Early Paleozoic intracontinental orogeny in the Yunkai domain, South China Block: New insights from field observations, zircon U–Pb geochronological and geochemical investigations

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Chaolei Yan[a], Liangshu Shu[a,*], Faure Michel[b], Yan Chen[b], Cheng Li[a]

[a]State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, 164 Xianlin Road, Nanjing 210023, China

[b]Institut des Sciences de la Terre d'Orléans, UMR 7327, CNRS, Université d'Orléans, 45071 Orléans, France

* Corresponding author E–mail: lsshu@nju.edu.cn

ABSTRACT

Debate on whether the Early Paleozoic tectono–magmatic event in South China is related to a subduction–collision or an intracontinental orogen has been lasted for decades within the geoscience community. This study deals with LA–ICP–MS zircon U–Pb ages, whole–rock chemistry, rare earth elements, trace elements and Hf isotopes from granitoid samples collected in the Yunkai domain in order to better constrain the Early Paleozoic tectonic evolution of the South China Block. The weighted mean $^{206}Pb/^{238}U$ ages for eight samples range from 426 Ma to 443 Ma, representing the crystallization ages of the magma. Fourteen samples were analyzed for geochemistry, all of which are characterized by a peraluminous signature with A/CNK values greater than 1.0. The REE geochemistry reveals enrichment in light rare earth element. LREE/HREE values range from 2.81 to 30.36 and $(La/Yb)_N$ vary from 1.23 to 55.14 (mean of 14 analyses is 14.69). All the samples exhibit distinct negative Ba, Sr and Nb anomalies and enrichment in Rb, Th, U and Pb. Hf isotopic analyses indicate negative εHf (t) values mainly ranging from -3 to -12, corresponding to two model age distributing from 1637 Ma to 2208 Ma. The geochemical analyses indicate that the Silurian granitic magmas in the Yunkai domain were derived from partial melting of crustal materials with little or no input of mantle source. These new data support the

intracontinental subduction model already proposed to account for the Early Paleozoic tectonic, metamorphic and magmatic event of South China.

Keywords: Early Paleozoic Granitoids; U–Pb geochronology; Geochemistry; Hf isotope; Yunkai domain; South China

1. Introduction

The Cathaysia and Yangtze blocks amalgamated in the Neoproterozoic (Fig. 1), forming the South China Block (SCB), and its subsequent Phanerozoic tectonic framework is an important constituent of tectonic evolution of Asia (Cawood et al., 2013; Li et al., 2008a, b, 2009; Rong et al., 2010; Song et al., 2015; Zhang and Zheng, 2013; Zhang et al., 2011; Zhao and Cawood, 2012). Furthermore, as recognized since 1920's (Grabau, 1924), the Middle Devonian terrigenous rocks unconformably covering Early Paleozoic folded rocks and granitoids, document an Early Paleozoic tectono–magmatic event widespread in the SE part of the South China Block (Fig. 1). This pre–Devonian orogeny has been improperly referred to as the "Caledonian orogeny", however as precise time constraints are now available (Song et al., 2015; Wang et al., 2007), and because this belt is unrelated to the true Caledonian belt of Norway and N America, this term should be abandoned. The Early Paleozoic orogeny of SE China is characterized by: i) the regional absence of Silurian strata, ii) the unconformity between middle Devonian coarse clastic sequence and Ordovician marine flysch sequence, iii) a greenschist to amphibolite facies metamorphism coeval with a ductile deformation, and iv) the occurrence of numerous S–type granitic plutons (BGMRFJ, 1985; BGMRGX, 1985; BGMRHN, 1988; BGMRJX, 1984; BGMRZJ, 1989; Charvet, 2013; Charvet et al., 2010; Faure et al., 2009; Li et al., 2010; Shu, 2012; Shu et al., 2008b, 2015; Yao et al., 2013, 2014). The geodynamic significance of this belt, whether as a collisional orogen or as an intracontinental one, has been debated since a long time. Guo et al. (1989) argued for the presence of Early Paleozoic ophiolites in the Yunkai and Wuyi massifs of the SE part of the South China Block. However, in the past decades, several investigations indicated that the previously proposed oceanic subduction and collision models do not properly account for the Early Paleozoic lithological and tectonic features of this part of the SCB (Charvet et al., 2010; Faure et al., 2009; Shu et al., 2014, 2015; Song et al., 2015; Wang et al., 2007, 2011, 2013b; Zhang et al., 2011). The main facts arguing against a collisional model are the lack of ophiolites, accretionary complexes and magmatic arc. Indeed, ophiolitic gabbros, once considered as Early Paleozoic, are in fact Neoproterozoic in age, ca. 850–800 Ma (Li et al., 2005; Shu et al., 2006, 2011). Moreover, most of the "basaltic rocks" interlayered in the Early Paleozoic strata have been reassessed as meta–greywacke (Shu et al., 2008a, 2014). Granitoid is an efficient rock to understand the tectonic evolution of the continental crust (e.g., Pearce et al., 1984; Pitcher, 1983). Some studies have dealt with the Early Paleozoic granitoids of the South China Block. However, precise chronological and geochemical data related to their petrogenesis are rare (e.g., Deng et al., 2012; Li et al., 2010; Liu et al., 2010; Shu et al., 2008a; Wang et al., 2010, 2011; Xia et al., 2014; Xu et al., 2011; Yang et al., 2010). This study presents zircon U–Pb geochronology, bulk geochemistry and Hf isotope analysis of granitoids from the Yunkai domain, providing new insights into the crustal evolution of the SE part of the SCB in Early Paleozoic.

