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ARTICLE

Origin of Early Cretaceous Guandian adakitic pluton in central eastern China: partial melting of delaminated lower continental crust triggered by ridge subduction

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ABSTRACT

Early Cretaceous adakite or adakitic plutons are widely distributed in central eastern China, e.g. lower Yangtze river belt (LYRB), the south Tan–Lu fault (STLF), and the Dabie orogen. Their genesis, however, remains controversial. In this contribution, we present detailed geochemical and geochronological study on the Guandian pluton in central Anhui Province, eastern China, which has been formerly regarded as a part of the north belt in the LYRB and lately classified in the STLF. Namely, it is located near the boundary between ridge subduction related slab melting and partial melting of lower continental crust (LCC). The Guandian pluton consists of quartz monzonite and is metaluminous and high-K calc-alkaline according to the chemical composition. The samples show high SiO_2 (59.15–62.32%), Al_2O_3 (14.51–15.39%), Sr (892–1184 ppm), Sr/Y (56.74–86.32), and low Y (12.65–18.05 ppm), similar to typical geochemical features of adakite. The Guandian adakitic rocks also exhibit high K_2O (2.88–3.86%), MgO (3.89–5.24%), and Mg# (55–60), negative anomalies of high field strength elements (e.g. Nb, Ta, and Ti), and positive anomalies of Ba, Pb, and Sr. LA-ICP-MS zircon U–Pb dating yielded a weighted average age of 129.2 ± 0.7 Ma. Calculations of zircon Ce^{4+}/Ce^{3+} (6.97–145) and $(Eu/Eu^*)_N$ (0.23–0.42) on the basis of *in situ* zircon trace element analysis indicate that the magma had a lower oxygen fugacity relative to the ore-bearing adakites in the LYRB and Dexing, which is consistent with the fact of ore-barren in the research area. In combination with previous research, we propose that Guandian adakitic pluton was formed by partial melting of delaminated LCC triggered by Early Cretaceous ridge subduction of the Pacific and Izanagi plates. During ridge subduction, physical erosion destructed the thickened LCC and resulted in delamination, while thermal erosion facilitated partial melting of the delaminated LCC.

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1. Introduction

The lower Yangtze river belt (LYRB), which is one of the most important metallogenic belts in China, has intensively been studied by geologists (Chang *et al*. 1991; Pan and Dong 1999; Chen *et al*. 2001; Mao *et al*. 2006; Yang and Lee 2011; Yang *et al*. 2011; Zhou *et al*. 2015). It extends from Wuhan, Hubei Province in the west to Zhenjiang, Jiangsu Province in the east. More than 200 deposits (Cu–Fe–Au, Mo, Zn, Pb, Ag) have been discovered in the LYRB, of which most are of the skarn, porphyry, or strata-bound type (Mao *et al*. 2006). Previous molybdenite Re–Os dating shown that the porphyry and skarn deposits in the LYRB formed at the 143–134 Ma (Sun *et al*. 2003b) and were genetically related to adakite (Zhang *et al*. 2001; Xu *et al*. 2002; Wang *et al*. 2004a, 2004b, 2006a, 2007a; Li *et al*. 2009; Ling *et al*. 2009; Xie *et al*. 2009, 2017a, 2017b; Liu *et al*. 2010; Deng *et al*. 2012, 2016; Hu *et al*. 2014).

The term 'adakite' was first introduced by Defant and Drummond (1990), referring to volcanic or intrusive rocks in Cenozoic arcs associated with subduction of young (≤25 Ma) oceanic lithosphere. It has attracted intensive attention owing to analogue to Archaean tonalite–trodhjemite–granodiorite (TTG) (Martin 1999) and close association

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The supplemental data for this article can be accessed here.

with formation of porphyry copper-gold deposits (Sajona and Maury 1998; Oyarzun *et al*. 2001; Sun *et al*. 2010, 2015). Adakite or adakitic rocks can be distinguished from normal arc magma by geochemical composition, e.g. $SiO_2 \geq 56\%$, high Sr (>400 ppm), Sr/Y (>20) and La/Yb (>20), and low Y (≤18 ppm). Adakite formed through partial melting of subducted oceanic crust, i.e. slab melting, was supported by experimental petrology (Rapp and Watson 1995; Rapp *et al*. 1999). However, following studies shown that the geochemical features of adakite can also be produced by alternative mechanisms, e.g. partial melting of thickened lower continental crust (LCC) (Chung *et al*. 2003; Hou *et al*. 2004; Wang *et al*. 2007a, 2007b; Xue *et al*. 2017), delamination of mafic LCC (Kay and Kay 1993; Xu *et al*. 2002; Gao *et al*. 2004; Wang *et al*. 2004a), or differentiation of parental basaltic magma (Castillo *et al*. 1999).

The genesis of Early Cretaceous adakite in the LYRB remains controversial and a variety of models have been proposed. Based on their low ε_{Nd} and high initial Sr isotope values compared to Cenozoic slab-derived adakites, it was proposed to be partial melts of thickened and/or delaminated LCC (Zhang *et al*. 2001; Xu *et al*. 2002; Gao *et al*. 2004; Wang *et al*. 2004b), partial melting of an enriched mantle source together with the involvement of variable amounts of lower crustal components (Xie *et al*. 2012), or the products of intracontinental magmatism, with no relation to plate subduction (Hou *et al*. 2007). However, more and more studies have shown that eastern China was influenced by the Palaeo-Pacific subduction in the late Mesozoic (Zhou and Li 2000; Wu *et al*. 2005; Zhou *et al*. 2006; Li and Li 2007; Sun *et al*. 2007, 2010; Ling *et al*. 2009, 2011). Adakite in the LYRB was proposed to be associated with plate subduction, e.g. flat subduction of Pacific plate followed by slab detachment or roll back (Liu *et al*. 2007; Yan *et al*. 2008, 2015; Li *et al*. 2013), ridge subduction coupled with opening of a slab window, based on spatial and temporal distribution of Cretaceous rocks and the plate drifting history (Sun *et al*. 2007, 2010; Ling *et al*. 2009; Li *et al*. 2012; Xie *et al*. 2012), or partial melting of an enriched mantle source metasomatized by dewatering from a delaminated flat-slab (Li *et al*. 2013).

