International Geology Review
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tigr20

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Ming-Xing Ling [a] [b], Fang-Yue Wang [a] [b], Xing Ding [a], Ji-Bin Zhou [a] & Weidong Sun [a] [c]

[a] Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China

[b] Graduate University of Chinese Academy of Sciences, Beijing, China

[c] Research Centre for Mineral Resources, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China

To cite this article: Ming-Xing Ling, Fang-Yue Wang, Xing Ding, Ji-Bin Zhou & Weidong Sun (2011): Different origins of adakites from the Dabie Mountains and the Lower Yangtze River Belt, eastern China: geochemical constraints, International Geology Review, 53:5-6, 727-740

To link to this article: http://dx.doi.org/10.1080/00206814.2010.482349

International Geology Review
Vol. 53, Nos. 5–6, April–May 2011, 727–740

Different origins of adakites from the Dabie Mountains and the Lower Yangtze River Belt, eastern China: geochemical constraints

Ming-Xing Ling[a,b], Fang-Yue Wang[a,b], Xing Ding[a], Ji-Bin Zhou[a] and Weidong Sun[a,c]*

[a]*Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China;* [b]*Graduate University of Chinese Academy of Sciences, Beijing, China;* [c]*Research Centre for Mineral Resources, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China*

(*Accepted 17 March 2010*)

Cretaceous adakites are widely distributed in the Lower Yangtze River Belt (LYRB) and the Dabie Mountains, east-central China. Adakites from the LYRB in general are closely associated with Cu–Au deposits, whereas Dabie adakites lack any mineralization. Based on geochemical characteristics, we show that these adakites have different origins; for example, adakites from the Dabie Mountains have more variable Sr/Y (6.47–1303) and systematically higher La/Yb (20.8–402), Th/U (2.28–50.6), and Nb/Ta (5.07–65.2) compared to adakites from the LYRB, Sr/Y (28.8–185), La/Yb (14.1–49), Th/U (0.33–8), and Nb/Ta (7.5–23). The systematically higher La/Yb of Dabie adakites supports their continental origin, because the La/Yb of the lower continental crust is more than 10 times higher than that of mid-ocean ridge basalt (MORB). Moreover, the lower continental crust is also highly enriched in Sr, with Sr/Y > 10 times that of MORB. Interestingly, with the exception of those from Fuziling, most Dabie adakites have Sr/Y comparable to normal adakites, suggesting the presence of residual plagioclase. Because Th and U do not fractionate significantly from each other during magmatism, the high but variable Th/U suggests that the protolith of Dabie adakites underwent subduction. The LYRB adakites can be plausibly interpreted as being a result of Early Cretaceous partial melting of a young, hot, descending oceanic slab during ridge subduction. By contrast, Dabie adakites were likely formed by partial melting of the lower continental crust attending ridge subduction.

Keywords: adakites; Dabie; ridge subduction; Cu deposits; slab melting

1. Introduction

Adakite, defined by its unique geochemical features such as $SiO_2 \geq 56$ wt.%, $Al_2O_3 \geq 15$ wt.%, $Y \leq 18$ ppm, $Yb \leq 1.9$ ppm, and $Sr \geq 400$ ppm, was initially named for rocks with clear contributions from partial melting of subducted young oceanic crust (Defant and Drummond 1990) and has gained wide interest in recent years. The formation of some adakites, however, is still controversial. In addition to slab melting, adakite was also proposed to be formed by partial melting of the lower continental crust (Chung *et al.* 2003; Gao *et al.* 2004), underplated new crust (Petford *et al.* 1996), or fractional crystallization of normal arc magmas (Castillo 2006; Macpherson *et al.* 2006; Richards and Kerrich 2007; Rodriguez *et al.* 2007).

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*Corresponding author. Email: weidongsun@gig.ac.cn

ISSN 0020-6814 print/ISSN 1938-2839 online

DOI: 10.1080/00206814.2010.482349
http://www.informaworld.com

Adakite has been reported to be closely associated with many ore deposits in the Lower Yangtze River Belt (LYRB), central eastern China (Wang *et al.* 2004a, 2004b, 2006, 2007b; Yang *et al.* 2007; Xie *et al.* 2008, 2009; Zhou *et al.* 2008), which is one of the most important metallogenic belts in China, containing more than 200 polymetallic (Cu–Fe–Au, Mo, Zn, Pb, Ag) deposits (Chang *et al.* 1991; Pan and Dong 1999; Mao *et al.* 2006), formed mainly at a very narrow period of time, that is, 138 ± 3 Ma (Sun *et al.* 2003b). Adakite from the LYRB was originally attributed to partial melting of thickened or delaminated lower continental crust, based mainly on isotopic characteristics and an assumption that there was no plate subduction in the Early Cretaceous (Zhang *et al.* 2001; Xu *et al.* 2002; Wang *et al.* 2004a, 2004b, 2006, 2007b).

