajno, F., Zhao, H.J., Zhao, C.S., Mao, Z.H., Wang, Y.J., 2015. Geochronology and geochemistry of the Shilu Cu–Mo deposit in the Yunkai area, Guangdong Province, South China and its implication. *Ore Geology Reviews* 67, 382–398.
- Zheng, W., Mao, J.W., Zhao, C.S., Ouyang, H.G., Wang, X.Y., 2016. Re–Os Geochronology of Molybdenite from Yinyan Porphyry Sn Deposit in South China. *Resource geology* 66, 63–70.
- Zhou, X.M., Sun, T., Shen, W.Z., Shu, L.S., Niu, Y.L., 2006. Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: a response to tectonic evolution. *Episodes* 29, 26–21.
- Zhu, W.G., Zhong, H., Li, X.H., He, D.F., Song, X.Y., Ren, T., Chen, Z.Q., Sun, H.S., Liao, J.Q., 2010. The early Jurassic mafic-ultramafic intrusion and A-type granite from northeastern Guangdong, SE China: age, origin, and tectonic significance. *Lithos* 119, 313–329.
- Zindler, A., Hart, S.R., 1986. Chemical geodynamics. *Annual Review of Earth and Planetary Sciences* 14, 493–571.

Figure Captions

Fig. 1. (a) Sketch tectonic map of China; (b) Distribution of Late Mesozoic A-type granitoids or alkaline intrusive rocks and within-plate basaltic rocks in South China (after Wang et al., 2005). The red star indicates the locality of the Yingwuling A-type granites. Eight main fault zones are marked by black bold lines: F_1 = Tan–Lu fault; F_2 = Changjiang fault; F_3 = Jiangshao fault; F_4 = Xunwu–Ruijin fault; F_5 = Shicheng–Chong’an fault; F_6 = Zhenghe–Dapu fault; F_7 = Fu’an–Nanjing fault and F_8 = Chang’ao fault.

Fig. 2. Sketch geological map of the Yunkai area (after Peng et al., 2006)

Fig. 3. Simplified geological map of the Yingwuling W–Sn polymetallic deposit (Zheng et al., 2013).

Fig. 4. Hand specimens and photomicrographs of Yingwuling granites. (A), (C) and (E), the Yingwuling biotite granite; (B), (D) and (F), the Yingwuling alkali feldspar granite. Qtz: quartz, Kf: K-feldspar, Pl: plagioclase, Bi: biotite.

Fig. 5. Chondrite-normalized REE patterns of zircon grains for medium-fine grained biotite granite and alkali feldspar granite. The chondrite values are from McDonough and Sun (1995).

Fig. 6. Representative cathodoluminescence (CL) images of zircons from the Yingwuling (a) biotite granite and (b) alkali feldspar granite. Circles indicate locations of analyzed sites, with numbers in the circles representing for spot numbers. The $^{206}\text{Pb}/^{238}\text{U}$ age for each spot is given.

Fig. 7. LA–ICP–MS zircon U–Pb concordia diagram for (a) biotite granite and (b) alkali feldspar granite.

Weighted mean ages and MSWD are shown in each figure.

Fig. 8. (a) K_2O versus SiO_2 plots for representative rocks from the Yingwuling granites (fields in the plot are from Rickwood, 1989) (b) Plot of A/NK versus A/CNK {A/NK = molar ratio of $[\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})]$; A/CNK = molar ratio of $[\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})]}$.

Fig. 9. (a) Chondrite-normalized REE patterns (after Boynton, 1984); (b) Primitive-mantle-normalized

spider diagrams (after Sun and McDonough, 1989).

Fig. 10. Harker diagrams for selected major and trace elements of the Yingwuling granites. (a) Na₂O, (b) Fe₂O₃^T, (c) MgO, (d) Al₂O₃, (e) TiO₂, (f) K₂O, (g) CaO, (h) Rb and (i) Y vs. SiO₂.

Fig. 11. Eu vs. Sr (a) and Ba (b) diagrams for the Yingwuling granites. Trends illustrate crystal fractionation of biotite (Bt), plagioclase (Pl) and K-feldspar (Kfs) starting with initial concentration.

Fig. 12. (a) FeO^T/MgO, (b) (Na₂O + K₂O)/CaO, (c) Ce and (d) Nb vs. 10000×Ga/Al discrimination diagrams (after Whalen et al., 1987), showing the A-type nature of the Yingwuling granitic intrusions.

Fig. 13. (a) Diagram of ε_{Hf}(t) vs. U–Pb ages for zircons from the Yingwuling granites with the shaded region indicating Hf isotope evolution for Cathaysia crustal basement from Xu et al. (2007) and He et al. (2010); (b) Diagrams of (⁸⁷Sr)/(⁸⁶Sr)_i versus ε_{Nd}(t). Basement data are cited from Shen et al. (1995).

