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Formation of the giant Chalukou porphyry Mo deposit in northern Great Xing'an Range, NE China: Partial melting of the juvenile lower crust in intra-plate extensional environment

Zhen-Zhen Li [a,b], Ke-Zhang Qin [a,*], Guang-Ming Li [a], Shunso Ishihara [c], Lu-Ying Jin [a,b], Guo-Xue Song [a], Zhao-Jun Meng [d]

[a] Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Geological Survey of Japan, AIST, Central 7, Tsukuba, 305-8567, Japan
[d] 706 Geological Party of Heilongjiang Geoexploration Bureau for Nonferrous Metals, Qiqihar, 161006, China

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ABSTRACT

The Chalukou porphyry Mo deposit (2.46 Mt @ 0.087% Mo), located in the northern Great Xing'an Range, NE China, is the largest Mo deposit discovered in China so far. The host rocks consist of aplite porphyry, granite porphyry and quartz porphyry, and are intruded into Lower Ordovician intermediate-felsic volcanic–sedimentary rocks and pre-ore monzogranite and are cut by post-ore feldspar porphyry, diorite porphyry and quartz monzonite porphyry. Here, we present the zircon U–Pb ages, whole-rock geochemistry, Sr–Nd isotopic and zircon Hf isotopic data for the pre-ore, syn-ore and post-ore intrusive rocks. The Chalukou ore-forming porphyries intruded during 147–148 Ma and have high-silica, alkali-rich, metaluminous to slightly peraluminous compositions and are oxidized. They are enriched in large ion lithophile elements (e.g. K, Rb, U and Th), light REE and depleted in high-field strength elements (e.g. Nb, P and Ti). Depletions in Eu, Ba, Sr, Nb, Ta, P and Ti suggest that they have experienced strong fractional crystallization of plagioclase, biotite, hornblende and accessory minerals. The pre-ore monzogranite (~172 Ma) also belongs to the high-K calc-alkaline series. Highly fractionated REE patterns ($(La/Yb)_N$ = 19.6–21.7), high values of Sr/Y (54–69) and La/Yb (29–32), are adakite-like geochemical features. The post-ore rocks (~141–128 Ma) have similar geochemical characteristics with ore-forming porphyries except that quartz monzonite porphyry shows no Ba–Sr negative anomaly. All intrusive rocks have relative low initial $^{87}Sr/^{86}Sr$ (0.705413–0.707889) and εNd (t) values (−1.28 to +0.92), positive εHf (t) values (+2.4 to +10.1) and young two-stage Nd and Hf model ages (T_{DM2} (Nd) = 863–977 Ma, T_{DM2} (Hf) = 552–976 Ma). These geochemical and isotopic data are interpreted to demonstrate that the ore-forming porphyries formed by partial melting of the juvenile lower crust caused by underplating of mafic magmas in an intra-plate extensional setting. The pre-ore monzogranite formed by partial melting of thickened lower crust in a collisional setting caused by closure of Mongol–Okhotsk Ocean. The post-ore feldspar porphyry shares a similar magma source with ore-forming porphyry, but the quartz monzonite porphyry has a relatively deeper magma source region and has not experienced as much fractional crystallization. The transformation from middle Jurassic compression to late Jurassic extension created favorable conditions for the generation and emplacement of the ore-forming magma. The juvenile lower crust provided the main source of molybdenum for Chalukou deposit. Enrichment of Mo by fractional crystallization played an important role in concentrating Mo during formation of the Chalukou Mo deposit. The age (~147 Ma), high fluorine, and associated Pb–Zn deposits are all different from other major porphyry Mo deposits in NE China; Chalukou is a new mineral deposit type in the Great Xing'an Range.

1. Introduction

A large number of porphyry molybdenum deposits developed in eastern China, and they are mainly distributed along the north and south margins of the North China Craton (NCC) (Chen et al., 2000; Li et al., 2005, 2007a; Mao et al., 2003, 2011; Zeng et al., 2009, 2012a, 2012b). For instance, the eastern Qinling belt, located in the south

* Corresponding author.
E-mail addresses: windylizhenzhen@163.com (Z.-Z. Li), kzq@mail.iggcas.ac.cn (K.-Z. Qin).