Plate reconstruction and other observations, however, suggest that there was plate subduction in the Early Cretaceous (Zhou and Li 2000; Zhou *et al.* 2006; Li and Li 2007; Sun *et al.* 2007a; Wang *et al.* 2011). Based on the distribution of adakite and rock assemblages, Ling *et al.* (2011) proposed a ridge subduction model. According to that model, LYRB adakite was formed by partial melting of subducting young, hot oceanic slabs close to the subducting ridge between the Pacific and Izanagi plates. The enriched isotope characteristics can be explained by the assimilation of enriched mantle materials and the continental crust (Ling *et al.* 2009).

In recent years, adakite has also been reported in the Dabie Mountains (Wang *et al.* 2007a; Xu *et al.* 2007; Huang *et al.* 2008), which was considered to be formed by partial melting of the basement of an overthickened crustal root during the early stage of extensional collapse of the Dabie Mountains (Xu *et al.* 2007), partial melting of thickened amphibole or rutile-bearing eclogitic lower continental crust (Wang *et al.* 2007a), or partial melting of the thickened lower continental crust (Huang *et al.* 2008).

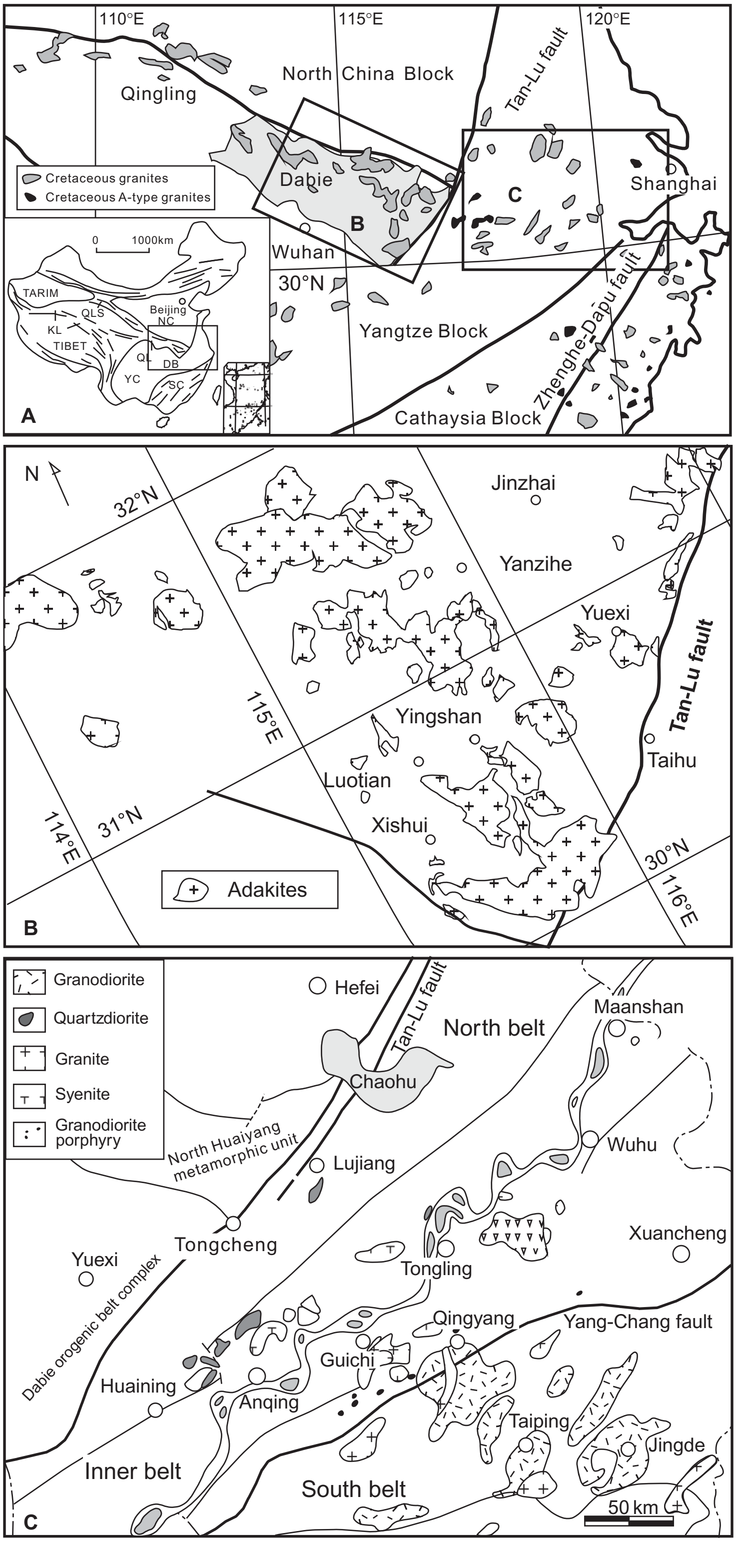
Considering the dramatic difference between the Dabie Mountains and the LYRB in terms of tectonic settings, we compared geochemical characteristics of adakite from these places (Huang *et al.* 2008; Ling *et al.* 2009 and references therein; Wang *et al.* 2007a; Xu *et al.* 2007). Our results show significant differences in geochemical characteristics between these two suites of adakites.