The Guandian pluton in Anhui Province, eastern China, has been formerly regarded as a part of the north belt in the LYRB and lately classified in the south Tan–Lu fault (STLF), referring to the areas adjacent to the STLF zone in the eastern Yangtze block and in the eastern margin of the Dabie orogen (Liu *et al*. 2010). Its genesis has been controversial and was proposed to be formed by anatectic magmatism of Archaean granulites in the LCC (Xing 1997), underplating and crust–mantle interaction originated from the transitional zone controlled by the Tan–Lu fault (Niu *et al*. 2002), lithospheric thinning of North China Craton (NCC) (Xu *et al*. 2004), or partial melting of delaminated LCC with subsequent interaction of mantle peridotite (Zi *et al*. 2008).

In this study, we conducted a detailed whole rock geochemistry and zircon U–Pb dating and trace element analysis of the Guandian pluton, in combination with previous research, to provide further constraints on its origin and tectonic evolution of central eastern China.

2. Geological background

The LYRB is located in the northern margin of the Yangtze block, which is separated from the Dabie–Sulu orogenic belt to the north by the Xiangfan–Guangji fault in the west and the Tan–Lu fault in the east. The Jiangshan–Shaoxing fault separates the Yangtze block from the Cathaysia block to the south (Figure 1(a)). The basement rocks of the Yangtze block are composed of biotite-hornblende gneisses and TTG (Pan and Dong 1999). Stratigraphic units in this area include late Palaeoproterozoic metasedimentary rocks, Sinian to Middle Triassic marine clastic sedimentary rocks and carbonates, Late Triassic to Cretaceous continental clastic rocks and volcanic rocks (Li *et al*. 2013; Zhou *et al*. 2015).

The LYRB is one of the most important metallogenic belts in China (Chang *et al*. 1991; Pan and Dong 1999). According to the spatial distribution, the ore deposits in the LYRB can be divided into seven ore deposits from the west to east: (1) Edong (e.g. Tongshangkou and Jiguanzui), (2) Jiurui (e.g. Chengmenshang and Wushan), (3) Anqing–Guichi (e.g. Yueshan), (4) Luzong (e.g. Shaxi), (5) Tongling (e.g. Shujiadian and Dongguashan), (6) Ningwu, and (7) Ningzhen (e.g. Anjishan) (Figure 1(b)) (Chang *et al*. 1991; Pan and Dong 1999; Zhou *et al*. 2015). The deposits were mainly formed in the Early Cretaceous (143–134 Ma) and are contemporaneous with widely outcropped Cretaceous igneous rocks in the LYRB (Sun *et al*. 2003b; Mao *et al*. 2006; Xie *et al*. 2007) and are adakitic in composition.

The Cretaceous igneous rocks in the LYRB have been divided into three belts: the south, inner, and north belts. The south belt generally consists of large plutons, with calc-alkaline characteristics. The inner belt consists of high-K calc-alkaline intermediate-acidic intrusive rocks (e.g. Tongling), high-Na calc-alkaline intermediate-basic intrusive rocks (e.g. Ningwu), shoshonite (e.g. Ningwu and Luzong), and A-type granite. The north belt has less intrusions compared with other two belts and has mainly calc-alkaline rocks.

The Guandian pluton is located in the north belt and one of the largest plutons distributed along the Tan–Lu fault with a NNE–SSW trend (Figure 1(c)). It is 30 km long and 4 km wide, with a total area of 42.5 km^2 (Zi *et al*. 2008). There are some other plutons distributed along the Tan–Lu fault, e.g. Wawuliu, Wawuxue, Fangjiangzhuang, Damaocun,