Fig. 14. Variation of ²⁰⁶Pb/²⁰⁴Pb vs ²⁰⁷Pb/²⁰⁴Pb (a) and ²⁰⁶Pb/²⁰⁴Pb vs ²⁰⁸Pb/²⁰⁴Pb (b) for the Yingwuling granites in western Guangdong Province. Northern Hemisphere Reference Line (NHRL) is from Hart (1984). Mantle source reservoirs BSE, MORB, DMM, EM I and EM II are from Zindler and Hart (1986).

Fig. 15. The A-type granite subdivision diagrams of Nb–Y–3×Ga (a) and Nb–Y–Ce (b) (after Eby, 1992) show that the Yingwuling granitic intrusions belong to the A₂ group; (c) Ta vs. Yb, (d) Rb versus (Yb + Ta) diagrams (after Pearce et al., 1984) for the Yingwuling granites. ORG = oceanic ridge granite; VAG = volcanic arc granite; syn-COLG = syn-collision granite and WPG = within plate granites.

Table Caption

Table 1 Isotopic ages for Late Mesozoic A-type granitoids or alkaline intrusive rocks in South China.

Supplementary table 1 LA-ICP-MS analytical results of zircon trace elements (in ppm) and Eu/Eu^* , $\text{Ce}^{4+}/\text{Ce}^{3+}$ ratios from the Yingwuling biotite granite and alkali feldspar granite.

Supplementary table 2 LA-ICP-MS U-Pb zircon age data for the study granites from the Yingwuling deposit.

Supplementary table 3 Major (in wt.%), trace and rare earth element (in ppm) compositions of the Yingwuling biotite granite and alkali feldspar granite.

Supplementary table 4 Sr-Nd-Pb isotopic compositions of the Yingwuling granitic intrusions.

Supplementary table 5 Zircon Lu-Hf isotopes for the Yingwuling biotite granite and alkali feldspar granite.