2. Geological background

2.1. The Dabie Mountains

The Dabie ultra-high-pressure metamorphic (UHPM) belt is the middle part of the Qinling-Dabie-Sulu Mountains in China (Mattauer *et al.* 1985; Meng and Zhang 1999, 2000; Sun *et al.* 2002a; Li and Yang 2003; Zhang *et al.* 2004), which is the largest UHPM belt in the world and resulted from the Triassic collision between the North and South China blocks (Figure 1a and b) (Li *et al.* 1993; Hacker *et al.* 1998; Liou *et al.* 2000; Ye *et al.* 2000; Sun *et al.* 2002b; Zhang *et al.* 2003, 2008; Liu *et al.* 2006; Yang *et al.* 2008).

The Dabie Mountains were divided into two terranes, the northern Dabie terrane and the southern Dabie terrane. The southern Dabie terrane is famous for coesite-bearing (Okay *et al.* 1989; Wang *et al.* 1989) and diamond-bearing eclogite (Xu *et al.* 1992), as well as other ultra-high-pressure mineral assemblages indicating that the continental crust has been subducted down to depths of more than 100 km (Ernst and Liou 1999; Ye *et al.* 2000; Zhang *et al.* 2007). Generally, the Dabie Mountains can be subdivided into five metamorphic zones from north to south: (1) Beihuaiyang greenschist-amphibolite facies zone; (2) Huwan cold eclogite melange zone; (3) northern Dabie complex zone; (4) southern


110°E
115°E
120°E
Qingling
North China Block
Tan-Lu fault
Cretaceous granites
Cretaceous A-type granites
Dabie
B
C
Shanghai
Wuhan
30°N
0
1000km
TARIM
QLS
KL
TIBET
Beijing
NC
QL
DB
YC
SC
Yangtze Block
Zhenghe-Dapu fault
Cathaysia Block
A
N
32°N
Jinzhai
Yanzihe
Yuexi
115°E
Yingshan
Tan-Lu fault
Taihu
Luotian
Xishui
114°E
31°N
30°N
116°E
Adakites
B
Granodiorite
Quartzdiorite
Granite
Syenite
Granodiorite porphyry
Hefei
Tan-Lu fault
North belt
Maanshan
Chaohu
North Huaiyang metamorphic unit
Lujiang
Wuhu
Xuancheng
Tongcheng
Yuexi
Tongling
Dabie orogenic belt complex
Qingyang
Yang-Chang fault
Guichi
Huaining
Anqing
Taiping
Jingde
Inner belt
South belt
50 km
C

Dabie UHPM zone; and (5) Hong'an-Susong high-pressure metamorphic zone (Li *et al.* 1993, 2001 and references therein; Zhang *et al.* 2007; Wang *et al.* 2008).

Adakite in the Dabie Mountains is distributed in Yunfengding, Egongbao, Fuziling (Wang *et al.* 2007a), Tiantangzhai (Wang *et al.* 2007a; Xu *et al.* 2007), Chituling (Huang *et al.* 2008), Shigujian, Duzunshan, Guanyinci, Daoshichong, etc. (Xu *et al.* 2007). Those adakitic rocks are all attributed to partial melting of the lower continental crust (Huang *et al.* 2008).

2.2. The Lower Yangtze River Belt

The LYRB is located in the east part of the Yangtze block in central eastern China (Chang *et al.* 1991; Chen *et al.* 1991; Xing and Xu 1995; Pan and Dong 1999; Zhou and Yue 2000; Chen *et al.* 2001; Zhou *et al.* 2008; Xie *et al.* 2009) (Figure 1a), which is separated from the Cathaysia block to the south by the Jiangshan-Shaoxing fault, the Proterozoic suture between the Cathaysia and Yangtze blocks (Li 1992; Li *et al.* 2005). The Xiangfan-Guangji and Tan-Lu faults are the northern and western margins of the LYRB, respectively (Chen *et al.* 2001), separating it from the Dabie Mountains.

