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Geochemical and thermodynamical modeling of magmatic sources and processes for the Xiarihamu sulfide deposit in the eastern Kunlun Orogen, western China

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ABSTRACT

Magmatic sulfide deposits in subduction-collision settings are genetically related to oxidized and hydrous magmas, where the degree of partial melting, fractional crystallization, and sulfide saturation are all expected to differ significantly from those in dry and reduced magmas associated with most giant magmatic sulfide deposits in intracratonic settings. This study provides petrological and geochemical data as well as multiple modeling approaches for the post-collisional Xiarihamu magmatic sulfide deposit of the eastern Kunlun Orogen to investigate melting mechanism and magmatic differentiation in an oxidized and hydrous magmatic system. Petrographical observations and whole-rock geochemistry suggest that the olivine orthopyroxenite, orthopyroxenite, websterite and gabbronorite in the Xiarihamu complex were cumulates. Pressures estimated from clinopyroxene and hornblende compositions and oxygen fugacities from hornblende and biotite compositions further suggest that these cumulates crystallized under moderate- to high-pressure, oxidized conditions. The Xiarihamu parental magma was high-MgO basalt as evidenced by multiple modeling methods. This parental magma was generated from a metasomatized mantle peridotite source in the spinel stability field with moderate melting degrees and then experienced a fractional crystallization process with a first iron-enriched and then silica-enriched trend under moderate-high pressures to form the observed crystallization sequence and mineral compositions. Minor amounts of wall rock assimilation during magmatic evolution were supported by Sr-Nd isotopic modeling. Sulfide saturation previously proposed by crustal sulfur addition at Xiarihamu was not straightforward but was likely caused by an oxygen fugacity decrease triggered by magmatic differentiation.

1. Introduction

Magmatic sulfide deposits currently account for ~56% of the world's Ni production and over 96% of platinum-group element (PGE) production (Mudd and Jowitti, 2014). Most giant magmatic sulfide deposits occur in intracratonic settings associated with relatively dry and reduced magmatic systems produced by mantle plume activity (Barnes et al., 2017; Naldrett, 2010). In this system, the degree of partial melting is believed to exert a strong control on the Ni-Cu-PGE contents of mantle-derived magmas because of the different partitioning of these elements between sulfides and silicates (Arndt et al., 2005; Wang et al., 2018). Low-degree partial melting should lead to very low abundances of Pd-group PGE (PPGE) and low to moderate abundances of Ni, whereas high degrees of partial melting should produce low abundances of PPGE and high abundances of Ni and Ir-group PGE (IPGE) (Naldrett, 2010). The mantle plume-related oceanic and continental flood basaltic magmas mainly crystallize plagioclase-dominated assemblages at low-moderate pressures, which drive the evolution of magmatic liquids along the tholeiitic differentiation trend, resulting in an iron enriched trend with decreasing magnesium contents in the melt (Husen et al., 2016). The solubility of sulfides in basaltic magmas increases with decreasing pressure and thus basaltic magmas emplaced at relatively shallow depths are unlikely to be saturated in sulfides (Jégo et al., 2016; Mavrogenes and O'Neill, 1999). It has long been debated and discussed that addition of crustal sulfur by direct melting and assimilation of wall rocks and xenoliths is the most

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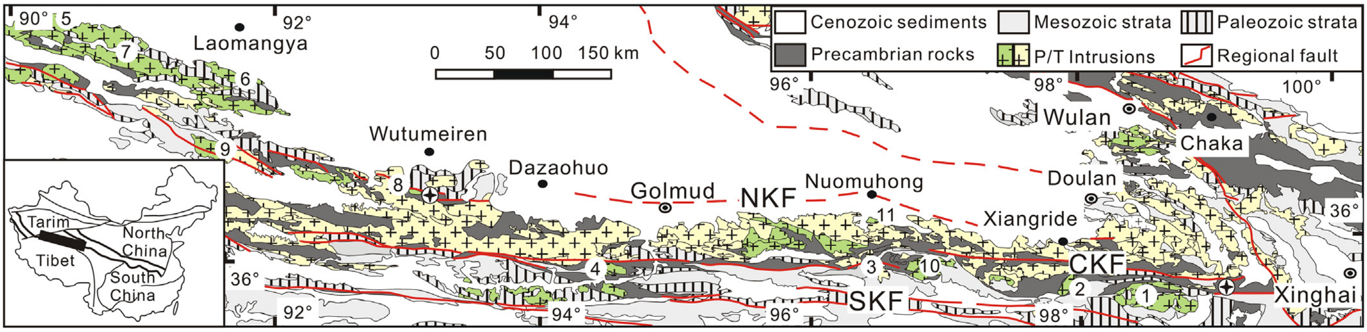