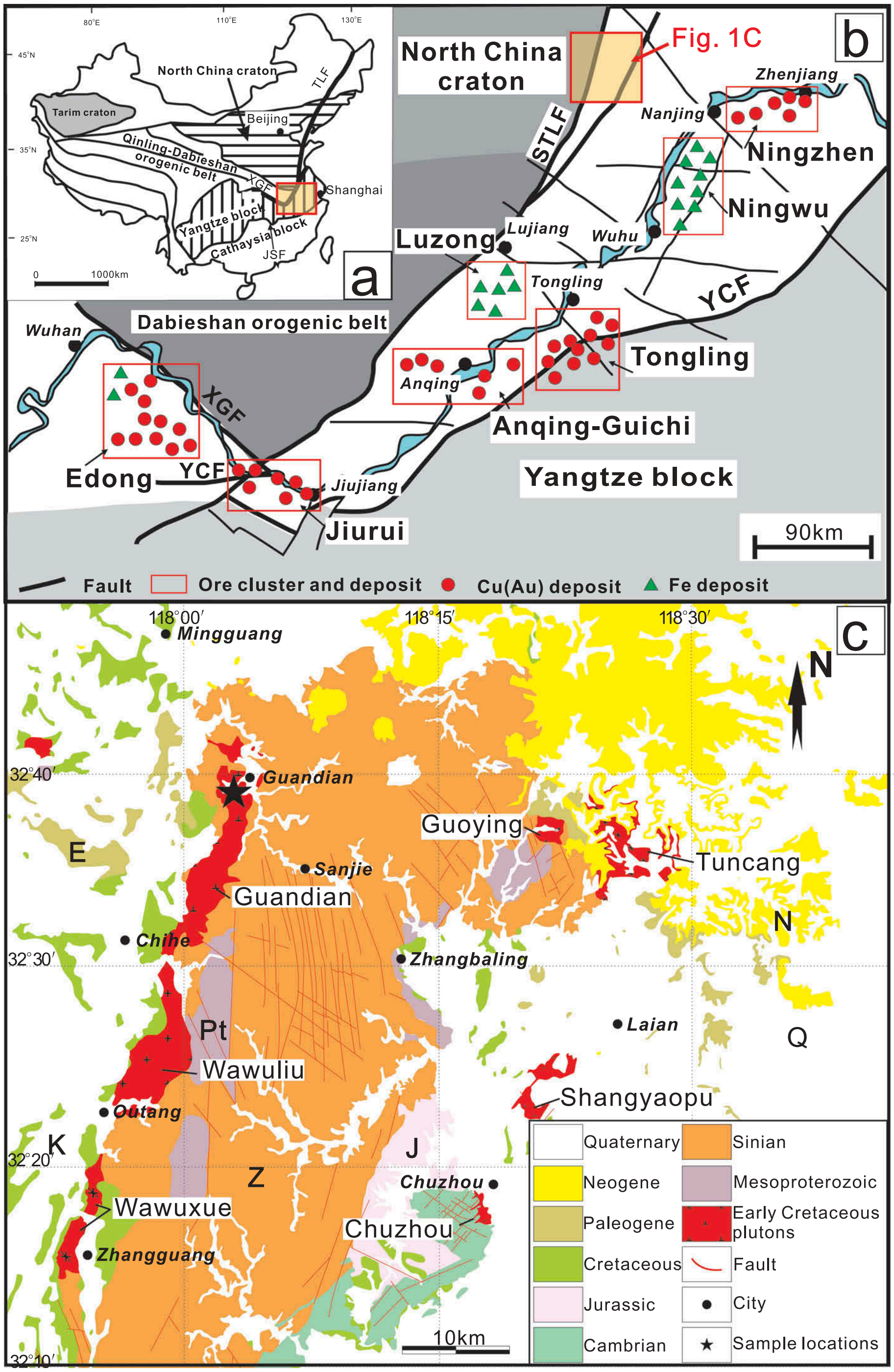

Figure 1. (a) A simplified structural map of China. (b) Geologic map of the lower Yangtze river belt, modified after Ling *et al*. (2009). (c) Geologic map of the south Tan–Lu fault area with sampling location, modified after 1:200,000 Geologic maps. XGF: Xiangfan–Guangji fault, YCF: Yangxing–Changzhou fault, STLF: South Tan–Lu fault.

Xiaolizhuang, and Chituling (Huang *et al*. 2008; Liu *et al*. 2010). The Guandian pluton is mainly composed of quartz monzonite, with major minerals of plagioclase, K-feldspar, quartz, biotite, and hornblende and accessory minerals of magnetite, apatite, titanite, and zircon.

3. Analytical methods

3.1. Major and trace element analyses

The major and trace elements of the bulk rock samples were analysed at the State Key Laboratory of Isotope

Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (SKLIG-GIGCAS).

For major elements, fresh rocks were first ground to <200 mesh and then fluxed with $Li_2B_4O_7$ (1:8) to make homogeneous glass discs at 1150–1200°C using a V8C automatic fusion machine (Analymate China). The bulk rock major elements were analysed using X-ray fluorescence spectrometry (Rigaku 100e) with precision better than 1% (Ma *et al*. 2007).

For trace elements, samples were carried out using fluxed glass discs (with sample to $Li_2B_4O_7$ ratio of 1:3) at 1150–1200°C using a V8C automatic fusion machine and analysed by LA-ICP-MS composed of an Agilent 7500a ICP-MS coupled with a RESOLution M-50 ArF-Excimer laser ablation system (λ = 193 nm). The laser energy was 80 mJ, spot size of 69 μm in diameter with repetition rate of 6 Hz, and 40 s ablation time. Both a double-volume sampling cell and Squid pulse smoothing service were used to improve signal quality (Liang *et al*. 2009; Tu *et al*. 2011). ^{29}Si was taken as an internal standard and NIST610 as an external standard. The analytical precision was better than 5%. The trace element experimental data were calculated by ICPMSDataCal 7.0 (Liu *et al*. 2008).

3.2. Zircon U–Pb dating and trace element analysis

Zircon U–Pb dating and trace element analysis were conducted at SKLIG-GIGCAS. Zircons were separated from samples by traditional heavy magnetic and liquid separation techniques, carefully examined under a binocular microscope, mounted with epoxy resin, and polished down to expose internal structures for LA-ICP-MS analyses. Cathodoluminescence (CL) and optical microscopy images were used to inspect the zircon morphology. The clearest, least fractured rims of the zircon crystals were selected as suitable targets for laser ablation. The laser energy was 80 mJ, spot size of 31 μm in diameter with repetition rate of 10 Hz, and 40 s ablation time. ^{29}Si was taken as an internal standard and NIST 610 and Temora as external standards. The analytical precision was better than 5%. The trace element data were processed by ICPMSDataCal 7.0 (Liu *et al*. 2008). Zircon Ce^{4+}/Ce^{3+} ratios were calculated with the software from the Research School of Earth Sciences, Australian National University (Ballard *et al*. 2002; Liang *et al*. 2006). Concordia and weighted average diagrams were constructed using Isoplot (Ludwig 2012).

4. Results

4.1. Whole rock major and trace elements

Whole rock major and trace element results are listed in Supplementary Table 1. The samples have high SiO_2 (59.15–62.32%), Al_2O_3 (14.51–15.39%), K_2O (2.88–3.86%), and Na_2O (3.58–4.42%) with total alkaline ($Na_2O + K_2O$) ranging from 6.75% to 7.95% and fall in the quartz monzonite area of the QAP diagram (Figure 2). They are metaluminous with aluminium saturation indices A/CNK (Al_2O_3/($CaO + Na_2O + K_2O$)) = 0.76–0.83 and A/NK (Al_2O_3/

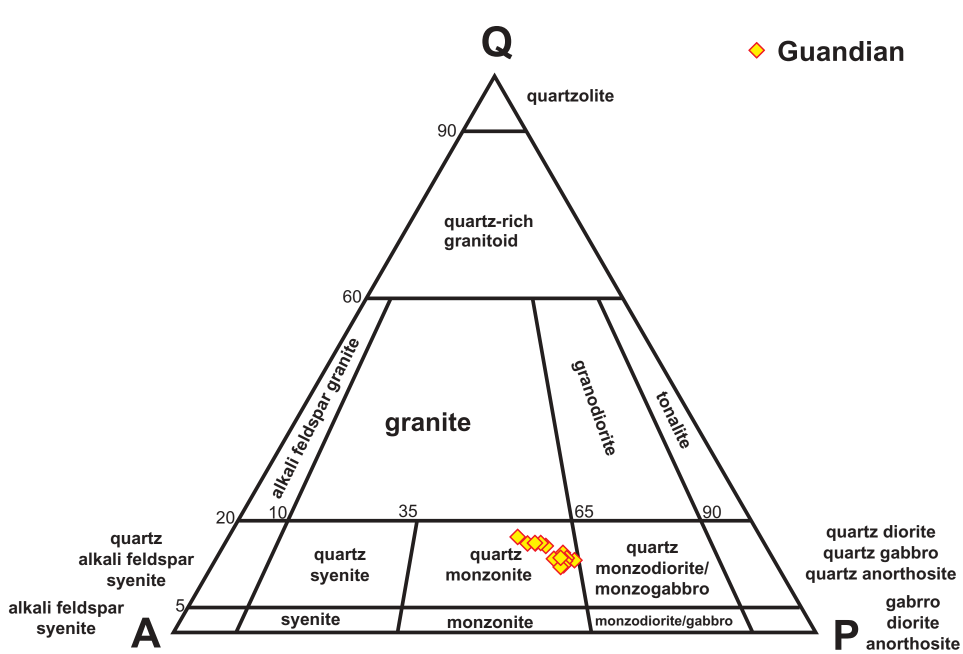

Figure 2. QAP diagram of the Guandian intrusive rocks. Q: quartz, A: alkali feldspar, P: plagioclase. Modified after Le Maitre *et al*. (1989).

