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Subduction metasomatism and collision-related metamorphic dehydration controls on the fertility of porphyry copper ore-forming high Sr/Y magma in Tibet

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ABSTRACT

Processes generating fertile magma and associated porphyry Cu deposits in post-collision tectonic settings remain uncertain. Dabu, located in the Gangdese porphyry Cu belt of southern Tibet, is a typical porphyry Cu–Mo deposit that formed in a post-collision setting. The deposit records two stages of magmatism: an Eocene (46 ± 1 Ma) barren monzogranite (EG); and a fertile Miocene (15 ± 1 Ma) monzogranite porphyry (MMP). These intrusions have similar Sr–Nd ($^{87}Sr/^{86}Sr_{(i)} = 0.70514$ to 0.70573, $\varepsilon Nd(t) = -2.78$ to $+0.77$) and zircon Hf ($\varepsilon Hf(t) = +3.46$ to $+8.85$) isotopic compositions that fall within the range of the Palaeocene–Eocene Gangdese Batholith and the coeval Linzizong volcanics and plot on a mixing line between Tethyan basalts and Indian Ocean pelagic sediments. These features, coupled with the variable Sr/Nd, Sr/Th, Ba/Th, and Rb/Y ratios of the intrusions, are indicative of a common source involving basaltic lower crustal melts underplated during the Palaeocene and Eocene. The basaltic material was sourced from a mantle wedge that was metasomatized by Neo-Tethyan slab-derived fluids and oceanic sediments. The MMP, however, formed under a higher magmatic oxygen fugacity than did the EG, as indicated by their higher zircon Ce^{4+}/Ce^{3+} ratios (87-1112) and higher fO_2 values ($\Delta FMQ = 5$), determined using ilmenite–magnetite mineral pairs. The decompression and discharge of SO_2 during the Linzizong volcanic event and the fractionation of magnetite could account for the low oxygen fugacity ($Ce^{4+}/Ce^{3+} = 58$–164; $\Delta FMQ = -0.3$) of the EG as well the limited development of porphyry deposits associated with the Gangdese Batholith.

The MMP and Miocene mineralization-related intrusions within other Gangdese porphyry Cu deposits have high Sr/Y and V/Sc ratios and a negative correlation between Dy/Yb and SiO_2, all of which are indicative of the crystallization of hornblende from a hydrous mafic melt. The EG and Gangdese Batholith, however, have low Sr/Y and V/Sc ratios and decreasing Sr concentrations over a wide range of SiO_2 contents, indicating that these intrusions formed from dry melts that had undergone significant plagioclase fractionation. Late-crystallized hornblende is generally present as small crystals within early formed feldspar phenocrysts in the EG, which is in good agreement with a rapid increase followed by a decrease in Y and Dy concentrations at ~60 wt.% SiO_2. In addition, apatite in MMP has F (2.66–3.72%) and Cl (0.06–0.53%) volatile contents that are higher than those of apatite from EG (0.85–1.50% F and 0.02–0.03% Cl). These geochemical and mineralogical characteristics suggest that EG formed from a relatively dry magma with $<4.0\%$ H_2O, whereas MMP formed from a more hydrous magma with $>5.5\%$ H_2O. It is here proposed that long-lived subduction caused the high oxygen fugacity conditions of the arc magma by adding oxidized components to the sub-arc mantle in addition to F, Cl, S, and Cu. Long-term metamorphic dehydration resulted from the India–Asia collision, and subsequent crust thickening and shortening was responsible for the high water contents by continuously replenishing the basaltic melts at the base of the lower crust. Both subduction-related metasomatism and late-collision-related metamorphic dehydration controlled the genesis of fertile magma that formed the post-collision porphyry Cu–Mo deposits of southern Tibet.