The magmatic rocks have been classified into three belts: the inner, south, and north belts (Chang *et al.* 1991; Xing 1999; Xing and Xu 1995) (Figure 1c). The inner belt contains high-K calc-alkaline intermediate-acidic intrusive rocks, high-sodium calc-alkaline intermediate-basic intrusive rocks, shoshonite, and A-type granite (Xing 1999). The south belt consists of calc-alkaline rocks, generally large plutons with some small bodies of granodiorite porphyry. Some A-type granites with younger ages have also been reported in the south belt (Wong *et al.* 2009). The north belt is also composed of calc-alkaline rocks, but it is poorly developed and seemingly more complicated than the other two belts, with fewer intrusive bodies (Xing 1999). Adakitic rocks from the LYRB are all distributed in the inner belt. A-type granites are systematically younger than adakite, which is probably related to a slab window (Ling *et al.* 2009). LYRB adakite was attributed either to partial melting of the lower continental crust (Zhang *et al.* 2001; Xu *et al.* 2002; Wang *et al.* 2006, 2007b) or to slab melting induced by ridge subduction (Ling *et al.* 2009).

3. Comparison of adakites from the Dabie Mountains and the LYRB

Given that the major elements (e.g. K_2O, Na_2O, and MgO) and isotopes (e.g. Sr, Nd) have been intensively investigated by previous authors, this article mainly focuses on the trace element characteristic of the adakites. A comparison of geochemical characteristics of adakites from the Dabie Mountains and the LYRB is made in this study, using data from the literature (Huang *et al.* 2008; Ling *et al.* 2009 and references therein; Wang *et al.* 2007a; Xu *et al.* 2007). Referring to Sr/Y–Y and La/Yb–Yb diagrams (Figures 2 and 3), most of the data collected from published literature fall in the adakite area confined by the global database GEOROC (GEOROC 2009).

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Figure 1. Distribution map of adakite from the Dabie Mountains and the Lower Yangtze River Belt in China. (a) Sketch map of eastern China with the locations of the Dabie Mountains and the Lower Yangtze River Belt (modified from Wang *et al.* 2007a). (b) Distribution map of adakite from the Dabie Mountains (modified from Wang *et al.* 2007a). (c) Distribution of magmatic rocks in the Lower Yangtze River Belt (modified from Ling *et al.* 2009). Granodiorite, quartz diorite, granite, syenite, etc. distributed in the inner belt are adakites.

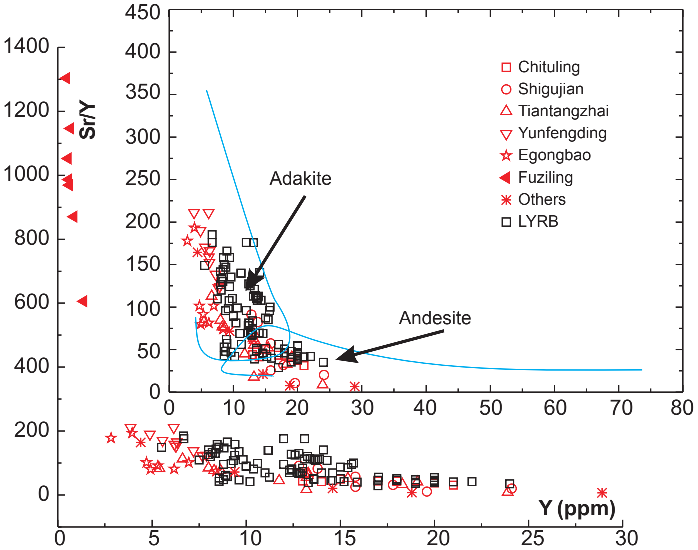

Figure 2. Diagram of Sr/Y versus Y. The adakite and andesite areas are defined using data from the GEOROC database (GEOROC 2009). Nearly all of the data are distributed in the adakite area, in which adakite from the Dabie Mountains has a relatively larger range than that from the Lower Yangtze River Belt and also slightly lower Sr/Y ratios, except adakite from Fuziling, which has extremely high Sr/Y up to 1303.