2. Geological setting

2.1 The general framework of SCB

The southern part of the South China Block (Fig. 1) also referred to as “the South China Fold Belt” is separated by the Neoproterozoic Jiangnan Orogen from the Yangtze Block (Grabau, 1924; Guo et al., 1989; Li, 1997; Li et al., 2009, 2012; Shu and Charvet, 1996; Shu et al., 2006, 2014; Wang et al., 2007). This NE–SW trending belt is a complex area that experienced several successive tectonic, metamorphic and magmatic events, namely: i) a Neoproterozoic (Tonian–Cryogenian, ca. 850 Ma) collision; ii) a Late Neoproterozoic (Cryogenian–Ediacarian, ca. 820–690 Ma) rifting event marked by volcaniclastic sedimentation and bimodal magmatism; iii) an Early Paleozoic orogeny marked by a Devonian angular unconformity, and iv) a Middle Triassic orogeny marked by a Late Triassic unconformity (BGMRGX, 1985; BGMRJX, 1984;

Faure et al., 2009; Lin et al., 2008; Shu, 2012).

The Neoproterozoic Jiangnan orogenic belt in the southeastern margin of the Yangtze Block is a NW–ward subduction–collision belt developed during the amalgamation of the Cathaysia and Yangtze blocks (Shu, 2012; Yao et al., 2014). Ophiolite, I–type granite, rhyolite, basalt and gabbro, dated at ca. 1000–855 Ma, crop out along the Shaoxing–Jiangshan–Guilin fault zone (Li et al., 2009; Shu, 2012; Yao et al., 2014). The amalgamation resulted in the collision of island arcs with the Yangtze Block and the closure of a back–arc basin. After the Middle Neoproterozoic orogeny, from ca. 820 to 690 Ma, the South China block experienced a rifting event coeval with a bimodal magmatism (Li et al., 2003, 2005; Shu, 2006; Shu et al., 2011; Wang and Li, 2003; Wang et al., 2006). In Cambrian times, the southern part of the rift was a littoral–neritic depositional environment whereas during the early–middle Ordovician period, this area was dominated by a neritic–bathyal setting (Rong et al., 2010; Shu et al., 2014). In the late Ordovician, the SE part of the South China Block underwent a sedimentological change to a littoral silico–clastic environment, along with the initiation of uplift processes (BGMRFJ, 1985;BGMRJX, 1984; Shu, 2012; Shu et al., 2014).

During the Silurian, extensive folding, thrusting, metamorphism and anatexis developed. The emplacement of numerous granitic plutons represents the end of the orogeny. These features are well recorded in the Wuyi, Jinggang, Nanling and Yunkai areas (Figs. 1 and 2). The maximum shortening can reach up to 67% in the Jinggang and Wuyi belts (Charvet et al., 2010; Shu, 2012; Shu et al., 2008a, 2015). Fold axes strike are dominantly E–W. The kinematic analysis in the Jinggang and Wuyi domains shows that the ductile shearing was directed to the S or SE, however, a northwestward vergence may develop in the northwestern part of the belt. Concerning the Early Paleozoic orogeny, two pre–Devonian litho–tectonic units have been identified: 1) A slate unit, composed of the Sinianto Ordovician marine sandy–muddy rocks, which experienced a low greenschist facies metamorphism before the intrusion of Silurian granitoids; 2) A metamorphic unit, comprising Neoproterozoic mica schist, amphibolite, paragneiss and orthogneiss, and locally Paleoproterozoic amphibolites, gneisses and gneissic granites (Faure et al., 2009; Shu, 2012; Shu et al., 2014; Yu et al., 2009). However, this orogeny is not well developed in the northwestern part of the South China Block where the Early Paleozoic strata did not experience any significant metamorphism, and only underwent slight brittle deformation, together with weak magmatism. From a geodynamic point of view, the Early Paleozoic orogeny of the South China Block was interpreted as the consequence of a rift closure from the Late Ordovician to Early Silurian. Therefore, the orogeny corresponds to an intracontinental event accommodated by the continental subduction of the southern part of the rift below its northern one (Faure et al., 2009). It is worth to note that the rift closure area that corresponds to a crustal scar instead of an ophiolitic suture does not coincide with the Neoproterozoic suture but is located within the Cathaysia Block. The upper part of the belt (i.e. the slate unit) is a fold–and–thrust belt limited at its base by a ductile décollement localized in the Sinian system. The lower part of the belt (i.e. the metamorphic unit underlying the basal décollement) was characterized by deep burial giving rise to an amphibolite facies metamorphism (Zhao and Cawood, 1999). During the exhumation of this lower part, those metamorphic rocks experienced retrogression and partial melting at ca. 444–420 Ma represented by migmatite and granitoid (Faure et al., 2009).

From the Middle Devonian to Early Carboniferous, quartz sandstone, feldspathic sandstone, conglomerate, and siltstone intercalated with chert, limestone and bioclastic limestone were deposited unconformably on the Early Paleozoic sequences (BGMRFJ, 1985; BGMRGX, 1985; BGMRJX, 1984； Shu et al., 2008b, 2015).

A Late Triassic regional unconformity implies a Middle Triassic orogeny (e.g., Chu et al., 2012; Faure et al., 2009; Lin et al., 2008; Shu, 2012; Wang et al., 2013b). The Triassic orogens are widespread around the margins and inside the South China Block. The Early Paleozoic metamorphic rocks were intensely reworked by the Triassic events.