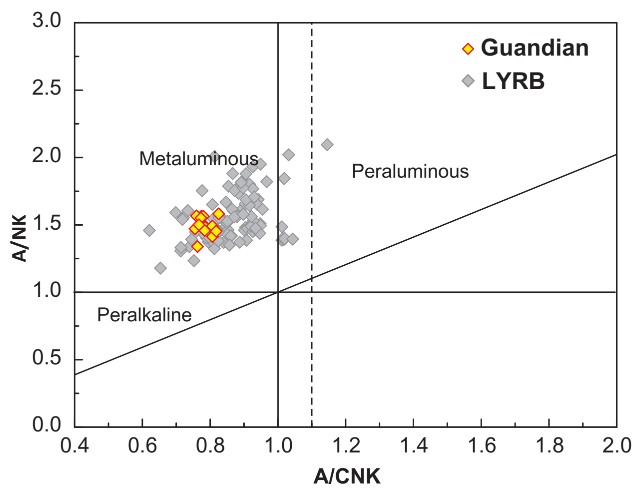

Figure 3. A/NK *versus* A/CNK diagram. A/NK: $Al_2O_3/(Na_2O + K_2O)$ (molar ratio), A/CNK: $Al_2O_3/(CaO + Na_2O + K_2O)$ (molar ratio). Literature data of LYRB adakite are from Ling *et al.* (2009).

($Na_2O + K_2O$)) = 1.34–1.58 (Figure 3) and belong to high-K calc-alkaline series (Figure 4(a)). In addition, they have relatively high MgO (3.59–5.24%) and Mg# (55–60) (Figure 4(b)). Harker diagrams show that SiO_2 has a strong negative correlation with TiO_2, $Fe_2O_3^T$, MgO, CaO, and P_2O_5; positive correlation with K_2O; but no correlation with Na_2O and Al_2O_3 (Figure 5), which may be related with crystallization of Ti-bearing phases (ilmenite, titanite, etc.), apatite, and mafic minerals during magmatic evolution.

The samples are characterized by enrichment of large ion lithophile elements and depletion of high field strength elements, with pronounced negative anomalies of Nb, Ta, and Ti and positive anomalies of Pb, Ba in the spider diagram (Figure 6(a)). They have high Sr (892–1184 ppm) and Sr/Y (56.74–86.32), and low Y (12.65–18.05 ppm), which are the typical geochemical features of adakite (Supplementary Table 1 and Figure 7). Chondrite-normalized REE patterns of these samples show LREE enriched, HREE depleted without Eu anomaly, with high $(La/Yb)_N$ = 15.32–21.13 and Eu/Eu* = 0.92–1.13 (Figure 6(b)).

4.2. *Zircon U–Pb dating and trace elements*

Three samples of the Guandian pluton were selected to conduct LA-ICP-MS zircon U–Pb dating and trace elements analysis. The results are listed in Supplementary Tables 2 and 3. Zircons from Guandian pluton are generally prismatic, transparent, and euhedral. CL images of the zircons display oscillatory zoning, with high Th/U (0.77–1.68), indicating a magmatic origin (Hoskin and Black 2000; Belousova *et al.* 2002). Zircon U–Pb dating of samples 1105-1, 1105-2, and 1105-3 yielded $^{206}Pb/^{238}U$ ages of 129.6 ± 1.1, 127.8 ± 1.1, and 129.9 ± 1.2 Ma, respectively, with a weighted average of 129.2 ± 0.7 Ma, indicating that the Guandian pluton intruded in the Early Cretaceous (Figure 8).

The zircons are LREE depleted and HREE enriched, with negative Eu anomaly and positive Ce anomaly (Figure S1). Calculations of zircon Ce^{4+}/Ce^{3+} (6.97–145) and $(Eu/Eu^*)_N$ (0.23–0.42) indicate a lower oxygen fugacity relative to the other ore-bearing adakites in the LYRB and Dexing porphyry deposit, which is one of the largest porphyry Cu deposits in eastern China (Figure 9). The Ti-in-zircon temperature ranges from 655 to 980°C, with an average of ~780°C (Watson *et al.* 2006).

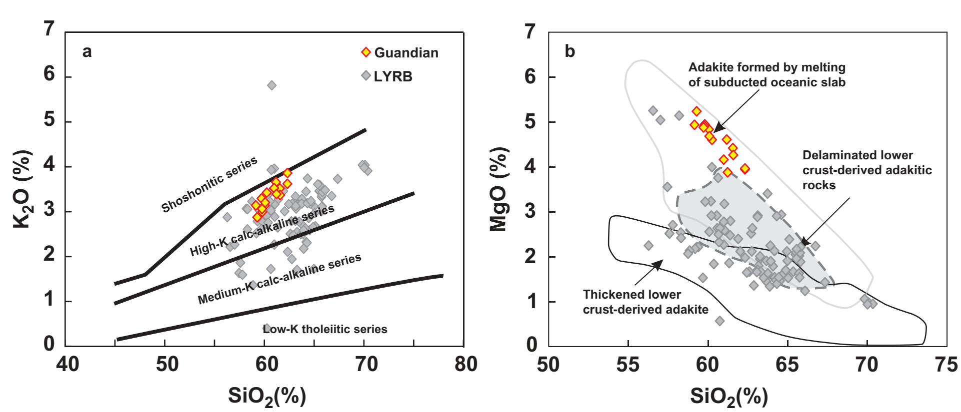

Figure 4. (a) K_2O *versus* SiO_2 diagram for the Guandian intrusive rocks. (b) MgO *versus* SiO_2 diagram for Guandian intrusive rocks. Data sources for LYRB samples are the same as Figure 3. The fields of subducted oceanic crust-derived adakites and thickened lower crust-derived adakitic rocks are after Wang *et al.* (2006b).