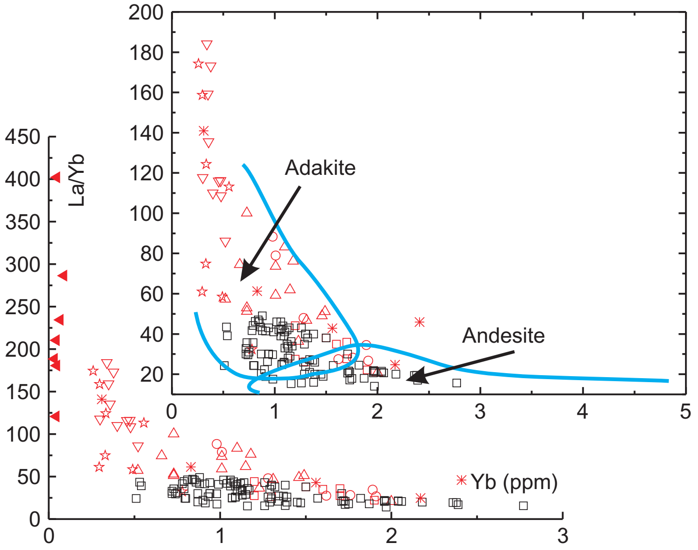

Figure 3. Diagram of La/Yb versus Yb. Symbols are the same as in Figure 2. The adakite and andesite areas are defined using data from the GEOROC database (GEOROC 2009). As in Figure 2, data of adakite from the Dabie Mountains are in a wide range, in which adakite from Fuziling has the highest La/Yb ratios. Adakite from the Lower Yangtze River Belt has much lower La/Yb than that from the Dabie Mountains.

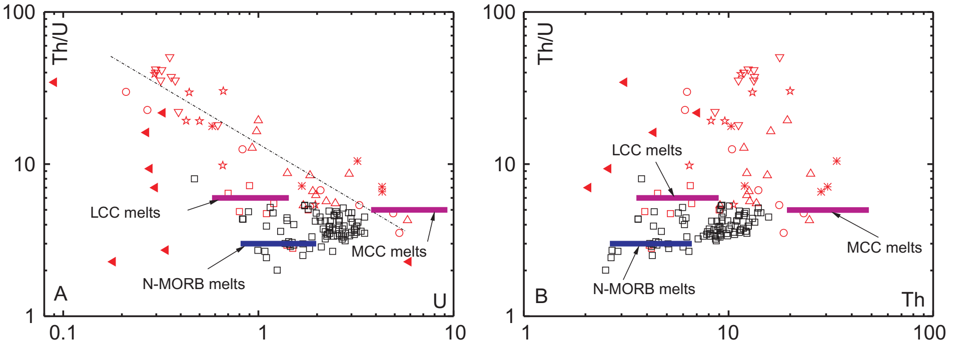

Figure 4. (a) Th/U versus U diagram. (b) Th/U versus Th diagram. Symbols are the same as in Figure 2. LCC, lower continental crust; MCC, middle continental crust. The compositions of lower and middle continental crusts were from Rudnick and Gao (2003), whereas those of MORB are the average values of Sun *et al.* (2008). Adakite from the Dabie Mountains has highly varied Th/U ratios, the same as U and Th concentrations, and shows a clear negative linear trend in the Th/U versus U diagram. Adakite from the Lower Yangtze River Belt has many focused Th/U ratios and U and Th concentrations.

Adakites from the Dabie Mountains and the LYRB have obviously different geochemical characteristics, for example, adakite from the Dabie Mountains has Sr concentration ranging from 142 to 1300 ppm, Y concentration from 0.452 to 28.9 ppm, and highly varied Sr/Y (6.47–1300), whereas adakite from the LYRB has much higher Sr concentration (369–2300 ppm), nearly the same range of Y concentration (5.51–24 ppm), and less variable Sr/Y (28.8–185) (Figure 2). Also, adakite from the Dabie Mountains has a wide range of La/Yb, varying from 20.8 to 402, whereas that of LYRB adakite ranges from 14.1 to 49 (Figure 3). It is worth mentioning that adakite from Fuziling in the Dabie Mountains has the highest Sr/Y and La/Yb among all samples studied (Figures 2 and 3), probably because of the combination of their lower continental origin and large amount of residual garnet in the source (see detailed discussion below). Furthermore, Dabie adakite has highly variable Th/U, ranging from 2.28 to 50.6 (Figure 4), with Nb/Ta ranging from 5.07 to 65.2 (Figure 5) and Zr/Hf from 25.4 to 47.4 (Figure 6). In contrast, LYRB adakite has much lower Th/U (0.33–8) (Figure 4), relatively lower Nb/Ta (7.5–23) (Figure 5), and almost the same range of Zr/Hf (23.3–40.2) (Figure 6).

Aforementioned evidence clearly shows that adakites from the Dabie Mountains were very likely formed by partial melting of the lower continental crust, whereas those from the LYRB were formed by partial melting of subducting oceanic slab.