2.2 Geology of the Yunkai domain

The NE trending Yunkai domain consists of a wide variety of plutonic, sedimentary and metamorphic rocks (Fig. 1; BGMRGX, 1985; Faure et al., 2016; Lin et al., 2008). In the study area, located in the NW part of the Yunkai domain, several stratigraphic units are exposed: 1) a set of low greenschist facies and folded Neoproterozic sedimentary rocks, comprising slate, sandy slate and conglomerate; 2) weakly metamorphosed and folded Early Paleozoic sequences mainly composed of metasandstone and metamudstone; 3) Post–Ordovician sedimentary rocks (Fig. 2).

In the Yunkai domain, Early Paleozoic biotite–muscovite granite and monzogranite are well exposed. These plutons are heterogeneously deformed with an unfoliated core to a gneissic, sometimes mylonitic, margin (BGMRGX, 1985). In the section, a progressive reduction in grain size from medium–coarse to fine grained can be observed from the pluton core to margin. Meanwhile, Early and Middle Triassic peraluminous plutons are also distributed in this area (Lin et al., 2008; Wang et al., 2007).

Our field observations indicate that the bulk architecture results of NE–SW and E–W trending upright and overturned folds (Fig. 2) with NW and N vergences, implying two tectonic deformation stages corresponding to Neoproterozoic and Early Paleozoic, respectively (Faure et al., 2016; Lin et al., 2008).

3. Sample description

Petrographic features and GPS locations of the analyzed samples are listed in Table 1. Sample 1571 is a fine to medium grained–massive two–mica granite composed of ca. 40% K–feldspar, 35% quartz, 10% plagioclase, 7% muscovite, 5% biotite and other accessories(Fig. 3A and 3F) (Table 1). Sample 1582 of monzogranite is mainly composed of 40% quartz, 35% K–feldspar, 15% albite, 5% muscovite and 5% other accessory minerals (Table 1). It is located in the boundary of the pluton, displaying a weak mineral fabric. Sample 1586 is a medium–grained massive K–feldspar muscovite granite with 45% K–feldspar, 40% quartz, 8% plagioclase, 5% muscovite and other accessories (Fig. 3B and 3G) (Table 1). From the pluton core to margin, a progressive reduction in grain size from medium–coarse to fine–grained can be observed. Sample 1601 exhibits a distinct granitic texture, with about 35% K–feldspar, 30% quartz, 20% biotite, 5~8% albite, 5% muscovite and other accessories (Fig. 3C and 3H) (Table 1). Sample 1621 of the muscovite granite is mainly composed of 40% quartz, 38% K–

feldspar, 12% plagioclase, 7% muscovite and 3% other accessory minerals (Table 1), polysynthetic twin and cross hatched twin are well developed in the plagioclase and microcline, respectively (Fig. 3D). Sample 1628 of the biotite-rich proto-mylonitic granite with feldspar augen shows about 40% K–feldspar, 30% quartze, 15~18% biotite, 10% plagioclase and other accessories (Table 1), in which the K–feldspar phenocrysts are commonly deformed (Fig. 3E and 3I). Sample 1630 is a well–foliated gneissic biotite granite composed of 45% microcline, 25% biotite, 15% quartz, 10% plagioclase and 5% other accessory minerals (Table 1). Sample 1633 also shows a gneissosity, but weaker than in Sample 1630. It is mainly composed of 40% microcline, 25% quartz, 20% biotite, 10% plagioclase and 5% other accessories. The dome–shaped granitic pluton displays obvious zoning with gneissic granite in the middle, and mylonitic granite around the margin.

In this study, five granite samples (1571, 1582, 1586, 1601, 1621), one mylonitic granite (1628) and two gneissose granites (1630, 1633) were collected for zircon U–Pb dating and Hf isotope analysis (see locations in Fig. 2). Fourteen rock samples (1571, 1571–1, 1582, 1586, 1586–1, 1601, 1601–1, 1601–2, 1601–3, 1621, 1621–1, 1628, 1630, 1633) were used for whole–rock geochemical study.

4. Analytical methods

Whole–rock major element contents were analyzed by ARL–9900 X–ray fluorescence spectrometer (XRF) at the Testing Center of Shandong Bureau of China Metallurgical Geology Bureau. The uncertainties reported in this study are 2% for major elements. Trace elements and rare earth elements (REE) were measured by Inductively Coupled Plasma– Mass Spectrometry (ICP–MS) (Finnigan Element II) at the Testing Center of Shandong Bureau of China Metallurgical Geology Bureau and ALS Chemex (Guangzhou) co., Ltd, respectively. International standards were used to define the analytical precision and accuracy throughout the analytical processes for ICP–MS. The uncertainties are 5 percent for trace elements. For the detailed analytical procedure we refer to those documented in Gao et al. (2003).

Zircons were separated from the crushed rocks using heavy liquid and magnetic techniques and then handpicked under a binocular microscope. The zircon grains were mounted in epoxy resin and polished to expose the approximate center of grains, and then coated with gold. Cathodoluminescence (CL) images of the zircons were obtained using a JEOL JXA8230 electron probe microanalyzer at the Testing Center of Shandong Bureau of China Metallurgical Geology Bureau.