Fig. 1. Geological map of the eastern Kunlun Orogen showing the distribution of the Paleozoic (P) and Triassic (T) intrusions. Subduction-related intrusions: 1-Zhiyu granite, 447 Ma (Zhou et al., 2016), 2-Kekesha quartz diorite, 515 Ma (Zhang et al., 2010), 3-Huxiaoqin hornblende diabase, 438 Ma (Liu et al., 2013), 5-Wutoushan gneissic granite, 485 Ma, 6-Shuangshixia granite, 462 Ma and 7-Naitoushan diorite, 446 Ma (W. Li et al., 2013b). Main collisional to post-collisional intrusions: 4-Wanbaogou A-type granite, 441 Ma (Wang et al., 2012), 8-Xiarihamu A-type granite, 391 Ma (Wang et al., 2013), 9-Kayakedengtage I-type granite, 394 Ma (Chen et al., 2006), 10-Helegangnaren A-type granite, 425 Ma (R.B. Li et al., 2013a), 11-Yuejinshan S-type granite, 407 Ma (Liu et al., 2012). Stars represent high-pressure eclogites with the ages of 450–430 Ma at Wenquan in the east (Meng et al., 2015) and of 411 Ma at Xiarihamu in the west (Qi et al., 2014). NKF, the Northern Kunlun Fault, CKF, the Central Kunlun Fault, SKF, the Southern Kunlun Fault. Insert is the tectonic divisions of China showing the location of the eastern Kunlun Orogen.

efficient process to lead to sulfide saturation in this system (i.e., more efficient than fractional crystallization, addition of volatiles, magma mixing, and crustal assimilation without sulfur addition; Keays and Lightfoot, 2010; Ripley and Li, 2013, 2017; Robertson et al., 2015).

A number of magmatic sulfide deposits also occur in subduction-collision settings (Barnes et al., 2017; Naldrett, 2010), including those in the Central Asian Orogenic Belt (Gao et al., 2013; Zhao et al., 2016). They are economically subordinate but may be potentially significant with the recent discovery of the giant Xiarihamu magmatic sulfide deposit in the eastern Kunlun Orogen in western China (C.S. Li et al., 2015a; Peng et al., 2016; Song et al., 2016; Zhang et al., 2016). Parental magmas related to such sulfide deposits in subduction-collision settings are generally considered to be derived from the mantle wedge metasomatized by slab-derived fluids and melts (Gao et al., 2013; Song and Li, 2009). As such, both the parental magmas and the mantle wedge are commonly believed to be hydrous and oxidized (Richards, 2015). In this scenario less (~6%) melting in the mantle wedge may be required and high degrees of partial melting are unlikely (Wilkinson, 2013). A hydrous and oxidized arc basaltic magma should initially crystallize the mineral assemblage dominated by pyroxenes and amphibole instead of olivine and plagioclase at moderate-high pressures, which usually produces the calc-alkaline differentiation trend with the silica enrichment (Greene et al., 2006; Hamada and Fujii, 2008; Jagoutz, 2010; Pichavant and Macdonald, 2007). The arc basalts have typically higher than depleted mantle values of $\delta^{34}S$ (up to and rarely above 13‰), reflecting a contribution from marine sulfates fixed in the subducted oceanic crust and transported into the mantle wedge by metasomatic fluids (Alt et al., 1993). The $\delta^{34}S$ values for the post-collisional magmatic sulfide deposits in the Central Asian Orogenic Belt and the eastern Kunlun Orogen are similar to those of the arc basalts but are generally interpreted to reflect the addition of crustal sulfur (C.S. Li et al., 2015a; Zhang et al., 2016; Zhao et al., 2016). Considering the fact that hydrous and oxidized magmas also contain high sulfur contents (Matjuschkin et al., 2016), the necessity of crustal sulfur addition for the magmatic ore formation in subduction-collision settings is doubtful. In other words, the key steps for the formation of magmatic sulfide deposits in subduction-collision settings may be fundamentally different relative to those formed in stable intracratonic settings.