4. Discussion

4.1. Sr/Y

Adakite from the Dabie Mountains is generally attributed to partial melting of the lower continental crust (Wang *et al.* 2007a; Huang *et al.* 2008). The lower continental crust has Sr/Y of more than 30, which is about 10 times higher than that of mid-ocean ridge basalt (MORB) (Sun and McDonough 1989; Rudnick and Gao 2003; Sun *et al.* 2008). Most adakite so far published has Sr/Y ranging from 20 to 200. Adakite from the LYRB has relatively concentrated Sr/Y (28.8–185) (Figure 2), well within the range of global adakite. In contrast, adakite from the Dabie Mountains has highly varied Sr/Y (6.47–1300) (Figure 2). All the samples with high Sr/Y were from Fuziling. Strontium is generally taken as a moderately incompatible element during mantle magmatism (Sun and McDonough 1989). It

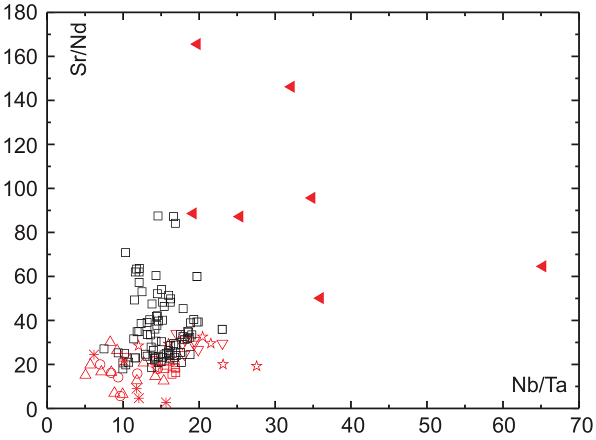

Figure 5. Sr/Nd versus Nb/Ta diagram. Symbols are the same as in Figure 2. Except data points of adakite from Fuziling, adakites from both the Dabie Mountains and the Lower Yangtze River Belt have restrictedly the same range of Nb/Ta ratios. Lower Sr/Nd ratios from the Dabie Mountains are likely because of more residual plagioclase in the source.

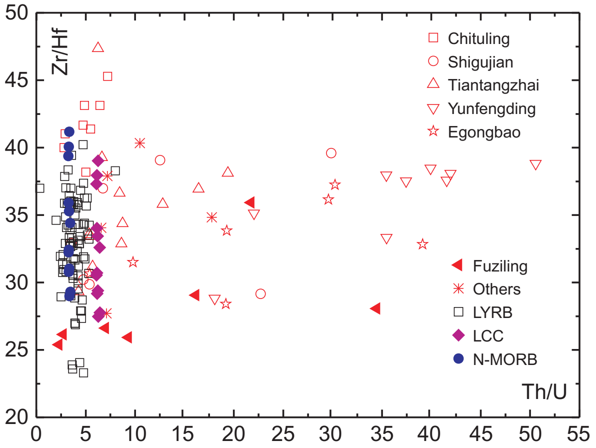

Figure 6. Diagram of Zr/Hf versus Th/U. The compositions of lower continental crust were from Rudnick and Gao (2003), whereas those of MORB are the average values of Sun *et al.* (2008). Melts of lower continental crust and subducted slab partial melting are both plotted for comparison. Th/U ratios of adakite from the Dabie Mountains vary widely from 2.28 to 50.6, whereas those from the Lower Yangtze River Belt are between 0.33 and 8. Apparently, adakite from the Lower Yangtze River Belt is related to partial melting of subducted oceanic slab represented by N-MORB, whereas that from the Dabie Mountains is associated with partial melting of lower continental crust.

is, however, highly compatible in plagioclase (GERM 2009), with a partition coefficient of ~3.7 for plagioclase in basaltic rocks (GERM 2009). Yttrium is also a moderately incompatible element during mantle magmatism (Sun and McDonough 1989), with geochemical behaviour similar to that of heavy rare earth elements. It is highly compatible in garnet. Therefore, plagioclase and garnet are the two most important minerals that control Sr/Y ratios.

LYRB adakite has Sr/Y comparable to global adakites. Considering that the lower continental crust has Sr/Y about 10 times higher than that of MORB, a large amount of residual plagioclase is required to form these adakites from partial melting of the lower continental crust. In this case, the partial melting occurred at fairly shallow depths. Alternatively, adakite formed by slab melting at eclogitic facies generally has no plagioclase in the source (Rapp and Watson 1995; Rapp *et al.* 2003; Xiao *et al.* 2006; Xiong 2006), such that the Sr/Y ratios can be dramatically elevated during slab melting. Therefore, LYRB adakite can be plausibly interpreted as being a result of ridge subduction induced partial melting, with limited contamination from enriched mantle sources and the continental crust (Ling *et al.* 2009).

The large variation of Sr/Y for the Dabie samples can be plausibly interpreted as being a result of partial melting of the lower continental crust with different proportions of garnet and plagioclase in the source. The high Sr/Y of Fuziling adakite indicates more residual garnet, with or without minor plagioclase. Other Dabie samples have Sr/Y comparable to those of the LYRB samples and adakites worldwide, indicating residual plagioclase. It is true that Sr/Y of Dabie samples can also be interpreted as being a result of slab melting. In other words, with the exception of very high Sr/Y, e.g. Fuziling samples, Sr/Y itself cannot discriminate slab melting from partial melting of the lower continental crust.