The laser ablation (LA)–ICP–MS analysis of zircon U–Pb isotopic compositions was performed at the State Key Laboratory for Mineral Deposits Research, Nanjing University, using an Agilent 7500a ICP–MS system attached to New Wave 213 nm laser ablation system with an in–house sample cell. Samples were analyzed in runs of ca. 15 analyses including five zircon standards and 10 sample points. The details of the analytical procedure are documented in Jackson et al. (2004). The U–Pb fractionation was corrected using zircon standard GEMOC GJ–1 with a $^{207}Pb/^{206}Pb$ age of 601±12 Ma and the accuracy was controlled using the zircon standard Mud Tank with an age of 735±12 Ma (Black and Gulson, 1978). The U–Pb ages were calculated from the raw signal data using the software Glitter (ver.4.4). Because the ^{204}Pb could not be measured owing to low signal and interference from ^{204}Hg in the gas supply, common lead correction was carried out using the EXCEL program common Pb correction (Andersen, 2002). For zircons older than 1000 Ma, because of large amounts of radiogenic Pb, the $^{207}Pb/^{206}Pb$ age is more reliable than $^{206}Pb/^{238}U$, whereas for zircons younger than 1000 Ma, as a result of the low content of radiogenic Pb and uncertainty of common Pb correction, the $^{206}Pb/^{238}U$ age is more reliable (Griffin et al., 2004).

Zircon Hf isotopic composition was analyzed by Neptune MC–ICP–MS, which is a double focusing multi–collector ICP–MS and has the capability of high mass resolution measurements in a multiple collector mode. During laser ablation analyses, the isobaric interference of ^{176}Lu on ^{176}Hf is negligible due to the extremely low $^{176}Lu/^{177}Hf$ value in zircon (normally <0.002). However, the interference of ^{176}Yb on ^{176}Hf must be intensively corrected since the contribution of ^{176}Yb to ^{176}Hf. This method can provide an accurate correction of the ^{176}Yb interference on ^{176}Hf (Kemp et al., 2006). During analysis, an isotopic ratio of $^{176}Yb/^{172}Yb = 0.5887$ was applied. Standard zircon 91500 was used for the external correction, with a $^{176}Hf/^{177}Hf$ value of 0.282300 ± 8

(2σ). The detailed analytical procedure is similar to the description by Yuan et al. (2008). Initial $^{176}Hf/^{177}Hf$ values were calculated based on Lu decay constant of 1.865E−11 (Scherer et al., 2001). Model ages were calculated under the assumption that the $^{176}Lu/^{177}Hf$ of average crust is 0.015, and the $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ ratios of chondrite and depleted mantle at the present are 0.282772 and 0.0332, 0.28325 and 0.0384, respectively (Blichert–Toft and Albarede, 1997). The model ages (TDM) provide only a minimum age for the source material of the magma from which the zircons crystallized.

5. Analytical results

5.1 Major and trace element compositions

The analytical results of major and trace elements of 14 representative samples are given in Table 2. Samples 1571, 1571–1, 1586, 1586–1, 1601–2, 1621, 1621–1, 1628, 1630, 1633 exhibit SiO_2 contents ranging from 69.91 to 77.46 wt%, and plot in the granite field in the total alkali–silica diagram, displaying (Na_2O+K_2O) versus SiO_2 (TAS) (Fig. 4A). However, Samples 1582, 1601, 1601–1 and 1601–3 plot in the field of quartz diorite, yielding SiO_2 contents between 65.03 and 69.67 wt%. As shown by a plot of Al/(Na+K) versus Al/(Ca+Na+K) (Fig. 4B), all samples fall in the peraluminous area with high A/CNK (>1.1), except Samples 1571, 1571–1 and 1586 which indicate slightly lower A/CNK (1.08, 1.08 and 1.05, respectively). According to Figure 4C, most of the samples belong to the high–K calc–alkaline affinity, while only Sample 1582 plots into the calc–alkaline field.

The most intuitive character of all samples analyzed for geochemistry is that they display similar chondrite–normalized steep rare earth (REE) element patterns revealing obvious enrichment in light rare earth element (LREE) with respect to heavy rare earth element (HREE) (Fig. 5A). LREE/HREE values range from 2.81 to 30.36, and $(La/Yb)_N$ vary from 1.23 to 55.14 (the mean of 14 analyses is 14.69) (Fig. 5A, Table2). All the samples mark distinct negative Eu anomalies (Eu/Eu* value of 0.06–0.59, the mean of 14 analyses is 0.4). On the primitive mantle–normalized spider diagrams (Fig. 5B), all samples exhibit strongly negative Ba, Sr and Nb anomalies and the enrichment of Rb, Th, U and Pb. Nb/Ta values range from 3.76 to 23.22 (average 9.50), consistent with the geochemical features of crustal derived granite (Corfu et al., 2003; Hoskin and Schaltegger, 2003; Pearce, 1996; Pearce et al., 1984).

5.2 Zircon U–Pb ages

Typical Cathodoluminescence (CL) images of zircons are presented in Figure 7. U–Pb results are listed in Table 3 and graphically illustrated in Figure 8. Zircons analyzed in this study range in length from 60 to 160 μm, with length/width ratio ranges from 2:1 to 4:1. Most of zircon grains display oscillatory zoning (Fig. 7) and high Th/U values (average 0.80; Table 3), indicating their magmatic origin (Corfu et al., 2003; Hoskin and Schaltegger, 2003).

Two hundred and twenty seven zircon U–Pb ages are obtained, which fall in the range of 409–1306 Ma. However, most of the data indicate ages between 409 to 460 Ma. These data plotted on concordia diagrams yield eight groups of weighted mean $^{206}Pb/^{238}U$ ages as 426 ± 3Ma (Sample 1571, 19 values out of total 25 data); 439 ± 3 Ma (Sample 1582, 21 values out of total 32 data); 436 ± 3 Ma (Sample 1586, 18 values out of total 25 data); 443 ± 3 Ma (Sample 1601, 18 values out of total 26 data); 430 ± 3 Ma (Sample 1621, 23 values out of total 30 data); 435 ± 3 Ma (Sample 1628, 23 values out of total 33 data); 431 ± 3 Ma (Sample 1630, 19 values out of total 29 data) and 429 ± 3 Ma (Sample 1633, 18 values out of total 27 data) (Fig. 8). The above results indicate a Silurian age for these granitoids.

