Economic Geology, v. 110, pp. 1861–1878

Oxidation Condition and Metal Fertility of Granitic Magmas: Zircon Trace-Element Data from Porphyry Cu Deposits in the Central Asian Orogenic Belt

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Abstract

The Central Asian Orogenic Belt (CAOB) hosts a number of porphyry Cu deposits, all associated with calc-alkaline granitic rocks and ranging in size from giant to small. Major- and trace-element compositions of whole rocks and zircons grains were measured from 13 ore-bearing intrusions in nine porphyry Cu deposits (with 0.6 to 12 Mt Cu), including Bozshakol, Nurkazghan, Kounrad, Borly, Aktogai, and Koksai in Kazakhstan, Baogutu, and Tuwu-Yandong in China, and Erdenet in Mongolia. All zircon grains show high Ce^{4+}/Ce^{3+} ratios, ranging from 29 to 592. Higher Ce^{4+}/Ce^{3+} ratios are recorded at a given crystallization temperature from deposits with larger Cu tonnages. Large (>4 Mt Cu) and intermediate (1.5–4 Mt Cu) size porphyry Cu deposits are associated with granitic intrusions that have zircons with Ce^{4+}/Ce^{3+} ratios greater than 120. There is also a clear relationship between calculated log (f_{O_2}) values and the size of deposits, with NNO + 2 values separating large and intermediate porphyry deposits from small deposits. The data of zircon Ce^{4+}/Ce^{3+} ratios and associated oxygen fugacity values in magma from ore-bearing intrusions indicate that more oxidized magmas are associated with the formation of larger porphyry Cu deposits. Such a conclusion may potentially be used in regional exploration for porphyry Cu deposits in the CAOB.

Introduction

Porphyry Cu deposits form in association with subduction-related oxidized magmas of intermediate to felsic composition (e.g., Ishihara, 1977; Dilles, 1987). This is consistent with the higher capacity of oxidized magmas to transport metals and S from the mantle to shallow crustal levels (Hattori and Keith, 2001; Richards, 2003; Cooke et al., 2005; Sillitoe, 2010).

Oxidation conditions of magmas may be evaluated based on whole-rock Fe^{3+}/Fe^{2+} ratio, compositions of Fe-Ti oxides and the presence of minerals indicative of high f_{O_2}, such as magnetite, hematite, and anhydrite. Geobarometry using oxide and sulfide minerals is not applicable to plutonic rocks due to the fast re-equilibration of such minerals at low temperatures (e.g., DeHoog et al., 2004). Furthermore, extensive hydrothermal alteration of porphyry Cu deposits commonly obliterates the primary minerals and whole-rock chemical compositions. Zircon is an exceptionally robust mineral that retains its primary chemical and isotope compositions from the time of crystallization (Cherniak et al., 1997), and provides chemical information related to parental magmas.

Among the rare earth elements (REE), Ce forms Ce^{4+} and Ce^{3+} under terrestrial conditions, and zircon preferentially incorporates Ce^{4+} into the Zr^{4+} site of its structure. Thus, zircon grains formed in an oxidized magma show positive Ce anomalies in chondrite-normalized plots of REE. Since the degrees of positive anomalies are related to the oxidation conditions of the parental magma, this Ce^{4+}/Ce^{3+} ratio has been used to indicate the oxidized nature of parental magmas of igneous rocks associated with porphyry deposits in northern Chile (Ballard et al., 2002), Tibet (Liang et al., 2006), and the Qinling (Han et al., 2013) and Zhejiang districts (Qiu et al., 2013) in China.

The Central Asian Orogenic Belt (CAOB) has a number of porphyry Cu deposits that have a significant difference in size, from the giant Oyu Tolgoi (>36 Mt Cu, 1,432 t Au; Yakubchuk et al., 2012) and Kal'makyr-Dalnee (>24 Mt Cu, >2,250 t Au; Singer et al., 2008) deposits, to small deposits at Borly (0.6 Mt Cu; Seltmann et al., 2004) and Baogutu (0.6 Mt Cu; Shen et al., 2010a). This wide range in size of numerous porphyry Cu deposits in the CAOB presents an opportunity to evaluate relationships between oxidation state and metal fertility of granitic magmas.

We examine the Ce^{4+}/Ce^{3+} ratio of zircon in the intrusive rocks from nine porphyry Cu deposits in the CAOB, including large deposits with 4 to 12 Mt Cu at Bozshakol, Nurkazghan, Kounrad, Aktogai, and Erdenet; intermediate-size deposits (of 4 to 1.5 Mt Cu at Koksai and Tuwu-Yandong, and small deposits at Borly and Baogutu with Cu less than 1.5 Mt (Fig. 1). The size of the Cu deposit (Table 1) is defined as the total metal produced in the past plus indicated reserves. This paper presents the results from the CAOB and compares those with the data from other deposits and barren granitoids.

Ore Deposits

Bozshakol

The Bozshakol deposit is situated in the northwestern part of central Kazakhstan (Fig. 1) with contained metal of 4.1 Mt Cu and 163 t Au (Table 1). The Bozshakol deposit is associated with late Cambrian tonalite porphyry dikes that

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Submitted: June 23, 2014
Accepted: April 25, 2015