Copper isotope evidence for a Cu-rich mantle source of the world-class Jinchuan magmatic Ni-Cu deposit

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ABSTRACT

A Cu-rich mantle source may play a key role in generating giant magmatic Ni-Cu deposits worldwide, but evidence for the source’s Cu enrichment and its mechanism is still rare. Copper isotopes can provide novel and direct insights into this issue since metasomatism that causes Cu enrichment in the mantle is commonly associated with a huge Cu isotope fractionation. Here we present the first Cu isotopic study on the world-class Jinchuan magmatic Ni–Cu deposit in China, including disseminated, net-textured, and massive sulfides. The disseminated and net-textured sulfides have variable δ65Cu values (+0.36 ± 0.38‰, n = 42), which are higher than those of massive sulfides (~0.44 ± 0.28‰, n = 11). The country rocks have a narrow δ65Cu range of 0.21 to 0.23‰, which is unlikely to have caused the large δ65Cu variations. The absence of a relationship between δ65Cu and whole-rock Cu contents rules out the possibility of surface weathering and diffusion-driven processes. Furthermore, the lack of correlation between δ65Cu and whole-rock Cu/Ni and Pd/Ir ratios excludes large Cu isotopic variations as a result of the progressive evolution of parental magma or sulfide melt. Numerical modeling indicates that the initially segregated sulfide melt has a mean δ65Cu of 0.44 ± 0.02‰ (2SD). Sulfide-liquid fractionation could have contributed to the enrichment of δ65Cu in the Cu-rich net-textured sulfides and depletion of δ65Cu in massive sulfides, respectively. The fractionated sulfide melts were fragmented and assimilated by new magma pluses, and consequently, the new segregated sulfide melts acquired lighter and more variable δ65Cu values in comparison with the initially accumulated sulfide melts. The estimated Cu isotopic composition of parental magmas for the Jinchuan Ni-Cu deposit is 0.54 ± 0.22‰ (2SD), which is up to ~0.5‰ higher than the mantle value. Copper transportation from oxidized subducted slabs to mantle peridotites and/or dissolution of Cu-bearing sulfides in the mantle caused oxidative breakdown and reprecipitation of sulfides and shifted the hybridized mantle source toward heavy δ65Cu as previously observed in mantle xenoliths. Our study, therefore, suggests that the source’s pre-enrichment is a key step in the generation of giant magmatic Ni-Cu deposits.

Keywords: Copper isotopes, initial Cu enrichment, mantle metasomatism, magmatic Ni-Cu deposits

INTRODUCTION

Magmatic Ni–Cu deposits have produced some of the world’s most valuable economic metals (Naldrett 2010; Barnes and Lightfoot 2005), including ~56% of the world’s Ni production, ~3% of Cu production, and >96% of platinum-group element (PGE) production. The generation of magmatic Ni-Cu deposits can be envisaged as four stages: (1) mantle melting to generate primary magmas; (2) minor sulfide removal or olivine crystallization during magma ascent; (3) significant sulfide segregation and coalescence in a dynamic magmatic conduit; and (4) internal fractionation of sulfide melt (Naldrett 2010). Mantle melting to generate primary magmas is the first and a key step, even though an efficient collection of metals by sulfides promotes full maturity of magmatic Ni-Cu deposits at shallow crustal levels (Barnes and Lightfoot 2005; Naldrett 2010). Especially, metasomatism is thought to introduce metals into the mantle via slab-derived fluid and/or melts (Fiorentini and Beresford 2008), and generate a metal-rich mantle source (e.g., Richardson and Shirey 2008; Griffin et al. 2013; Mungall and Brenan 2014). To date, geochemical evidence for a metal-rich mantle source largely relies on trace elements (e.g., Pt/Pd) and radiogenic Sr-Nd-Re-Os isotopes instead of isotopic systematics of the ore-forming metals (e.g., Maier and Barnes 2004; Zhang et al. 2008; Richardson and Shirey 2008). Therefore, possible metal enrichment in the mantle sources of magmatic Ni-Cu deposits is still poorly constrained, in particular from ore-forming metal isotopes.

In recent years, Cu isotope behaviors during mantle metasomatism, partial melting of mantle sources, and magma differentiation have been well established (e.g., Liu et al. 2015, 2019; Savage et al. 2015; Huang et al. 2016a, 2017; Wang et al. 2019). Oxidative breakdown and reprecipitation of sulfides during mantle metasomatism can cause significant Cu isotope fractionation, as widely observed in mantle peridotites and pyroxenites (e.g., Liu et al. 2015; Wang et al. 2019). For instance, some metasomatized mantle peridotites have much higher δ65Cu values (up to +1.82‰) than that of the primitive mantle (0.06 ± 0.20‰; Liu et al. 2015). High δ65Cu values in some of orogenic and xenolith peridotites (up to +0.61‰) were

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