5.3 In situ Hf isotopes

More than half of the U–Pb dated zircons were chosen for in–situ Hf isotopic analysis. The Hf analyses were executed near the fields used for U–Pb dating spots. For purpose of discussing the Hf isotopic evolution history, the initial $^{176}Hf/^{177}Hf$ values and εHf (t) were calculated using the zircon $^{206}Pb/^{238}U$ ages. The results of the Hf isotopic analyses are presented in Table 4, and the εHf (t) versus U–Pb age diagram is illustrated in Figure 9.

Lu–Hf isotopic results for the eight granitoid samples are similar. All samples show negative εHf (t) values, ranging from -0.80 to -38.96. For the individual plutons, the ranges are -4.44 to -17.51 (average of -7.60 for Sample 1571), -1.58 to -4.56

(average of -3.00 for Sample 1582), -3.00 to -38.96 (average of -15.42 for Sample 1586), -0.80 to -25.17 (average of -11.06 for Sample 1601), -4.48 to -11.55 (average of -7.25 for Sample 1621), -1.70 to -15.20 (average of -7.92 for Sample 1628), -4.35 to -12.02 (average of -7.67 for Sample 1630), -5.06 to -10.68 (average of -6.99 for Sample 1633), respectively. Correspondingly, on the εHf (t) versus U–Pb age plot, the two model ages ($T_{DM}2$) mainly concentrate on 1481–2208 Ma, while sparsely distribute in 2208–3843 Ma (Fig. 9). These results indicate that all of the analyzed granitic rocks are derived from the partial melting of Paleoproterozoic continental basement rocks. 14 groups of two-model-age data greater than 2.3 Ga may indicate that the magma has been contaminated by ancient crustal material to a certain extent. In addition, all the isotopic data are plotted under the CHUR line, suggesting that the involvement of a mantle component in the granitic magma was negligible.

6. Discussion

6.1 Crystallization age of the granitoids

The 227 zircons from all eight granitoid samples from the Yunkai domain yield similar weighted mean U–Pb ages between 426 and 443 Ma (Fig. 8, Table 3), indicative of a Silurian crystallization age. Many works have been undertaken to investigate the formation age of the Early Paleozoic granites in the South China Block (Li et al., 2010; Shu et al., 1999, 2008a, 2008b; Song et al., 2015; Wang et al., 2007, 2013b; Zhang et al., 1998; Zhao et al., 2013; Zhong et al., 2013). For example, the granitoids for the Xuefeng, Guidong, Zhuguang, Wugong and Wuyi Moutains display zircon U–Pb ages of 410–430 Ma, 422–427 Ma, 414–434 Ma, 428–462 Ma, 431–441 Ma, respectively (Chu et al., 2012; Li, 1990, 1994; Lou et al., 2006; Xu et al., 2011) (Fig. 1). Also, $^{40}Ar/^{39}Ar$ age can be utilized to trace the evolution process of the plutons (Kay et al., 2011; Maksaev et al., 2004; McDougall and Harrison, 1999; Reynolds et al., 1981). Xu et al. (1992) reported two synkinematic phengites from the mylonites that yield $^{40}Ar/^{39}Ar$ plateau age of 428 Ma from the Dexing–Shexian shear zone in the northern margin of the Yangtze Block. Wang et al. (2007) showed that the synkinematic phengite of the mylonitic rocks from the Nanfeng–Yingtan shear zone at the northern margin of the northern Wuyi domain yields $^{40}Ar/^{39}Ar$ plateau at 423–426 Ma. In the Jiuling Mts, biotite and muscovite from mylonites yield $^{40}Ar/^{39}Ar$ weighted plateau ages ranging from 379 Ma to 468 Ma (Chu and Lin, 2014). Lastly, Shu et al. (2015) indicated that the $^{40}Ar/^{39}Ar$ data on newly grown biotites from deformed K–granites and biotite schist occurring along the Shaoxing–Pingxiang fault zone show pseudoplateau ages of 428–433 Ma. These $^{40}Ar/^{39}Ar$ ages reflect the regional deformation time that can be interpreted as the contemporary period of the granitic magmatism. In addition, the timing of the magmatic activities can be constrained by geological occurrence. To the east of Hezhou, Cambrian strata are intruded by granite (section A–B in Fig. 2). Moreover, the Silurian and lower Devonian sequences are absent in this area, along with the pre–Devonian strata unconformably covered by the middle Devonian sequence. According to the geological literatures (BGMRGX, 1985; Faure et al., 2009; Shu et al., 2008a; Wang et al., 2007), it was probably related to a doming induced by thermal event. Therefore, the field observations support the view that the Early Paleozoic magmatic event in the Yunkai domain occurred during the Silurian.