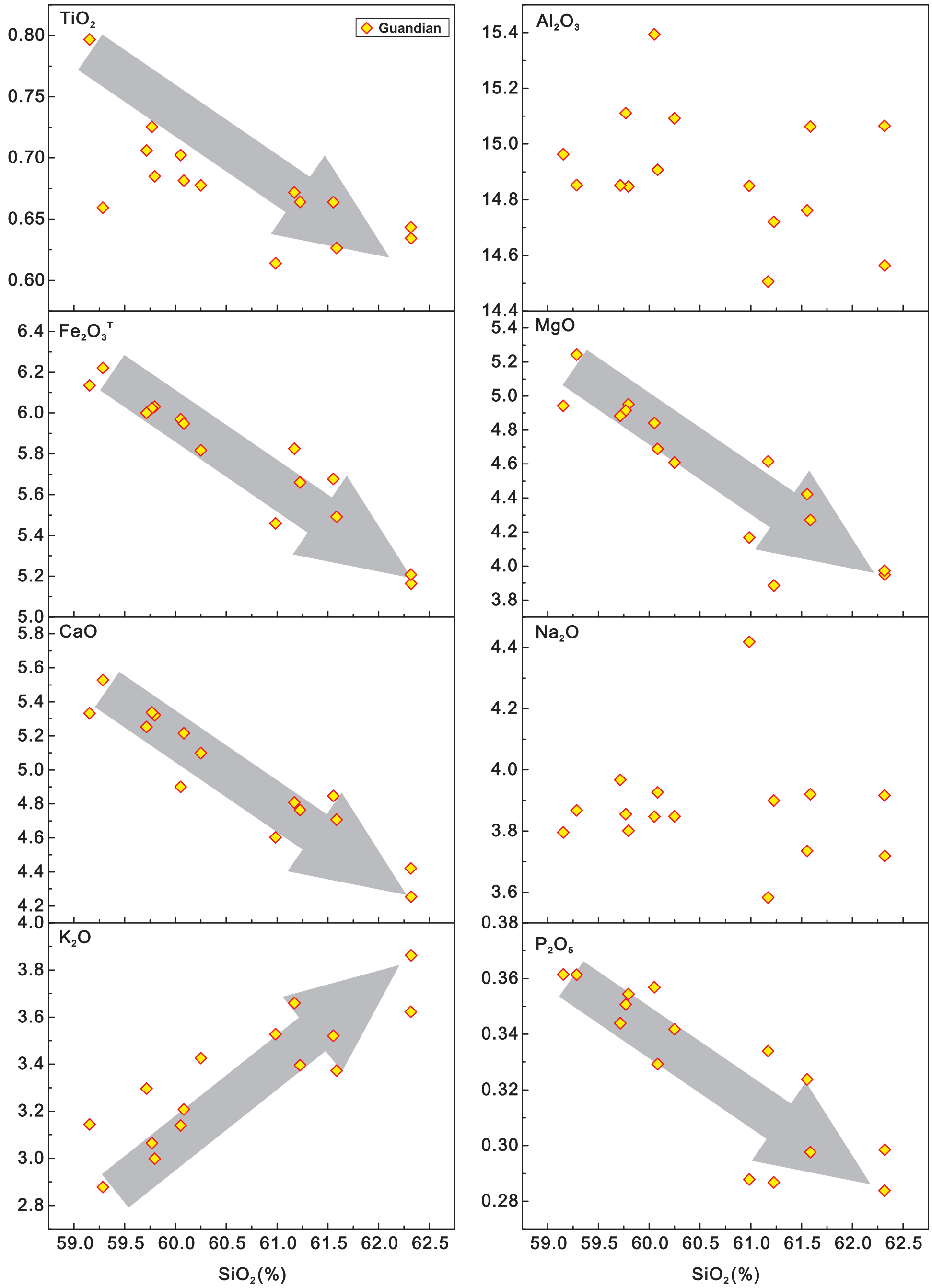

Figure 5. Harker diagrams of the Guandian intrusive rocks. SiO_2 has a strong negative correction with TiO_2, $Fe_2O_3{}^T$, MgO, CaO, and P_2O_5; positive with K_2O; but no correction with Na_2O and Al_2O_3.

5. Discussion

5.1. Origin of the Guandian pluton

The Guandian pluton has geochemical characteristics of adakite, e.g. high SiO_2 (59.15–62.32%), Al_2O_3 (14.51–15.38%), Sr (892–1184 ppm), Sr/Y (57.63–86.32), and low Y (12.65–18.05 ppm) (Supplementary Table 1 and Figure 7). In the Sr/Y and $(La/Yb)_N$ diagram, the Guandian adakitic rocks fall in the overlapping area of slab melting constrained by adakite from the Circum Pacific and partial melting of the LCC defined by adakitic rocks from the Dabie orogen (Figure 10; Liu *et al.* 2010; Ling *et al.* 2013). However, chemical compositions of Guandian adakitic pluton, like the K_2O/Na_2O, Mg#, MgO, Cr, and Ni contents, are generally similar to the other plutons in the STLF, e.g. Fangjiangzhuang, Damaocun, Xiaolizhuang, and Chituling which have been identified as high-Mg adakitic rocks (Huang *et al.*

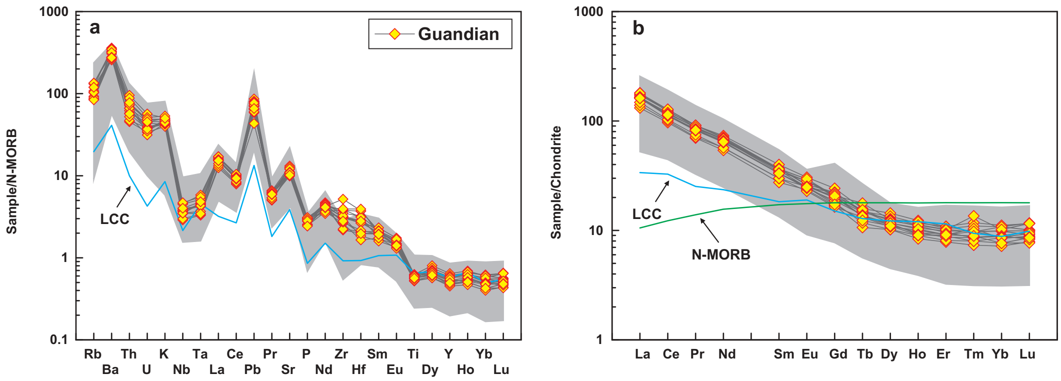

Figure 6. (a) Spider diagram of the Guandian intrusive rocks. (b) Chondrite-normalized REE pattern of the Guandian intrusive rocks. Chondrite and N-MORB data are from Sun and McDonough (1989). LCC data are from Rudnick and Gao (2003). Shadow zones indicate adakite from the LYRB. Data sources for LYRB samples are the same as Figure 3. LCC: Lower continental crust.