1. Introduction

Porphyry Cu deposits are commonly found in volcanic-arc tectonic settings above subduction zones and are generally associated with intermediate to felsic calc-alkaline magma (Richards, 2003, 2009; Seedorff et al., 2005; Sillitoe, 2010; Hou et al., 2011; Deng et al., 2014a,b). Recent

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research, however, has identified numerous porphyry-type deposits that formed in non-arc or post-collision settings, including porphyry deposits in the Alpine–Himalayan Tethyan Orogen such as the Kerman porphyry belt in Iran, and the Gangdese, Yulong and Ailaoshan porphyry belts of Tibet and Yunnan (Hou et al., 2009; Shafiei et al., 2009; Richards et al., 2012; Lu et al., 2013, 2015; Mao et al., 2014; Richards, 2014; Zheng et al., 2015). A variety of models have been proposed to explain the source of the magma that formed these post-collision porphyry Cu deposits. Hou et al. (2011) suggest that the adakite-like magma is derived from the partial melting of a thickened juvenile mafic lower crust or a delaminated thickened lower crust and that the breakdown of amphibole within these eclogite and garnet amphibolite sources contributed to the generation of the highly oxidized and hydrous fertile magma that formed non-arc porphyry Cu deposits. Richards (2009, 2011b) suggests that the fertile magma that formed post-subduction porphyry deposits is probably the product of the remelting of previously subduction-modified mantle lithosphere or hydrous lower-crustal cumulates residual from the first stages of arc magmatism, which stresses the inheritance of previously subduction-associated arc magma features with abundant F, Cl, S and Cu, and high oxidation states (Shafiei et al., 2009; Li et al., 2011; Wu et al., 2014).

Lee et al. (2012) propose that remelting of Cu-rich pyroxenite cumulates triggered by magnetite crystallization and the onset of sulfide saturation in the deep roots of arcs are important steps in the generation of porphyry Cu deposits. The authors also emphasize that the magmatism-related thickness and maturity of continental arcs controls on the concentration of Cu in the resulting magma, rather than sourcing any Cu from the mantle or subducting slab (Chiaradia, 2013; Lee, 2013). Lu et al. (2015) propose that the ore-forming high Sr/Y porphyries in southern Tibet are derived from high-pressure differentiation of hydrous mafic partial melts of the mantle, rather than from the melting of a thickened mafic lower crust.

The high oxygen fugacity conditions during the formation of primary melts and the high water content of these melts are both critical for the generation of fertile magma and associated porphyry deposits (Sillitoe, 2010; Richards, 2011a,b; Sun et al., 2013a, 2015; Loucks, 2014). The reason for this is that water, as the most abundant volatile component, can lower the solidus of silicate assemblages, leading to the formation of a magmatic–hydrothermal ore-forming system. Such a system is dominated by hydrous melts and a water-rich volatile phase at shallow crustal levels with the decrease in temperature and pressure (Wolf and Wyllie, 1994; Eichelberger, 1995; Burnham, 1997; Richards, 2011b; Liu et al., 2012). In addition to water, chloride and sulfur are also critical components of economic porphyry Cu deposits, because chloride controls the partitioning of Cu and other base metals. Furthermore, sufficient chloride can transport large quantities of metals as chloride complexes in a hydrothermal fluid, whereas sufficient initial sulfur in magma can mobilize metals such as Cu and Mo from the asthenospheric mantle wedge above subduction zones and yield a sulfur-rich aqueous fluid (Cline and Bodnar, 1991; Cline, 1995; Pokrovski et al., 2008; Richards, 2015). A relatively high oxidation state of magma ensures that the bulk of the sulfur dissolved in the melt is present as sulfate, resulting in the retention of sulfide-compatible (i.e. chalcophile) elements in the evolving magma until they are partitioned into exsolving hydrothermal fluids (Carroll and Rutherford, 1985; Richards, 2003).

The Gangdese metallogenic belt in Tibet contains porphyry Cu–Mo deposits that formed in a post-collisional setting, such as Qulong, Zhunuo, and Dabu (Zheng et al., 2004, 2007b, 2014a; Yang, 2008; Wu et al., 2014). The belt was subjected to a long-lived northward subduction of the Neo-Tethyan oceanic slab and the subsequent collision of the Indian and Asian plates (Zhu et al., 2013). Subduction-associated arc magma represented by the Palaeocene–Eocene Gangdese Batholith, however, has little potential of forming economic porphyry Cu deposits, especially when compared with Miocene intrusions in the area (Wen, 2007; Ji et al., 2009). Wang et al. (2014b,c) studied the temporal and geochemical evolution of igneous rocks along the eastern part of the Gangdese magmatic belt in southern Tibet. They conclude that increasing magmatic water volume and oxygen fugacity from Palaeocene–Eocene to the Oligocene–Miocene magmatism is essential in the formation of post-subduction porphyry Cu deposits. Yang et al. (2015), however, suggest a mixing model involving ultra-potassic melts and melts derived from the juvenile lower crust to explain the high K_2O concentrations of adakite-like rocks in the Qulong porphyry Cu deposit. The authors emphasize that the water necessary for the formation of the porphyry Cu systems in continental collision zones is generally added by ultra-potassic magma instead of dehydrating slabs. These possibilities show that understanding the key factors and processes that control the fertility of Miocene mineralization-related intrusions in southern Tibet and whether the magma is linked to earlier subduction-related processes can provide important constraints on the genesis of post-collision porphyry deposits and guide mineral exploration in the area.