6.2 Source and petrogenesis of the Early Paleozoic granitoids

A number of studies have addressed the origin and petrogenesis of the Early Paleozoic granites in the South China block (e.g., Shu et al., 1999, 2015; Wang et al., 2007, 2010, 2011; Zhang et al., 2011; Zhao et al., 2013). Song et al. (2015) showed that Early Paleozoic granites collected from the Jiangnan Orogen and the eastern part of the SCB display εHf (t) values of -1.44 to -36.84 with two stage model ages of Hf isotope range from 1.3 Ga to 3.7 Ga, which indicates that the Early Paleozoic granites were derived from crustal source without or with a small input of mantle materials. Additionally, the Early Paleozoic granites from Xuefeng, Jinggang and Yunkai domains show Sr–Nd isotopic compositions with initial $^{87}Sr/^{86}Sr$ ratios of 0.70924–0.72935, negative $\varepsilon_{Nd}(t)$ values of -4.7 to -11.5 and Proterozoic Nd model ages (Wang et al., 2013b, and references therein). The results of this study indicate that the samples collected from the Yunkai area also support crustal sources for the genesis of the granitic magmas. Geochemically, the granite samples are K–feldspar megacryst rich, and display high total alkali and alumina contents, which all plot in the peraluminous field (Fig. 4B). Geochemically, in the tectonic discrimination diagrams (Fig. 6), most of the granitoid samples plot in the post–collision field. The geochemical signatures indicate that the Early Paleozoic granitic magmas represent typical anatectic products of continental crust. They were generated during the Silurian post–orogenic collapse event, developed after the intracontinental thickening event. Isotopically, all 125 isotopic data are under the CHUR line (Fig. 9). This feature agrees with the melting of a continental basement with little or no input of juvenile crust (Song et al., 2015). Two–stage continental crust model ages of the analyzed zircon grains show a concentration of 1481–2208 Ma ages (Fig. 9), which reveals that some Paleoproterozoic rocks probably exist beneath the South China Block. Moreover, 13 groups of εHf (t) values less than -15 reveal that Archean material may exist beneath the South China Block or not far away.

Recently, some mafic rocks have been dated at 409–434 Ma. The Taoyuan hornblende gabbro complex, located to the north of the Wugongshan domain, was formed by magma mixing and mingling, whose mafic member originated from a metasomatized lithospheric mantle during the Silurian (Zhong et al., 2013). These authors interpreted this rock to be generated from the post–orogenic collapse stage of an intracontinental tectonic regime. Moreover, several gabbroic plutons have been identified in the Yunkai area (Wang et al., 2013a). It is proposed that the generation of the source of the mafic magmas was located within Mesoproterozoic to Early Neoproterozoic asthenospheric mantle, metasomatised by paleosubduction–modified wedge derived fluids during asthenospheric upwelling in the Silurian, resulting in the melting of the continental lithospheric mantle. Similar mechanism is well inspired by de Jong et al. (2015) and references therein. According to the above lines of evidence, it seems that the granitic magmas in this study area were generated by partial melting of continental crust without contribution of juvenile crustal components.

Generally, the granites can be used to explore petrogenesis and tectonic settings (Abdallah et al., 2007; Castro, 2014; Foden et al., 2015; John and Blundy, 1993; Shu et al., 2008a; Song et al., 2015; Vigneresse, 2014; Wang et al., 2007). Field observation shows that the granite structures were gradually changed from the center to the margin of the plutons. Foliation characterized by the preferred orientation of quartz, feldspar and mica is common at the pluton margin (Fig. 3). Regional–scale folding during the Early Paleozoic was widespread together with extensive thrusting and ductile shearing. Various fold types, such as overturned, chevron, recumbent, and sheath, thrust sheets, and mylonitic shear zones are widely developed in the pre–Devonian units (Charvet et al., 2010; Li et al., 2010; Shu et al., 1997; Xu et al., 2011; Yao et al., 2011). The intense folding and shortening accommodated by intracontinental subduction might raise the temperature of parent rocks (Shu, 2006; Song et al., 2015; Zhang et al., 2011). Furthermore, additional heat would be provided by radioactive crustal elements concentrated during the ductile deformation. Thus the heat budget would trigger partial melting of the continental crust able to generate the Early Paleozoic granitic magma. Also, dehydration melting of the hydrous minerals, such as micas, probably plays important roles in the partial melting process. After its burial, the thickened crust was quickly eroded and recovered it normal thickness. The metamorphosed continental rocks were gradually exhumed and decompressed under an extensional tectonic setting, resulting in the rise of the granitic magma and its emplacement in the upper crust (Faure et al., 1996).

6.3 Tectonic setting of the South China Block in the Early Paleozoic

A large–scale tectono–magmatic event took place in the southeastern South China Block during the Silurian (Charvet et al., 2010; Faure et al., 2009; Shu et al., 2014; Wang et al., 2007). But the tectonic setting of the Early Paleozoic magmatism is still controversial. Guo et al. (1989) proposed that a subduction zone was developed along the Zhenghe–Dapu section in the Sinian–Late Ordovician period, resulting in the arc–continent collision and the formation of a large–scale fold belt. According to the geochemical features of the granites in the Yunkai belt, Peng et al. (2006, 2016a, 2016b) suggested an ocean–continent subduction–collision and a post–collisional extension–delamination–underplating model for the South China Block in the Early Paleozoic. Similarly, a subduction–related mechanism in the northern margin of the Yunkai domain during the Early Paleozoic was assumed by Qin et al. (2013) owing to the arc magmatic geochemical characters of the Hudong plutonic complex.