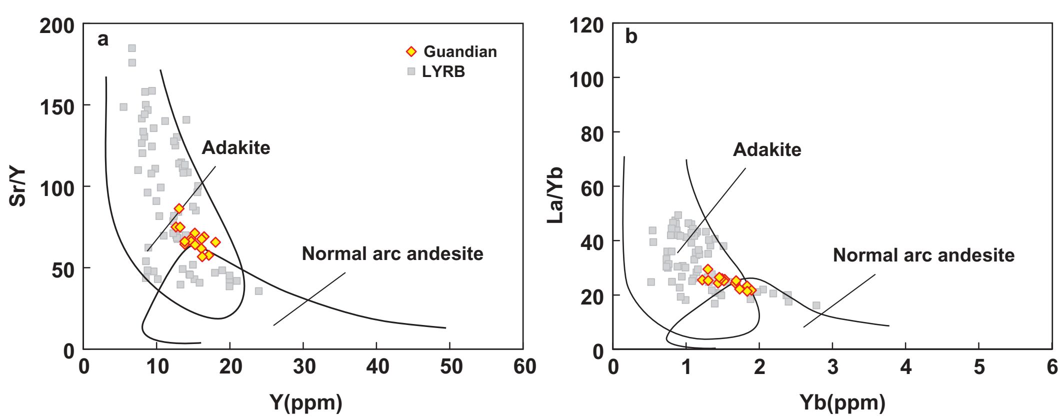

Figure 7. (a) Sr/Y *versus* Y and (b) La/Yb *versus* Yb discrimination diagrams for the Guandian intrusive rocks (Defant and Drummond 1990). Data sources for LYRB samples are the same as Figure 3.

2008; Liu *et al*. 2010), and it is contrast to those from the LYRB (Ling *et al*. 2009, 2011; Liu *et al*. 2010).

The origin of Guandian pluton was controversial and several genesis models have been recommended by previous researchers (Xing 1997; Niu *et al*. 2002; Xu *et al*. 2004; Zi *et al*. 2008). Xu *et al*. (2004) classified the Guandian pluton as a part of the NCC and suggested that it was associated with lithospheric thinning of NCC. Although the Guandian pluton is located in the east of the Tan–Lu fault and close to the NCC, it is generally regarded as a part of the Yangtze block (Figure 1). Most importantly, Early Cretaceous magmatism in the NCC associated with extension environment is systematically younger, with a peak at 125 Ma (Wu *et al*. 2005), than that of the Yangtze block which started from 140 to 125 Ma (Sun *et al*. 2007).

The Guandian pluton was also proposed to be formed by underplating of magma originated from the crust–mantle transitional zone and crust–mantle interaction during the later stage of Early Cretaceous strike-slip movement of the Tan–Lu fault (Niu *et al*. 2002). This is supported by geochronology evidence of the pluton and mylonite related with the Tan–Lu fault, as well as the NNE–SSW distribution of Early Cretaceous plutons outcrop near the Tan–Lu fault, e.g. Guandian, Wawuliu, and Wawuxue plutons (Figure 1). However, on the basis of isotopic composition, the pluton seems to have a primary contribution from the LCC (Xing 1997; Zi *et al*. 2008). Xing (1997) proposed that anatectic magmatism of Archaean granulites in the LCC accounts for the formation of the Guandian pluton, on the basis of whole rock Sr, Nd, Pb, and O isotopic composition. Furthermore, a detailed geochemical study indicated that partial melting of delaminated LCC with subsequent interaction of mantle peridotite accounted for the origin of the Guandian pluton, which is supported by the enriched $^{87}Sr/^{86}Sr$ (0.7059–0.7062), $\varepsilon_{Nd}(t)$ (−17.6 to

