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The formation of Qulong adakites and their relationship with porphyry copper deposit: Geochemical constraints

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ABSTRACT

Qulong porphyry Cu deposit is the largest Cu deposit in China so far discovered, with total reserves of 10.6 Mt Cu@0.5% and 0.5 Mt Mo@0.03%. The petrogenesis of the Miocene intrusion and its genetic association with Cu mineralization have been debated. This study presents new results on whole rock major and trace elements, Sr–Nd isotopes, zircon U–Pb dating, Hf–O isotopic compositions of the Qulong ore-bearing and barren adakites. All the Qulong adakites studied here have low MgO (<2 wt.%), high K_2O (between 2 wt.% and 6 wt.%), with K_2O/Na_2O ratios ranging from 0.2–2.0. The SiO_2 contents are mostly higher than 64 wt.%. These are dramatically different from ore-forming adakites in the circum-Pacific region and other places in general. Ore-bearing adakites have systematically higher SiO_2 and K_2O compared with barren ones, likely due to the addition of Si and K during alteration and mineralization. Magmatic zircons from these two series of intrusions have U–Pb ages of 16.6 ± 0.5–17.0 ± 0.6 Ma and 16.7 ± 0.3–17.4 ± 0.4 Ma, respectively, which are identical to each other within analytical errors but are systematically older than although marginally overlap with the Re–Os isochron ages of 15.36 ± 0.21–16.41 ± 0.48 Ma. The Qulong porphyries have geochemical characteristics of typical adakites, with Sr = 259–1195 ppm, Y = 1.91–9.12 ppm, Yb = 0.2–0.92 ppm, Sr/Y = 49–202 ppm, and $(La/Yb)_n$ = 13–49 for both ore-bearing and barren adakites. In a Sr/Y versus $(La/Yb)_n$ diagram, most of the samples plot in the low part of circum-Pacific field, close to the field defined by Dabie adakites. Some of the ore-bearing adakites even plot in the Dabie adakite field, indicating that both slab melts and lower continental crust melts have been involved. Zircons from the ore-bearing adakites have $\delta^{18}O$ ranging from 5.1 to 7.3‰ (average 6.4‰) and εHf(t) from 1.9 to 10.4‰, which plot close to MORB. Similarly, zircons from the barren adakite have $\delta^{18}O$ ranging from 4.0 to 7.4‰ (average 6.3‰) and εHf(t) from 5.6 to 9.3‰, mostly plotting close to MORB values, too. In-situ zircon Hf–O isotopic measurements for the most samples yield a binary mixing trend between mantle- and crustal-derived melts, with mantle-related sources as the main contributor. Whole-rock Sr–Nd isotopes also show small variations, with $(^{87}Sr/^{86}Sr)_i$ = 0.704904–0.705053 and εNd(t) = −0.04–0.61. The dramatic differences between Qulong and circum-Pacific adakites suggest that either Qulong porphyry Cu deposit is unique, or the ore-bearing adakites are not the ore-forming porphyry. Considering the identical geochemical characteristics of the ore-bearing and barren adakites, the textures (some samples are not porphyry) and the systematically older ages compared to Re–Os isochron ages, the latter is preferred. In contrast to earlier adakitic granites, recently studied porphyries in the central phase of the Qulong deposit have zircon U–Pb ages identical to the Re–Os ages, and thus are more likely to be the ore-forming porphyry. All these suggest that slab melting rather than partial melting of Gangdese arc materials is responsible to the Qulong porphyry Cu deposit.

1. Introduction

Numerous studies have been carried out on Miocene (26–10 Ma) adakitic porphyries in the Gangdese belt (Chung et al., 2003, 2009; Gao et al., 2003b, 2007b, 2010b; Guo et al., 2007; Hou et al., 2003,

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2004b; Qu et al., 2004, 2007; Xu et al., 2010). These adakites extend roughly east-westward along the Gangdese belt, to the north of the Yarlung Tsangpo suture zone in southern Tibetan Plateau (Meng et al., 2003b; Zheng et al., 2004). It is the largest Cu–Mo mineralization belt in China.