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margin of NCC, with more than 5 Mt Mo resource, is one of the most important Mo mineralized belts in the world (Li et al., 2005, 2007a; Mao et al., 2003, 2011; Zhu et al., 2009). Recently, several superlarge porphyry Mo deposits have been discovered in northeastern China (e.g. Chalukou, Luming, Daheishan, etc.) (C.H. Wang et al., 2009; Ge et al., 2007a, 2007b; Meng et al., 2011; Yang et al., 2012), thus, that area has become another important Mo province in China and in the world (C. Zhang et al., 2013; Z. Zhang et al., 2013).

The Chalukou Mo deposit, with a Mo metal resource of 2.46 Mt (Meng et al., 2011), is a newly discovered giant porphyry Mo deposit in North Great Xing'an Range in NE China and is the largest Mo deposit discovered in China to the present. According to the classification of porphyry Mo deposits from Carten et al. (1993) and Westra and Keith (1981), the Chalukou deposit shares many common geologic features with high-fluorine porphyry Mo deposits (e.g. Climax and Henderson, Carten et al., 1988; Clark, 1972; Seedorff and Einaudi, 2004a, 2004b; Wallace et al., 1978; White et al., 1981), whereas the Mo deposits (Luming, Daheishan) in the Jilin-Heilongjiang belt, eastern of NE China (Zhangguangcai Range) should be classified as fluorine-poor monzogranite–granodiorite porphyry Mo systems (e.g. Endako, Mutschler et al., 1981; Selby et al., 2000). Furthermore, this deposit also shows different geologic features with those Mo deposits on the north and south margins of the NCC (Mao et al., 2003, 2011; Zeng et al., 2009, 2012a, 2012b). Thus, the Chalukou Mo deposit may represent a unique porphyry mineralization event in China.

Some significant questions in the study of porphyry-type deposits involve the petrogenesis of ore-forming magmas and their tectonic setting. With regard to the high-fluorine porphyry Mo deposits (e.g. Climax, Henderson) in USA, they developed in the back-arc rift-related extension environment (Carten et al., 1993) and their ore-forming rhyolite porphyries originated primarily by the partial melting from old lower crust and experienced complex magma mixing with basaltic magmas and protracted crystallization (Farmer and DePaolo, 1984; Johnson et al., 1990; Stein and Crock, 1990) or interaction between mafic and felsic magmas (Audétat, 2010; Pettke et al., 2010). Numerous studies demonstrated that the deposits in the north and south margins of NCC mainly formed in a post-collision extension setting and ore-related magmas derived from old lower crust source (Bao et al., 2009; Chen et al., 2000; Hou and Yang, 2009; Zhu et al., 2009). Since there is no systematic research on the Chalukou deposit (Jin et al., 2014; Li et al., 2014; Liu et al., 2014; Meng et al., 2011), its magma source, and tectonic setting are unclear. In this paper, we describe the geology of the Chalukou Mo deposit, and identify the emplacement sequence of magmatism in Chalukou ore-district, and focus on the petrology, geochronology and geochemistry of the magmatic rocks to solve the genetic problems mentioned above.

2. Geology of the Chalukou porphyry molybdenum (Mo) deposit

2.1. Regional geologic setting

Northeastern China is the easternmost part of the Central Asian Orogenic Belt (CAOB) (Jahn et al., 2000; Sengör and Burtman, 1993; Xiao et al., 2003), and has undergone two stages of evolution under different tectonic settings. In the Paleozoic, evolution of the Paleo-Asian Ocean caused several micro-continental blocks and/or terranes to join together – Erguna, Xing'an and Songliao from the northwest to the southeast – separated by a series of northeast-trending faults (Li, 2006; Wu et al., 2011) (Fig. 1a). Recent studies have shown that the Erguna Terrane has a Neoproterozoic metamorphic basement (Ge et al., 2007a). The Early Paleozoic granites in the Erguna Terrane formed in a post-orogenic setting suggesting that the collision between the Erguna Terrane and the Xing'an Terrane took place before ~490 Ma (Ge et al., 2005). However, the existence of Precambrian basement is not widespread in the Xing'an Terrane and Songliao Terrane. These two terranes are regarded as island arc terranes based on island arc volcanic and sedimentary assemblages, and were sutured before the Permian (Wu et al., 2002, 2011) (Fig. 1b).