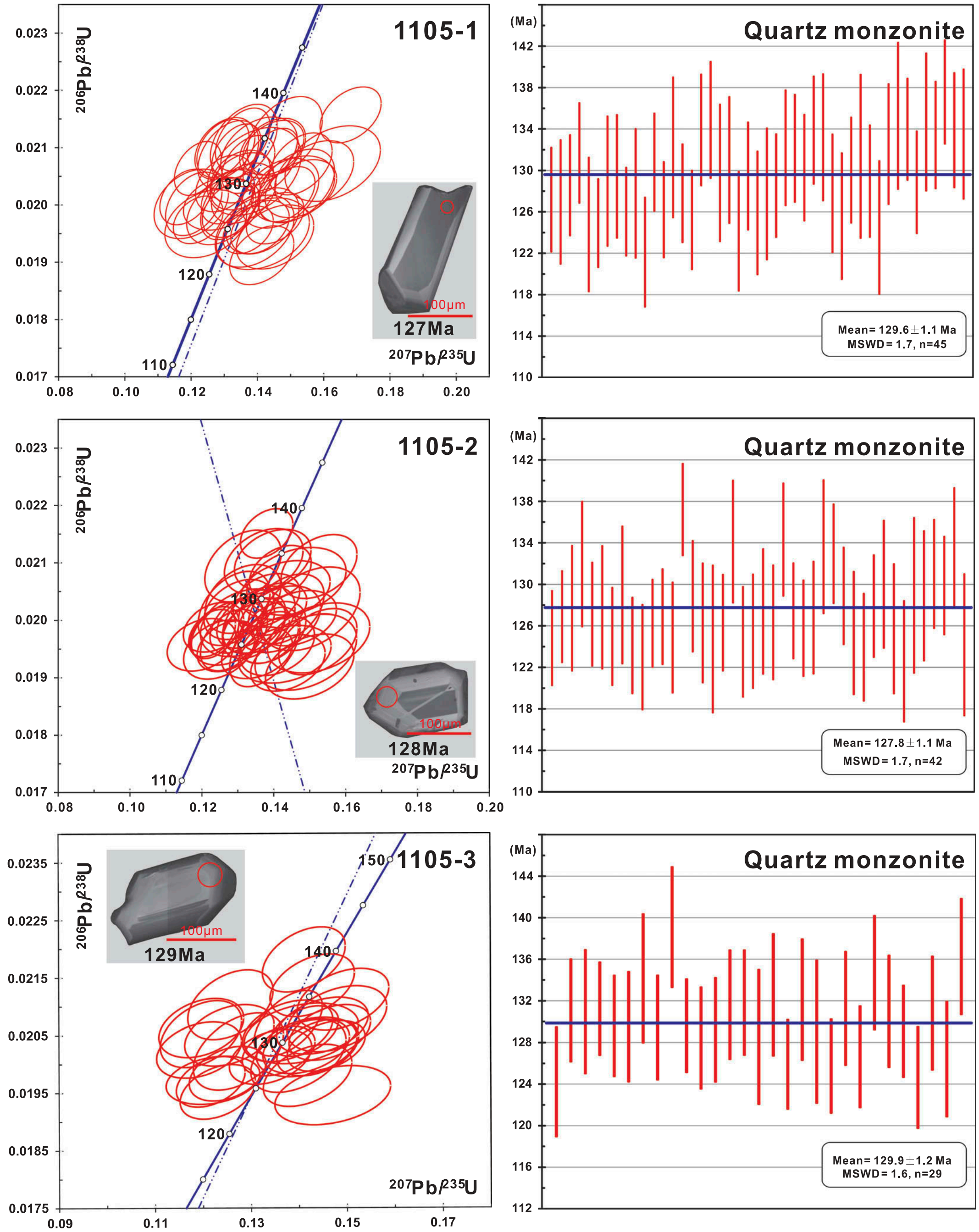

Figure 8. Zircon U–Pb concordia diagrams with representative CL images of the Guandian intrusive rocks. The weighted mean $^{206}Pb/^{238}U$ ages for samples 1105-1, 1105-2, and 1105-3 are 129.6 ± 1.1, 127.8 ± 1.1, and 129.9 ± 1.2 Ma, respectively.

−15.3) and $\varepsilon_{Hf}(t)$ (−26.3 to −22.6) isotope compositions (Zi *et al*. 2008), and high MgO (3.59–5.24%) and Mg# (55–60).

Detailed geochemical study indicated that adakitic rocks from the STLF formed by partial melting of delaminated eclogitic LCC (Liu *et al*. 2010), which is also furtherly supported by *in situ* zircon Hf and O isotope research (Wang *et al*. 2013). On the contrary, adakite from the LYRB was probably formed by partial melting of subducted oceanic crust during ridge subduction (Ling *et al*. 2009).

There are several requirements that partial melting of delaminated LCC will happen. Initially, it requires crustal thickening to produce a dense eclogitic LCC (Gao *et al*. 2004). Second, in addition to gravity caused by density contrast (Kay and Kay 1993), an extra impetus is preferred to trigger delamination. Finally, rising temperature faster than its solidus with

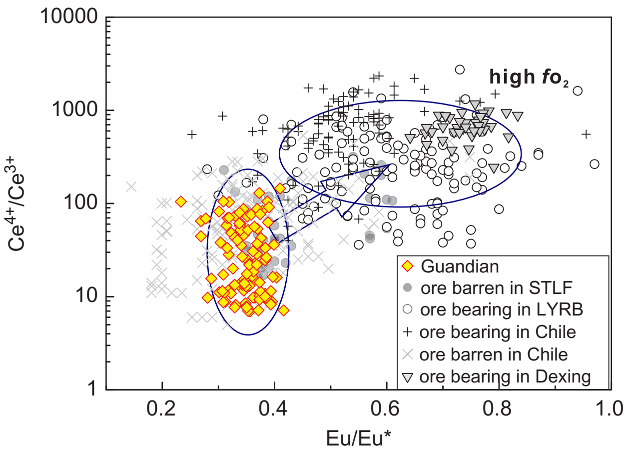

Figure 9. Zircon Ce^{4+}/Ce^{3+} *versus* Eu/Eu* diagram for the Guandian intrusive rocks. STLF: South Tan–Lu fault, LYRB: lower Yangtze river belt. Data of the STLF and the LYRB are from Wang *et al*. (2013, 2014). Data of Chile and Dexing are from Ballard *et al*. (2002) and Zhang *et al*. (2013).

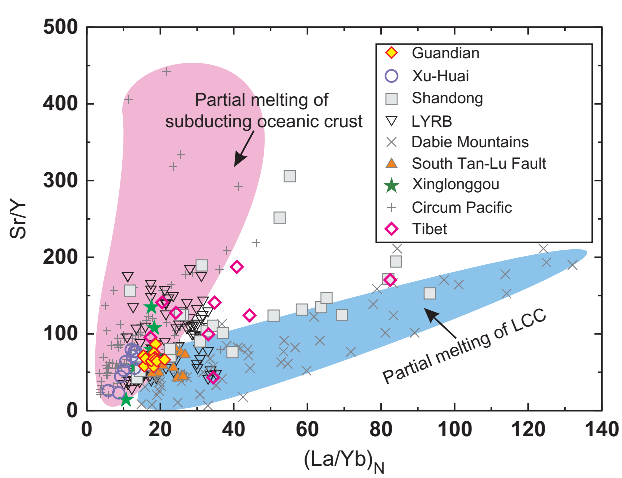

Figure 10. Sr/Y *versus* $(La/Yb)_N$ diagram. Data of Guandian intrusive rocks are in this study. Literature data are from Ling *et al*. (2013) and references therein.

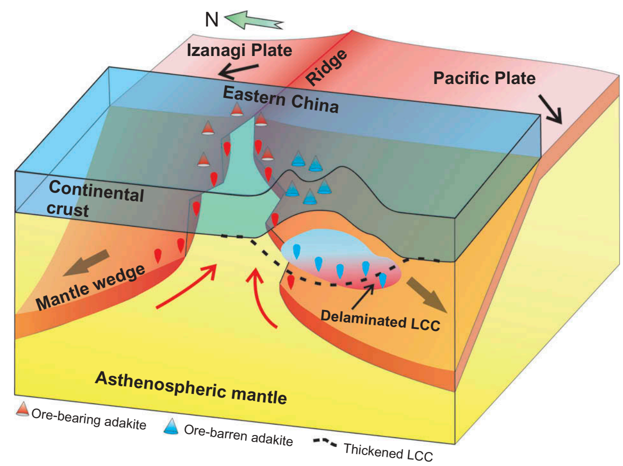

Figure 11. The genesis model of the Guandian pluton. The Guandian adakitic pluton was formed by partial melting of delaminated lower continental crust triggered by Early Cretaceous ridge subduction of the Pacific and Izanagi plates.

increasing depths to facilitate partial melting during delamination (Ling *et al*. 2009). Unlike young and hot subducted oceanic slabs which can much more easily be melted, the LCC is generally much drier and thus requires a higher temperature to melt.