Porphyry Cu (Au) deposits are one of the most important economic mineral associations (Cooke et al., 2005; Sillitoe, 2010; Sun et al., 2013, 2015), mostly distributed along convergent margins, such as the circum-Pacific belt and the Tethys belt (Cooke et al., 2005; Qu et al., 2001; Sillitoe, 1997; Sun et al., 2010, 2011, 2012b). Considering that porphyry Cu deposits are usually closely associated with adakites (Ling et al., 2009, 2011, 2013b; Oyarzun et al., 2001; Sun et al., 2011, 2013), it is very important to study the origin and relationship of adakites with the Gangdese porphyry copper deposits.

Various models have been proposed for the petrogenesis of these adakites (Chung et al., 2003; Gao et al., 2003b, 2007b; Guo et al., 2007; Hou et al., 2004b; Li et al., 2011; Qu et al., 2004, 2007; Xu et al., 2010), including: (1) partial melting of the subducted Neotethyan oceanic crust (Gao et al., 2003b; Hou et al., 2003, 2004b; Qu et al., 2004); (2) partial melting of the thickened Lhasa mafic lower crust (Chung et al., 2003, 2005; Guo et al., 2007; Li et al., 2011); (3) partial melting of an upper mantle source metasomatized by slab-derived melts (Gao et al., 2007b); (4) partial melting of the subducted Indian continental crust beneath the southern Lhasa terrane (Xu et al., 2010).

The debate is partial because Qulong and also other adakites that host porphyry deposits suffered pervasive hydrothermal alteration that has modified their primary textural and chemical characteristics (Xiao et al., 2012a; Yang et al., 2009; Zheng et al., 2004). Zircon is an accessory mineral commonly found in intermediate-acid magmatic rocks, and it is highly resistant to disturbance by hydrothermal alteration and weathering, which can preserve information on magma composition and thus is an excellent tool to trace the magma source through trace element and isotope information (Watson and Cherniak, 1997).

In this paper, we analyze the trace elements and in-situ U–Pb and Hf–O isotopes in zircon from ore-bearing and barren adakites from the Qulong deposit. Combined with whole rock geochemistry, Sr–Nd isotopes, zircon U–Pb ages, trace elements and Hf–O isotope compositions were studied, aiming at better constraints on the formation of these adakites and their association with the porphyry mineralization.

2. Geological background and sample descriptions

2.1. Regional geology

The Tibet plateau, the largest plateau on Earth, is part of the Alps–Himalayan orogenic belt (Allegre et al., 1984; Chung et al., 1998, 2005; Yin and Harrison, 2000), formed due to the continental collision and subduction of India underneath Eurasia (Allegre et al., 1984; Chung et al., 2012; Yin and Harrison, 2000). It is mainly composed of four blocks, which, from north to south, include: the Songpan–Ganzi flysch complex belt, the Qiangtang block, the Lhasa terrane and the Himalayas (Yin and Harrison, 2000: Fig. 1A). The Qiangtang and Lhasa blocks, which constitute the main body of the Tibet plateau, were derived from the northern margin of Gondwana continent, and its evolution history involves a series of plate tectonics processes, i.e., break-up, drift, and attachment of the Paleozoic and Mesozoic micro-blocks to the southern margin of the Asian continent (Audley-Charles et al., 1988; Yin and Harrison, 2000; Zhu et al., 2011). The Qiangtang block is bounded to the northwest by the Tarim block, and to the northeast by the Songpan–Ganzi mixtite belt and the Yangtze block. The Lhasa terrane, located between the Bangonghu–Nujiang suture zone and the Yarlung Tsangpo suture zone of the Late Jurassic and the Early Cretaceous, is a huge tectonic-magmatic belt (Chang and Zhang, 1973) with large Cretaceous and Cenozoic batholiths. The Lhasa terrane in the southern Tibetan Plateau is divided into northern, central, and southern subterranes (Fig. 1A), separated by the Shiquan River–Nam Tso Mélange Zone and the Luobadui-Milashan Fault (Pan et al., 2006; Zhu et al., 2012b).