Nevertheless, the field geological evidences are always the first hand and most important information concerning the tectonic setting. The Ordovician orogenic event (ca. 470–460 Ma), referred to as the Grampian Phase in the British Isles or Taconian Phase in western New England (McKerrow et al., 2000), is generally accepted as being due to collision of the rifted Laurentian margin with a continent facing arc. The model was put forward on the basis of relatively clear field evidence of deformation, ophiolite obduction and stratigraphy in the orogen (Dalziel, 1997; Dewey and Shackleton, 1984; Dewey and Ryan, 1990; Van Staal et al., 1998). Comparing to the classical collisional belts, however, evidence for oceanic basin, ophiolite suite and subduction complex associated with an Early Paleozoic subduction is absent in the South China Block. Contemporaneous arc volcanics and high pressure metamorphic rocks have so far never been documented in South China. Turbidites with Bouma sequences are also lacking in spite of widely developed thick flysch sedimentary successions (BGMRFJ, 1985; BGMRGX, 1985; BGMRJX, 1984; Wang et al., 2010; Shu, 2012; Shu et al., 2014). Consequently, it is unreasonable to interpret the Early Paleozoic tectonics of South China as related to an oceanic subduction and a subsequent collision. On the contrary, an intracontinental orogeny accommodated by a continental subduction is likely (e.g., Charvet et al., 2010; Chen et al., 2010; Faure et al., 2008; Shu et al., 2008a; Song et al., 2015).

In the present study, the lithofacies paleogeography of South China provides constraints on the source direction of thick siliciclastic sediments in the Southeast basin that were mainly derived from the southeast, such northwestward sedimentary transport is also supported by several palaeocurrent indicators preserved in the Cambrian-Ordovician strata, indicating that a paleoplate probably existed to the southeast of SE SCB (Ren, 1964; Ren et al., 1990; Rong et al., 2010; Shu, 2012; Shu et al., 2008a; Wu et al., 2010). Regional–scale folding during the Early Paleozoic is widespread in the South China Fold Belt (BGMRFJ, 1985; BGMRGX, 1985; BGMRJX, 1984; Jahn et al., 1990; Shu et al., 1991; Song et al., 2015). Moreover, kinematic studies in the South

China Block show a fan–shaped thrust pattern, with top–to–the-northwest in the northwestern part of SE South China Block and top–to–the-southeast in the southeastern part of SE South China Block (Faure et al., 2009; Lin et al., 2008, 2011; Shu et al., 2014). Such double–vergent thrusting may develop in intraplate settings, associating with syntectonic magmatism, like Petermann and Alice Springs belts in central Australia (Haines et al., 2001; Raimondo et al., 2009, 2010, 2014; Wade et al., 2005) or the Middle Triassic Xuefengshan belt in the central part of South China (Chu et al., 2012).

It is widely accepted that the SE SCB has experienced crustal thickening and anatexis in the Early Paleozoic (Wang et al., 2010; Zeng et al., 2008). Continent-continent collision may cause thickening of the continental crust over a large wide zone (1,000 km), with far-field continental shortening, and last for 50 million years. Such zones are characterized by a wide orogenic plateau, with surrounding and internal basins bordered by thrust belts (Dewey, 2005).

According to the available geological investigations, therefore, we propose that the Early Paleozoic tectono-magmatic event in SE SCB is probably related to the continent-continent collision. A Suspected East China Sea Block subducted northwestward beneath the SE SCB together with the NW SCB subducted southeastward beneath the SE SCB (Fig. 10D), resulting in the crustal thickening and intracontinental deformation which may be caused by the stress generated at plate boundaries and stress transmission with the lithosphere acting as an effective stress guide (Aitken et al., 2013; Gorczyk and Vogt, 2015; Raimondo et al., 2014). Subsequently, regional extension occurred in response to crustal thickening at an earlier stage of the orogeny (Dewey, 1988; Strachan, 1994). The clockwise metamorphic P–T paths in Chencai, Wuyi and Yunkai regions indicate that the SE SCB experienced isothermal decompression (Li et al., 2010; Wang et al., 2012; Zhao and Cawood, 2012), representing the progressive release of stress and rapid crustal denudation after the crustal thickening and uplift. Coincidently, the Sr–Nd isotopic compositions of Early Paleozoic granites from the South China Block are similar to those of Caledonian, Hercynian tectonic belts and other classical collisional belts (Jahn, 2004; Jahn et al., 2014), which probably represent the similar dynamic mechanism during the decompression and remelting of the crustal sources.

6.4 Geodynamic evolution of the South China Block from the Neoproterozoic to Early Paleozoic

A possible spatial and temporal geodynamic evolution model accounting for the Neoproterozoic to Early Paleozoic geological events is proposed in the following.

The Jiangnan orogen is a collisional belt developed during the assembly of the South China block (Charvet et al., 2010; Li et al., 2002; Shu et al., 2011; Yan et al., 2015; Yao et al., 2012; Zhao and Cawood, 2012). Previous studies have shown that the Cathaysia and Yangtze blocks collided at ca. 860 Ma along the Shaoxing–Pingxiang–Guilin fault zone (Shu et al., 2015; Yao et al., 2014) (Figs. 1 and 10A). During the Late Neoproterozoic, a regional–scale rifting event affected the South China Block, resulting in the development of fault–bounded basins. The bimodal volcanic rocks contemporaneous to the rifting were dated at 820–690 Ma (Wang and Li, 2003) (Fig. 10B). During the Cryogenian–Ediacarian (Sinian) to Early Paleozoic, from 690 to 460 Ma, the southeastern part of the South China Block was in a depositional stage. Stratigraphic sequences in this period are characterized by graptolite bearing sandy–muddy rock associations, overlying the rift deposits. Proximal deposits, coarse grain sandstone, conglomerate and ripple–mark structures suggest a littoral–shelf–slope depositional environment (Shu, 2012; Shu et al., 2014) (Fig. 10C).