In the Mesozoic, the tectonics were dominated by evolution of the Paleo-Pacific Ocean in the east and the Mongol–Okhotsk Ocean in the northwest (Fig. 1b), resulting in the accretion of the Jiamusi Massif and Nadanhada Terrane in the easternmost part of NE China and widespread magmatism (Wu et al., 2011; Xu et al., 2013). The remarkable magmatism predominated by the formation of I- and A-type granitoids and mafic to felsic volcanic rocks can be subdivided into three stages: Late Triassic–Middle Jurassic (228–160 Ma), Late Jurassic–early Early Cretaceous (150–138 Ma) and late Early Cretaceous–Late Cretaceous (133–88 Ma) (Wu et al., 2011; Xu et al., 2013). The Late Triassic–Middle Jurassic magmatic rocks are distributed mainly in the eastern NE China in the Jilin–Heilongjiang belt and Lesser Xing'an Range, which are connected with the subduction of the Paleo-Pacific Ocean (Ge et al., 2007a, 2007b; Wu et al., 2011). In western NE China (in the Great Xing'an Range, GXR), the Late Jurassic–Early Cretaceous (160–115 Ma) magmatism predominate, with minor Late Triassic–Middle Jurassic magmatism (L.C. Zhang et al., 2008; Wu et al., 2011; Zhang et al., 2010). Referring to the tectonic setting, some researchers have proposed that they are associated with evolution of the Paleo-Pacific Ocean (J.H. Zhang et al., 2008; Sui et al., 2007; Zhang et al., 2010), whereas L.C. Zhang et al. (2008) emphasized the extensional setting, which is similar to that of the Basin and Range Province of the United States. Nonetheless, more researchers stand for the impact of the Mongol–Okhotsk Ocean based on the confirmation of the southward subduction of the Mongol–Okhotsk Ocean and the temporal and spatial distribution of granitoids and volcanic rocks (Chen et al., 2008; Qin et al., 1999; Wu et al., 2011; Xu et al., 2013; Ying et al., 2010). Although the tectonic settings differ, the Mesozoic granitoids of NE China share the same isotopic features of low initial Sr and high Nd isotopic values, which imply that they derived from juvenile crustal material and recorded an important continental growth during the Phanerozoic (Jahn et al., 2000; Wu et al., 2000, 2002, 2003a, 2003b, 2011). Corresponding to the generation of granites and volcanic, large hydrothermal vein Pb–Zn–Ag deposits, epithermal Au–Ag–Cu deposits and porphyry Cu–Mo–Au deposits occurred in the GXR (Zeng et al., 2012a, 2012b).

The Chalukou porphyry Mo deposit is located in the southern Yilehulishan area, in the north Great Xing'an Range (NGXR) and tectonically in the northwestern Xing'an Terrane (geographic coordinates: 123°52′30″E, 51°09′30″N) (Fig. 1). This deposit is situated at the western margin of the Jinsong volcanic edifice, which emitted a large volume of dacite–rhyolite volcanic–sedimentary rocks in the Mesozoic. Although several polymetallic deposit (Wuzhixian Pb–Zn, Tayuan Mo–Ag, Xigou Cu–Mo) and small–medium scale polymetallic deposits have been found in the Yilehulishan area and the NGXR, respectively, discovery of the Chalukou porphyry deposit is a breakthrough in the NGXR.

2.2. Strata and faults in the Chalukou ore district

The strata are composed mainly of the Neoproterozoic–Lower Cambrian Dawangzi Formation, Lower Ordovician intermediate-felsic volcanic–sedimentary rocks and Late Jurassic–Early Cretaceous dacite–rhyolite volcanic–sedimentary rocks (Baiyingaolao Formation) (Figs. 1, 2). The Dawangzi Formation is distributed in the southeastern and northwestern parts of the ore district and is composed mainly of quartz chlorite schist and quartz biotite schist with a small amount of marble. Ordovician volcanic–sedimentary strata, ore-bearing wallrocks of Mo and Pb–Zn mineralization, are distributed in the central part of the ore district. These strata consist mainly of rhyolite, dacite, andesite and volcanic tuff that have undergone slight deformation and metamorphism. The results of zircon U–Pb dating imply that Ordovician volcanic rocks formed in the Late Ordovician (472–475 Ma, unpublished data). The Baiyingaolao Formation, generated from the eruption of the Jinsong caldera, is widely distributed in the east part of the Chalukou ore district.