4.2. La/Yb

The lower continental crust has La/Yb ratio of ~10, which is ~15 times higher than that of MORB (Sun and McDonough 1989; Rudnick and Gao 2003; Sun *et al.* 2008). Lanthanum is an incompatible element, whereas Yb is moderately incompatible during mantle magmatism (Sun and McDonough 1989). Ytterbium, however, is highly compatible in garnet, whereas La is not. Therefore, La/Yb ratios of adakites are very sensitive to garnet. In contrast to Sr/Y ratios, La/Yb is not obviously affected by plagioclase. Moreover, garnet is a major mineral in both eclogite and granulite (for the lower continental crust). For these reasons, adakites formed by partial melting of the lower continental crust in the presence of garnet should have systematically higher La/Yb, which is much more sensitive than Sr/Y in discriminating slab melting from lower continental crust melts. This is exactly the case for Dabie adakite.

As shown in Figure 3, adakite from the Dabie Mountains has wide-ranging La/Yb ratios, ranging from 20.8 to 402, which is systematically higher than normal adakites. The high La/Yb ratios support models of the lower continental crust partial melting (Wang *et al.* 2007a, Huang *et al.* 2008), whereas the large range of La/Yb ratios is consistent with the large variation of Sr/Y, which indicates variable amount of residual garnet in the source. It is worth mentioning that adakite from Fuziling in the Dabie Mountains has the highest Sr/Y and La/Yb ratios (Figures 2 and 3), likely because of more residual garnet, less residual plagioclase in the source.

LYRB adakite has La/Yb ranging from 14.1 to 49 (Figure 3), comparable to normal adakites (Figure 3). A garnet-free source is required to form this kind of adakites by partial melting of the lower continental crust (with La/Yb of ~10). Given that garnet is a major mineral in both eclogitic and granulitic rocks, this assumption is unfavourable. Therefore, we propose that La/Yb of the LYRB adakite can be plausibly interpreted as being a result of slab melting.

4.3. Th/U

Adakite from the Dabie Mountains has highly varied Th/U, as well as U and Th concentrations (Figure 4). Large variations of U concentration and Th/U of adakite from the Dabie Mountains can be explained by U loss during subduction and collision in the Triassic, because U is more mobile than Th (Hawkesworth *et al.* 1997), especially at temperatures lower than 600°C. This is supported by the negative linear trend in a Th/U versus U diagram (Figure 4a).

The Th/U values of LYRB adakite is systematically lower and much less variable, falling around the field of slab melts (Figure 4). Considering the similarity between U and Th, the variable Th/U of LYRB adakite is still significant. It is likely because of Th/U fractionation during subduction. Nevertheless, the Th/U characteristics strongly support the slab melting model (Ling *et al.* 2009).

4.4. Nb/Ta

Adakite from the Dabie Mountains has Nb/Ta = 5.1–65.2, Nb = 1.01–27.3 ppm, Ta = 0.023–2.28 ppm, whereas that from the LYRB has relatively lower Nb/Ta (7.5–23, with an average of 15.1), Nb = 0.3–22.4 ppm with an average of 10.0 ppm, and Ta = 0.04–1.4 ppm with an average of 0.7 ppm (Figure 5). Adakite from Fuziling has much higher and more fractionated Nb/Ta than others. With the exception of Fuziling samples, adakites from the Dabie Mountains and the LYRB have nearly the same range of Nb/Ta, which are from 5.1 to 27.6 with an average of 14.1 and from 7.5 to 23 with an average of 15.1, respectively (Figure 5).

Niobium and Ta are usually not fractionated from each other. Highly fractionated Nb/Ta ratios have been reported in subduction zones, which are attributed to dehydration during the prograde blueschist to amphibole–eclogite transformation before rutile appeared (Xiao *et al.* 2006; Ding *et al.* 2009; Liang *et al.* 2009). The highly variable Nb/Ta suggests that both Dabie and LYRB adakites are related to plate subduction. Given that the LYRB is dramatically different from the Dabie Mountains in tectonic settings, that is, it has not been subducted during the Triassic collision, the fractionated Nb/Ta in LYRB adakites, in fact, also supports the ridge subduction induced slab melting model.