During the Late Ordovician and Early Silurian, the tectonic framework of South China was mainly controlled by a regional compression characterized by km–scale folds and thrusts, the development of southeast–directed décollement shearing, amphibolite facies metamorphism. During the late to post–thickening evolution, crustal melting characterized by migmatites and granitic plutons took place (Charvet et al., 2010; Faure et al., 2009; Shu, 2006, 2012; Shu et al., 2008a, 2015; Song et al., 2015; Wang et al., 2013b; Zhang et al., 2011). These structural, metamorphic and magmatic features were related to the northwest–ward continental subduction of the southeastern part of the Neoproterozoic rift. This continental area can be considered as a part of the inferred East China Sea Block proposed since a long time (Ren, 1964; Ren et al., 1990) (Fig. 10D). Subsequently, during the Devonian, the South China Block was in a stable sedimentary environment.

7. Conclusions

According to the zircon geochronology, and geochemical study of granitoids in the NW part of the Yunkai domain, we reach the following conclusions:

(1) The analyzed plutons mostly crystallized during 426–443 Ma, suggesting an Early Paleozoic magmatic event in the Yunkai domain;

(2) All granites are peraluminous and represent typical anatectic products of continental crust, mostly plot in the post–collision field in tectonic discrimination diagrams. Hf isotopic data indicate that parent magma was derived from Paleoproterozoic–Mesoproterozoic crustal components with little or no input of mantle sources;

(3) The intracontinental orogeny already proposed to account for the Early Paleozoic plutonic event in the South China Block is well supported by our new investigations.

Acknowledgments

We wish to express our gratitude to the editor Sun-Lin Chung, the reviewers Koen de Jong and Yuejun Wang and the anonymous reviewer for their very helpful and constructive suggestions that greatly improved this paper. We also express our appreciation to Dr. Yao J.L. for the help during whole studying process of this study and to Wang J.Q. and Song M.J. for their assistance during the work of zircon dating and Hf isotopic analysis. We acknowledge the financial supports provided by The Major State Research Development Program of China (Grant No. 2016YFC0600202), National Natural Science Foundation of China (Nos. 41330208, 41572200) and State Key Laboratory for Mineral Deposits Research (Nanjing University) (ZZKT–201603).

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Figure captions

Figure 1. Tectonic outline of China and the distribution map of Early Paleozoic granites in the South China Block (Shu et al., 2015; Song et al., 2015), the numbers 1–5 are corresponding to the Xuefeng, Guidong, Zhuguang, Wugong and Wuyi, respectively.

Figure 2. Geological sketch map of the Yunkai domain with cross sections A–B and C–D (BGMRGX, 1985).

Figure 3. Representative field photos and photomicrographs. (A) Photomicrograph of Sample 1571 (two–mica granite) in Yonghe of Lianshan county; (B) Photomicrograph of Sample 1586 (muscovite granite) in Xindi of Wuzhou city.; (C) Photomicrograph of Sample 1601 (two–mica granite) in Songguangling of Cenxi city; (D) Photomicrograph of Sample 1621 (muscovite granite) in Beijie of Xinyi city; (E) Photomicrograph of Sample 1628 (biotite mylonitic granite) in Lingshan of Rongxian county; (F) Field photograph of Sample 1571; (G) Field photograph of Sample 1586; (H) Field photograph of Sample 1601; (I) Field photograph of Sample 1628. Mineral abbreviations: Kfs, K–feldspar; Mc, microcline; Pl, plagioclase; Ms, muscovite; Bt, biotite; Qtz, quartz.

Figure 4. Geochemical features of the granitoids from the Yunkai domain. (A) (Na_2O+K_2O) versus SiO_2 diagram (Cox et al., 1979); (B) Al/(Na+K) versus Al/(Ca+Na+K) diagram (Maniar and Piccoli, 1989); (C) SiO_2 versus K_2O diagram (Rollision, 1993).

Figure 5. Distribution of (A) rare earth elements and (B) trace elements for the samples derived from the Yunkai domain. The normalization values for (A) and (B) are cited from Sun and McDonough (1989) and McDonough and Sun (1995), respectively.

Figure 6. Tectonic discrimination diagrams for the Early Paleozoic granites from the Yunkai domain. (A) Rb versus (Y+Nb) diagram (after Pearce, 1996; Pearce et al.,1984); (B) Rb versus (Yb+Ta) diagram (after Pearce, 1996; Pearce et al., 1984).

Figure 7. Cathodo–luminescence images of zircons from the granitoids of the Yunkai domain, attached with analyzed locations and U–Pb ages.

Figure 8. U–Pb concordia plots for the zircon grains from eight granitoid samples.

Figure 9. Plot of Epsilon Hf(t) versus U–Pb age of zircons from eight granitoid samples.

Figure 10. Geodynamic evolution models for the South China Block from Neoproterozoic to Early Paleozoic. (A) Collision of Yangtze and Cathaysia blocks (Shu, 2012; Yao et al., 2014); (B) Rifting stage of the Yangtze–Cathaysia Block (Shu, 2012; Yao et al., 2014); (C) Stable depositional stage of the SE South China Block (Ren, 1964; Shu et al., 2014, 2015); (D) Intraplate Orogeny stage of the SE South China Block (Shu, 2012; Shu et al., 2014, 2015). SCB: South China Block. Depth is not in proportion.

Tables

Table 1 GPS locations of the samples and petrologicaldescriptions.

Table 2 Major and trace element data for representative samples from the Yunkai domain.

Table 3 U–Pb data of the zircons from eight granitoid samples from the Yunkai domain.

Table 4 Hf isotope analyses of the zircons from eight granitoid samples from the Yunkai domain.