Table 1

Location	Lithology	Age (Ma)	Method	Reference
Bozhushan	Granite	86.25 ± 0.34	LA-ICPMS Zircon U-Pb	Chen et al., 2015
Baishishan	Alkali feldspar granite	91.0 ± 1.0	LA-ICPMS Zircon U-Pb	Zhao et al., 2015
Baishishan	Subordinate granite	91.7 ± 0.7	LA-ICPMS Zircon U-Pb	Zhao et al., 2015
Jingangshan	Alkali feldspar granite	86.2 ± 0.6	LA-ICPMS Zircon U-Pb	Zhao et al., 2015
Wushan	Alkali feldspar granite	92.0 ± 0.6	LA-ICPMS Zircon U-Pb	Zhao et al., 2015
Wushan	Porphyritic alkali feldspar granite	92.1 ± 0.6	LA-ICPMS Zircon U-Pb	Zhao et al., 2015
Dayuancun	Granite	95 ± 2	SHRIMP Zircon U-Pb	Wang et al., 2005
Daheshan	Quartz syenite porphyry	86 ± 3	SHRIMP Zircon U-Pb	Wang et al., 2005
Maotan	Granite	99.28 ± 1	K-Ar whole rock	Wu et al., 1998
Maotan	Granite porphyry	97.36 ± 1	K-Ar whole rock	Wu et al., 1998
Qingtian	Alkaline granite	101.2 ± 2.1	LA-ICPMS Zircon U-Pb	Qiu et al., 1999
Taohuadiao	Alkaline granite	92.9 ± 0.6	LA-ICPMS Zircon U-Pb	Qiu et al., 1999
Putuoshan	Moyite	93.6 ± 0.4	LA-ICPMS Zircon U-Pb	Qiu et al., 1999
Putuoshan	Quartz monzodiorite	110.2 ± 1.1	LA-ICPMS Zircon U-Pb	Qiu et al., 1999
Kuiqi	Alkaline granite	93.5 ± 3	Rb-Sr whole rock	Martin et al., 1994
Gushan	Biotite granite	104 ± 5	Rb-Sr whole rock	Martin et al., 1994
Liangnong	Quartz diorite	100.6 ± 0.1	Ar-Ar biotite	Chen et al., 1991
Liangnong	Monzogranite	101.2 ± 0.3	Ar-Ar biotite	Chen et al., 1991
Longwangtang	Granite	109.4 ± 0.2	Ar-Ar biotite	Chen et al., 1991
Longwangtang	Moyite	110.1 ± 0.4	Ar-Ar biotite	Chen et al., 1991
Shantouzheng	Quartz diorite	108.1 ± 1.6	Ar-Ar hornblende	Chen et al., 1991
Damaoshan	Alkali-feldspar granite	108.9 ± 2.1	SHRIMP Zircon U-Pb	Jiang et al., 2011
Damaoshan	Syenogranite	109.9 ± 3.1	SHRIMP Zircon U-Pb	Jiang et al., 2011
Haiyang	K-feldspar granite	116.8 ± 1.7	LA-ICPMS Zircon U-Pb	Li et al., 2014
Haiyang	Syenite	115.8 ± 2.2	LA-ICPMS Zircon U-Pb	Li et al., 2014
Honggong	Quartz diorite	124.4 ± 0.3	Ar-Ar biotite	Chen et al., 1991
Huashan	Granite	125 ± 2	SHRIMP Zircon U-Pb	Wang et al., 2005
Sucun	Moyite	134.89 ± 2.73	Ar-Ar K-feldspar	Wang et al., 2005
Maotan	Alkaline feldspar granite	125.4 ± 2.2	LA-ICPMS Zircon U-Pb	Li et al., 2012
Huayuangong	Alkaline feldspar granite	125.3 ± 1.2	LA-ICPMS Zircon U-Pb	Li et al., 2012
Xiangshuijian	Alkaline feldspar granite	125.4 ± 1.4	LA-ICPMS Zircon U-Pb	Li et al., 2012
Chengshan	Alkaline granite	126.5 ± 2.1	LA-ICPMS Zircon U-Pb	Fan et al., 2008
Huashan	Quartz syenite	126.2 ± 0.8	LA-ICPMS Zircon U-Pb	Fan et al., 2008
Huangmeijian	Quartz syenite	125.4 ± 1.7	LA-ICPMS Zircon U-Pb	Fan et al., 2008
Zongyang	Alkaline granite	124.8 ± 2.2	LA-ICPMS Zircon U-Pb	Fan et al., 2008
Baijuehuajian	Granite	126 ± 3	SHRIMP Zircon U-Pb	Wong et al., 2009
Huangmeijian	Alkaline feldspar quartz syenite	127.1 ± 1.4	LA-ICPMS Zircon U-Pb	Li et al., 2011
Ejinao	Alkaline syenite	127.5	Ar-Ar hornblende	Bao et al., 2000
Fanchang	Alkali feldspar granite	121 ± 1	LA-ICPMS Zircon U-Pb	Su et al., 2013
Huangshan	Alkali feldspar granite	129 ± 1	LA-ICPMS Zircon U-Pb	Su et al., 2013
Tongshan	Syenogranite	129.0 ± 2.3	SHRIMP Zircon U-Pb	Jiang et al., 2011
Sanqingshan	Alkali feldspar granite	130 ± 2	LA-ICPMS Zircon U-Pb	Sun et al., 2015
Sanqingshan	Syenogranite	131 ± 2	LA-ICPMS Zircon U-Pb	Sun et al., 2015
Yangmeiwan	Granite	135.9 ± 2.1	LA-ICPMS Zircon U-Pb	Yang et al., 2012
Daqiaowu	Granitic porphyry	134.3 ± 1.2	LA-ICPMS Zircon U-Pb	Yang et al., 2012
Xiangshan	Rhyodacite	135.1 ± 1.7	LA-ICPMS Zircon U-Pb	Yang et al., 2010
Xiangshan	Rhyodacite porphyry	134.8 ± 1.1	LA-ICPMS Zircon U-Pb	Yang et al., 2010
Qianlishan	Granite	152 ± 2	SHRIMP Zircon U-Pb	Li et al., 2004b
Nankunshan	Alkali syenite	158 ± 5	SHRIMP Zircon U-Pb	Li et al., 2007
Yangmei	Syenite	161.6 ± 0.9	Ar-Ar hornblende	Li et al., 2004a
Tong'an	Syenite	163.2 ± 0.9	Ar-Ar hornblende	Li et al., 2004a
MaShan	Monzonite	163.6 ± 2.0	Ar-Ar hornblende	Li et al., 2004a
Baimianshi	Rhyolite	164.8 ± 0.6	Rb-Sr whole rock	Kong et al., 2000
Zhaipei	Granite	171.6 ± 4.6	SHRIMP Zircon U-Pb	Li et al., 2003
Tabei	Syenite	161.6 ± 2.2	Ar-Ar hornblende	Li et al., 2003
Chebu	Gabbro	172.9 ± 4.3	SHRIMP Zircon U-Pb	Li et al., 2003
Quannan	Syenite	164.6 ± 2.8	SHRIMP Zircon U-Pb	Li et al., 2003
Potou	Moyite	178.15 ± 0.84	Rb-Sr whole rock	Fan et al., 2000
Wengong	Granite	192 ± 1	SHRIMP Zircon U-Pb	Zhu et al., 2010
Keshubei	Granite	189 ± 3	SHRIMP Zircon U-Pb	Li and Li, 2007

Figure. 1

Figure. 2

Figure. 3

Figure. 4

Figure. 5

Figure. 6

Figure. 7

Figure. 8

Figure. 9

Figure. 10

Figure. 11

Figure. 12

Figure. 13

Figure. 14

Figure. 15