The Xiarihamu sulfide deposit in the Eastern Kunlun Orogen is the largest magmatic sulfide deposit in subduction-collision settings. Presently, a comprehensive set of published data about mineral chemistry, whole-rock major- and trace-element, PGE and Sr-Nd-Os-S isotopes as well as zircon U-Pb and Lu-Hf isotopes for the deposit indicate a controversial petrologic and ore genesis. The parental magma has been proposed to be either boninite (C.S. Li et al., 2015a) or high-MgO basalt (Du et al., 2014; Jiang et al., 2015; Song et al., 2016) originated from an enriched (Jiang et al., 2015; Zhang et al., 2016) or depleted (Wang et al., 2014) mantle by low-degree partial melting of mantle peridotite (Jiang et al., 2015; Zhang et al., 2016) or mantle pyroxenite (Song et al., 2016). Sulfide retention in the mantle source (Song et al., 2016; Zhang et al., 2016) or previous sulfide segregation during magma ascent (Du et al., 2014) has been applied to interpret the PGE depletion. Relatively uniform sulfide $\delta^{34}S$ values (2.2–6.8‰) have been exclusively explained by the addition of crustal sulfur (Du et al., 2014; C.S. Li et al., 2015a; Zhang et al., 2016). In this paper, we report on detailed field observations, mineral chemistry, whole-rock major- and trace-element compositions, and Sr-Nd isotopes of fresh mafic and ultramafic rocks from the Xiarihamu complex and simultaneously apply multiple geochemical and thermodynamical modelings to constrain the degrees of partial melting in the mantle source, the parental magma, and the feasible differentiation trend during magmatic ascent.

2. Geological setting

The Kunlun Orogen is the western segment of the Central China Orogenic Belt that separates the Tarim and North China cratons to the north from the Tibetan and the South China Block to the south (Fig. 1). It can be divided into western and eastern parts by the Altyn Fault. The eastern Kunlun Orogen, connected with the western Qinling Orogen in the east, is situated between the Qaidam Block to the north and the Hohxil-Bayanhar Block to the south. It is underlain by a Mesoarchean-Mesoproterozoic basement (Chen et al., 2011; He et al., 2016a), and has witnessed multistage subduction and collision from Neoproterozoic to Early Mesozoic (Bian et al., 2004; Chen et al., 2015; He et al., 2016b; Meng et al., 2013a; Yang et al., 1996; Zhang et al., 2012, 2014; Zhu et al., 2006).

The eastern Kunlun Orogen consists of the Northern, Middle and Southern Kunlun terranes separated by the Northern, Central and Southern Kunlun Faults (Fig. 1) (Jiang et al., 1992; Liu et al., 2005; Xu et al., 2006). Early Paleozoic high-pressure eclogites (450–411 Ma) and granulites (508 Ma) (Li et al., 2006; Meng et al., 2013b, 2015; Qi et al., 2014), and high-temperature granulites (460–430 Ma) (Yu, 2005; Zhang et al., 2003) have been reported to occur in the Precambrian metamorphic rocks of the Middle Kunlun Terrance (Fig. 1). The Central Kunlun Fault represents an Early Paleozoic suture zone containing exposed ophiolites with zircon U-Pb ages of 518–509 Ma (Feng et al., 2010; Yang et al., 1996). The Southern Kunlun Fault is considered to represent a composite suture zone and is characterized by associated ophiolites having two distinct age groups of 516–467 Ma and 345–333 Ma (Bian et al., 2004; L. Chen et al., 2001a; Liu et al., 2011).