This manuscript presents a detailed petrographic, mineralogical, and geochemical comparison of a barren Eocene monzogranite (EG) with a fertile Miocene monzogranite porphyry (MMP) associated with the Dabu porphyry Cu–Mo deposit in southern Tibet. The oxidation state of the magma associated with the intrusions and the water contents of their initial melts are discussed here. This is followed by the comparison between the data collected in this study and published data for the Miocene ultra-potassic rocks in southern Tibet, the Gangdese Batholith, and the coeval Linzizong volcanics to further constrain the relationship and differences among these igneous rocks (Miller et al., 1999; Gao et al., 2007; Mo et al., 2007, 2008; Wen, 2007; Zhao et al., 2009; Ji et al., 2012; Lee et al., 2012; Liu et al., 2014; Wang et al., 2014a). These data are finally used to develop a new petrogenetic model that can account for the formation of both barren and fertile intrusive rocks associated with the Gangdese porphyry Cu deposits (GPCD).

2. Regional geology

The Tibetan Plateau is part of the Alpine–Himalayan orogenic belt and is divided into the Songpan–Ganzi, Qiangtang, Lhasa, and Himalaya terranes (Fig. 1a; Yin and Harrison, 2000). The Lhasa Terrane, also called the Gangdese orogenic belt, is a ~2500 km long tectono-magmatic belt (or domain) that is ~150–300 km wide and bound by the Bangong–Nujiang and Indus–Yarlung Zangbo sutures (Fig. 1b; Pan et al., 2006). The terrane is divided into northern, central, and southern domains that are separated by the Shiquanhe–Nam Tso Mélange Zone and the Luobadui–Milashan Fault (Fig. 1b; Zhu et al., 2011a). The central Lhasa Domain contains Precambrian rocks and either represents a microcontinent derived from the Australian Gondwana or has rifted off the Indian Gondwana (Yin and Harrison, 2000; Zhu et al., 2011b). In contrast, the southern and northern domains are characterized by juvenile crust with a locally preserved Precambrian crystalline substrate and were more recently accreted during their movement across the Tethyan Ocean (Ji et al., 2009; Zhu et al., 2011a; Hou et al., 2015a).

The Lhasa Terrane consists of Precambrian crystalline rocks unconformably overlain by Paleozoic to Mesozoic marine sedimentary units and arc-type volcanics, abundant Mesozoic and Cenozoic intrusions, and three medium- to high-grade metamorphic belts (Yin and Harrison, 2000; Pan et al., 2006; Zhu et al., 2013; Zhang et al., 2014b). Recently, authors have suggested that the eastern part of the terrane underwent amphibolite and granulite facies metamorphism during the Mesozoic and Cenozoic (e.g. Dong et al., 2010; Zhang et al., 2014b). The Gangdese Batholith and Linzizong volcanics formed as an Andean-style magmatic-arc along the southern flank of the terrane (Fig. 1b). These units are attributed to the northward subduction of Tethyan oceanic lithosphere from the Jurassic to the Palaeogene (Mo et al., 2008; Wen et al., 2008; Ji et al., 2009; Lee et al., 2012).

Post-collisional ultra-potassic rocks are located in the western part of the Lhasa Terrane, with ages ranging from 24 to 8 Ma, and commonly crop out along northward trending normal faults (Miller et al., 1999; Gao et al., 2007; Zhao et al., 2009; Liu et al., 2013; Wang et al., 2014a).