Ridge subduction is a promising plate tectonic process that can provide both physical erosion and thermal erosion. Flat subduction of a spreading ridge will result in strong physical subduction-related erosion of the thickened LCC and subsequently trigger the delamination of the LCC. Furthermore, ridge subduction, probably accompanied by opening of a slab window, will provide associated magmatism and extra heat, i.e. thermal erosion, to facilitate partial melting of delaminated LCC (Ling *et al*. 2013). Here, we propose that the Guandian adakitic pluton was formed by partial melting of delaminated LCC, triggered by ridge subduction in the Early Cretaceous (Figure 11).

Based on the distribution of igneous rocks, e.g. adakite, A-type granite, and Nb-enriched basalts, as well as other lines of evidence, ridge subduction of the Pacific and Izanagi plates was proposed to explain the genesis of Cretaceous magmatism and associated mineralization in central eastern China (Ling *et al*. 2009, 2013). The ridge subduction model has been tested by further geochemical and geochronological study of A-type granites, including A_1 and A_2 subgroup, in central eastern China (Li *et al*. 2012). Detailed geochemical comparison of adakite or adakitic rocks from the LYRB, Dabie orogen, and STLF (Liu *et al*., 2010; Ling *et al*. 2011) indicated that the LYRB adakite formed by slab melting and the other two have origin of the LCC (Liu *et al*. 2010; Ling *et al*. 2011). Subsequent structure geological research pointed out that the compressional period (145–136 Ma) in central eastern China was dominated by Palaeo-Pacific–Izanagi ridge subduction beneath the LYRB, as well as adakite and Cu–Au mineralization (Li *et al*. 2014). Additionally, a geophysical tomographic research provided a direct evidence to support Cretaceous ridge subduction in eastern China (Ouyang *et al*. 2014).

5.2. *Porphyry mineralization, slab melting, and oxygen fugacity*

Porphyry deposits are the one of the most important resources of Cu, Au, Mo, Ag, Zn, Sn, and W (Cooke *et al*. 2005; Sillitoe 2010; Sun *et al*. 2010, 2015, 2016, 2017), which account for ~80% Cu and ~95% Mo of the world's total reserves (Sun *et al*. 2015). Majority of the porphyry systems are associated with oxidized magma (Ballard *et al*. 2002; Mungall 2002; Liang *et al*. 2006; Sun *et al*. 2013; Zhang *et al*. 2017), which is normally adakitic in chemical composition (Sun *et al*. 2011, 2012, 2015, 2017).

In principle, high oxygen fugacity and slab melting are the two keys to formation of porphyry deposits (Sun *et al*. 2012). Cu, Au, and Mo are chalcophile elements, whose partitioning in magma is largely controlled by the behaviour and speciation of sulphur, while the status of sulphur is controlled by oxygen fugacity (Sun *et al*. 2015). It has been proposed that oxygen fugacity of log fO_2 > FMQ + 2 (i.e. ΔFMQ + 2) is the magic number for porphyry mineralization, where FMQ represents oxygen buffer of fayalite–magnetite–quartz (Mungall 2002; Sun *et al*. 2013). Most of porphyry Cu deposits are distributed along the eastern Pacific margin, accounting for about 60% of the world's total Cu resource (Cooke *et al*. 2005), which are generally associated with slab melting of ridge subduction (Sun *et al*. 2010). Modelling indicated that partial melting of subducted young oceanic slabs at high oxygen fugacity (>ΔFMQ + 2) may form magmas with initial Cu contents up to >500 ppm, which is favourable for porphyry mineralization (Sun *et al*. 2017).

In contrast with oceanic crust, which has Cu concentration (60–130 ppm) (Sun *et al*. 2003a), the LCC has lower Cu concentration of 27 ppm (Rudnick and Gao 2003), resulting in that slab melts will have higher initial copper concentrations than LCC melt (Sun *et al*. 2011). Moreover, the subduction zone is more oxidizing than the LCC, which benefits to Cu–Au mineralization (Sun *et al*. 2012). Therefore, adakite formed by slab melting is more favourable for porphyry mineralization than formed by partial melting of LCC in terms of initial Cu concentration.

Adakite or adakitic rocks formed by slab melting or partial melting of LCC are contrast in chemical and isotopic compositions (Liu *et al*. 2010; Ling *et al*. 2011), as well as oxygen fugacity (Wang *et al*. 2013). Zircon is a common refractory mineral in rocks which can preserve the original chemical composition of magma, including trace elements. The trace element concentrations of zircon can be taken to calculate Ce^{4+}/Ce^{3+} ratio and Eu/Eu* anomaly to evaluate oxygen fugacity of magma (Ballard *et al*. 2002; Liang *et al*. 2006). The ore-bearing adakite in the LYRB and Dexing porphyry deposit in central eastern China have much high oxygen fugacity than ore-barren adakitic rocks in the Dabie orogen and the STLF, as indicated by zircon Ce^{4+}/Ce^{3+} ratios and Eu/Eu* (Wang *et al*. 2013; Zhang *et al*. 2013, 2017). Zircon Ce^{4+}/Ce^{3+} (6.97–145) and $(Eu/Eu^*)_N$ (0.23–0.42) of the Guandian adakitic pluton are similar to other plutons in the STLF but lower than those of the LYRB and Dexing (Wang *et al*. 2013; Zhang *et al*. 2013, 2017). This indicates the Guandian adakitic pluton originated from magma with low oxygen fugacity, which is also the case for the other plutons in the STLF (Figure 9). This is consistent with magma having origin of the LCC, as well as ore-barren fact in the STFL.

6. Conclusion

The Guandian pluton is metaluminous and high-K calc-alkaline and characterized by typical chemical composition of adakite, e.g. high SiO_2 (59.15–62.32%), Al_2O_3 (14.51–15.39%), Sr (892–1184 ppm), Sr/Y (56.74–86.32), and low Y (12.65–18.05 ppm). LA-ICP-MS zircon U–Pb dating of the Guandian pluton yielded a weighted average age of 129.2 ± 0.7 Ma. Zircon Ce^{4+}/Ce^{3+} (6.97–145) and $(Eu/Eu^*)_N$ (0.23–0.42) indicate lower oxygen fugacity relative to the ore-bearing adakites in the LYRB and Dexing, which is consistent with the fact of ore-barren in the STLF. We propose that the Guandian pluton was formed by partial melting of delaminated LCC, triggered by Early Cretaceous ridge subduction of the Pacific and Izanagi plates. Physical erosion destructed the thickened LCC and resulted in delamination, while thermal erosion facilitated partial melting of the delaminated LCC.

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Disclosure statement

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