4.5. Ridge subduction

All the facts discussed above support the ridge subduction model for LYRB adakite. According to that model, there was a ridge subduction affecting the LYRB in the Cretaceous, and adakite from the LYRB was formed by partial melting of subducting young, hot oceanic slabs close to the subducting ridge between the Pacific and Izanagi plates (Ling *et al.* 2009). Subduction resulted in higher oxygen fugacity (Brandon and Draper 1996; Sun *et al.* 2007b), which is favourable for Cu–Au mineralization (Mungall 2002; Sun *et al.* 2004; Liang *et al.* 2006).

In contrast to the LYRB adakite, the geochemical features of Dabie adakite indicate obvious lower continental crust origin (Figures 5 and 6). It is well known that the Dabie Mountains was formed during the Triassic collision between the North and South China blocks (Li *et al.* 1993; Hacker *et al.* 1998; Ye *et al.* 2000; Sun *et al.* 2002b; Zheng *et al.* 2003; Liu *et al.* 2006), with dehydration and retrograde metamorphism during continental subduction. The Triassic collision and subduction had thickened the lower continental crust, resulting in a high-pressure metamorphic belt. Dabie adakite was most likely formed during the destruction of the thickened mountain belt. Nevertheless, most Dabie adakites were formed at shallow depths in the presence of plagioclase, therefore, they were not likely related to delamination. Remarkably, Dabie adakite formed at nearly the same period of time. In case LYRB adakite was formed during ridge subduction, Dabie adakite may also be genetically related to ridge subduction in the Early Cretaceous. In other words, Dabie adakite was triggered by ridge subduction: the flat subduction of the ridge may have physically destroyed the root of the Dabie Mountains, whereas the following slab window provided additional heat, which promoted the partial melting (Figure 7).

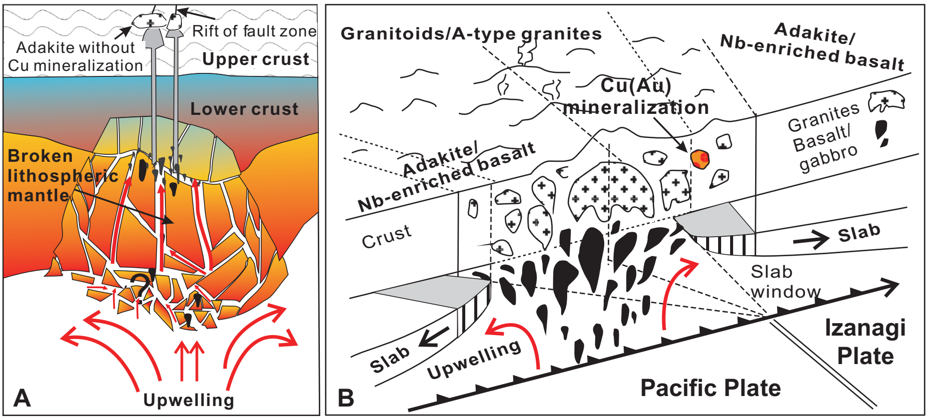

Figure 7. Formation model of adakite from the Dabie Mountains and the Lower Yangtze River Belt. (a) Formation of adakite from the Dabie Mountains; (b) formation of adakite from the Lower Yangtze River Belt (modified from Ling *et al.* 2009). Adakite from the Dabie Mountains was formed by partial melting of lower continental crust, initiated by the subduction of the ridge between the Pacific and Izanagi plates in the Cretaceous. Adakite from the Lower Yangtze River Belt was formed by partial melting of subducting young, hot oceanic slabs close to the subducting ridge (Ling *et al.* 2009).

The different origin of Dabie and LYRB adakites is also consistent with the fact that LYRB adakite is closely associated with Cu–Au deposits, whereas Dabie adakite is not. MORB has Cu (and Au) several times higher than that of the lower continental crust (Sun and McDonough 1989; Rudnick and Gao 2003; Sun *et al.* 2003a; Sun *et al.* 2004), therefore slab melting is much more favourable for Cu (Au) mineralization (Sun *et al.* 2011).

5. Conclusions

Geochemical features indicate different sources for adakites from the Dabie Mountains and the LYRB. The source of the Dabie adakite magma was subduction-modified lower continental crust, characterized by the presence of residual plagioclase. We propose that the Dabie adakites formed by partial melting of the lower continental crust, initiated by Cretaceous ridge subduction. In contrast, the LYRB adakites were formed by partial melting of a subducting young, hot oceanic slab close to the spreading ridge, contaminated by enriched components or the continental crust.

Acknowledgements

This work was supported by the Key Research project of the Chinese Academy of Sciences (KZCX1-YW-15), Ministry of Science and Technology of China (973) (2006CB403505), the Natural Science Foundation of China (No. 40525010), and the CAS/SAFEA International Partnership Programme for Creative Research Teams. We sincerely thank Professor Qiang Wang for constructive review and comments. Contribution No. IS-1214 from GIGCAS.

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