In southern Tibet, the Lhasa terrane consists mainly of the Gangdese orogenic belt, which was resulted from the northward subduction of the Neo-Tethyan oceanic lithosphere beneath Asia and the subsequent India–Asia collision (Yin and Harrison, 2000). The Gangdese orogenic belt is composed mainly of Late Paleocene–Early Eocene (60–40 Ma) Linzizong Formation volcanic rocks and Cretaceous–Tertiary (120–24 Ma) granite batholiths (Allegre et al., 1984; Mo et al., 2008). According to previous studies, multiple metallogenic events occurred in the different tectonic settings of the Indo-Asian collision, identified as the main-collisional convergent setting (~65–41 Ma), the late-collisional transform setting (~40–26 Ma), and the post-collisional crustal extension setting (~25–0 Ma) (Chung et al., 2005; Hou et al., 2006). The Cenozoic porphyries were emplaced into the same terrane occupied by the older Gangdese granite batholiths, creating a narrow porphyry copper metallogenic belt north of and along the Yarlung Tsangpo suture zone. Contained within this metallogenic belt are scores of Cenozoic porphyry Cu (Mo) deposits and smaller ore occurrences.

With several ore deposits, i.e., Qulong, Jiama, Chongjiang, Tinggong, Bangpu and Zhunuo et. al., discovered in recent years, south Gangdese has become a huge porphyry Cu–Au–Mo deposit belt, and has the potential of becoming the largest Cu–Au–Mo resource in China (Qu et al., 2001). These deposits are of Cenozoic age, with most significant porphyry Cu–Mo ore bodies forming in the Miocene (14–17 Ma) (Meng et al., 2003a, 2004; Rui et al., 2003; Wang et al., 2012; Ying et al., 2010).

The Qulong porphyry copper deposit, located in the east part of the Gangdese belt (latitude 29°36′–29°40′ N, longitude 91°33′–91°37′E), about 50 km east of Lhasa city (Fig. 1A), was found by the Regional Geological Team of the Tibetan Geological Survey. By 2009, Qulong porphyry deposit, with reserves of 10.6 Mt Cu@0.5% and 0.5 Mt Mo@0.03% (Xiao et al., 2012a), together with the adjacent Jiama porphyry–skarn deposit, had become the largest porphyry–skarn type copper mining area in China.

2.2. Geology of the deposit

The Qulong deposit is hosted in the Jurassic Yeba Formation. Three recognizable nearly east–west-trending lithologic units of the Jurassic Yeba Formation, with an age of 174.4 Ma (Dong et al., 2006), were present in the Qulong district (Fig. 1B): (1) A basal member, consisting of andesitic crystal tuff and ignimbrite with intense hornfels, contacts metamorphism mainly in the south-central part of the district. (2) A middle member, comprising medium to thin limestone and laminated slate with propylitization metamorphism, is found largely to the north of the deposit. (3) An upper member consisting of sericitic slate, tuff and small amounts of rhyolite, is distributed throughout the mapped area. For more details, please refer to Yang et al. (2009).

The magmatic rocks are of Jurassic and Miocene ages and include: (1) Middle Jurassic ductilely deformed granite porphyry, (2) Miocene granodiorite–adamellite, (3) Miocene monzogranite porphyry related to the two main stages of mineralization, and (4) diorite porphyry associated with a late stage of mineralization (Fig. 1B).

2.2.1. Magmatic rocks

2.2.1.1. Jurassic intrusive rocks. Mineralization in the Jurassic porphyries, characterized by abundant pyrite veins and quartz–sericite alteration with local minor epidote alteration, tends to be fracture controlled. Sulfide mineral-bearing veins are typically planar and composed primarily of quartz and pyrite at all exposed levels with sericite alteration selvedges. The whole rock chemical analyses of the porphyry show that the rock contains about 74% to 82% SiO_2, 3.3% to 6.5% K_2O and 2.4% to 4.3% Na_2O, and thus belongs to high-K calc-alkaline series (Yang et al.,