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Geochronology and fluid inclusion study of the Yinjiagou porphyry–skarn Mo–Cu–pyrite deposit in the East Qinling orogenic belt, China

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ABSTRACT

The Yinjiagou Mo–Cu–pyrite deposit of Henan Province is located in the Huaxiong block on the southern margin of the North China craton. It differs from other Mo deposits in the East Qingling area because of its large pyrite resource and complex associated elements. The deposit's mineralization process can be divided into skarn, sulfide, and supergene episodes with five stages, marking formation of magnetite in the skarn episode, quartz–molybdenite, quartz–calcite–pyrite–chalcopyrite–bornite–sphalerite, and calcite–galena–sphalerite in the sulfide episode, and chalcedony–limonite in the supergene episode. Re–Os and ^{40}Ar–^{39}Ar dating indicates that both the skarn-type and porphyry-type orebodies of the Yinjiagou deposit formed approximately 143 Ma ago during the Early Cretaceous. Four types of fluid inclusions (FIs) have been distinguished in quartz phenocryst, various quartz veins, and calcite vein. Based on petrographic observations and microthermometric criteria the FIs include liquid-rich, gas-rich, H_2O–CO_2, and daughter mineral-bearing inclusions. The homogenization temperature of FIs in quartz phenocrysts of K-feldspar granite porphyry ranges from 341 °C to >550 °C, and the salinity is 0.4–44.0 wt% NaCl eqv. The homogenization temperature of FIs in quartz–molybdenite veins is 382–416 °C, and the salinity is 3.6–40.8 wt% NaCl eqv. The homogenization temperature of FIs in quartz–calcite–pyrite–chalcopyrite–bornite–sphalerite ranges from 318 °C to 436 °C, and the salinity is 5.6–42.4 wt% NaCl eqv. The homogenization temperature of FIs in quartz–molybdenite stockworks is in a range of 321–411 °C, and the salinity is 6.3–16.4 wt% NaCl eqv. The homogenization temperature of FIs in quartz–sericite–pyrite is in a range of 326–419 °C, and the salinity is 4.7–49.4 wt% NaCl eqv. The ore-forming fluids of the Yinjiagou deposit are mainly high-temperature, high-salinity fluids, generally with affinities to an H_2O–NaCl–KCl ± CO_2 system. The $\delta^{18}O_{H2O}$ values of ore-forming hydrothermal fluids are 4.0–8.6‰, and the $\delta D_{V\text{-}SMOW}$ values are between −64‰ and −52‰, indicating that the ore-forming fluids were primarily magmatic. The $\delta^{34}S_{V\text{-}CDT}$ values of sulfides range between −0.2‰ and 6.3‰ with a mean of 1.6‰, sharing similar features with deeply sourced sulfur, implying that the sulfur mainly came from the lower crust composed of poorly differentiated igneous materials, but part of the heavy sulfur came from the Guandaokou Group dolostone. The $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ values of sulfides are in the range of 17.331–18.043, 15.444–15.575, and 37.783–38.236, respectively, which is generally consistent with the Pb isotopic signature of the Yinjiagou intrusion, suggesting that the Pb chiefly originated from the felsic–intermediate intrusive rocks in the mine area, with a small amount of lead from strata. The Yinjiagou deposit is a porphyry–skarn deposit formed during the Mesozoic transition of a tectonic regime that is EW-trending to NNE-trending, and the multiepisode boiling of ore-forming fluids was the primary mechanism for mineral deposition.

1. Introduction

The East Qinling molybdenum (Mo) belt (EQMB) extends from the San–Bao Fault in the north to the Shang–Dan Fault in the south and from the Jinduicheng deposit of Luonan County, Shaanxi Province, in the west to the Qiushuwan deposit of Zhenping County, Henan Province, in the east. To date, 7 superlarge deposits

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(>50 × 10^4 t Mo) of Mo–W (i.e., Jinduicheng, Nannihu, Sandaozhuang, Shangfanggou, Yechangping, Yuchiling, and Donggou), 3 large deposits [(10–50) × 10^4 t Mo] of Mo (i.e., Leimengou, Shijiawan, and Huanglongpu), and 10 medium-sized Cu–Mo deposits [(2–10) × 10^4 t Mo, such as Qiushuwan] have been discovered. The total Mo metal resource exceeds 5 × 10^6 t, which is greater than that of the Climax–Henderson porphyry Mo ore district in the western United States, making it the largest Mo ore district in the world (Li et al., 2007a; Mao et al., 2008, 2011a; Hou and Yang, 2009). Molybdenum can appear in independent minerals, such as in the Yuchiling and Jinduicheng Mo deposits, or associated with Au, Ag, W, Fe, Cu, Pb, Zn, rare-earth elements (REEs), and pyrite in multielement minerals, such as in the Qiushuwan Cu–Mo deposit, the Dahu Au–Mo deposit, the Nannihu and Sandaozhuang Mo–W deposits, the Shangfanggou Mo–Fe deposit, the Huanglongpu Mo–REE deposit, and the Yinjiagou Mo–Cu–pyrite–Fe–Au–Pb–Zn–Ag deposit (Chen and Guo, 1993; Chen et al., 2009). Previous studies have described extensive investigations of the Mo deposits in the EQMB to determine type, mineralization age, the characteristics of ore-forming fluids, and the geodynamic setting of the deposits. The Mo mineralization in the EQMB can be classified into porphyry, porphyry–skarn, skarn, and vein types; of these deposits, porphyry and porphyry–skarn are the two primary types (Chen et al., 1994; Li et al., 2007a; Huang et al., 2009). Important Mo mineralization is confined to the Late Jurassic and Early Cretaceous (Du et al., 1994; Huang et al., 1994; Stein et al., 1997; Li et al., 2003, 2004, 2012; Mao et al., 2005, 2011b; Guo et al., 2006; Ye et al., 2006, 2008; Jiao et al., 2009; Zhou et al., 2009; Yang et al., 2010; Liu et al., 2011), though limited pre-Jurassic mineralization has also been reported (Huang et al., 1994, 2009; Li et al., 2007b, 2008, 2009a,b, 2011; Wei et al., 2009; Deng et al., 2012). Previous studies involved investigations of the ore-forming fluids for most of the Mo deposits in the EQMB, such as the Jinduicheng (Xu et al., 1998), Sandaozhuang (Shi et al., 2009), Nannihu (Yang et al., 2012), Shangfanggou (Yang et al., 2009), Yuchiling (Li et al., 2009c), and Zhaiwa (Deng et al., 2012) Mo deposits, and Sr–Nd–Pb isotopic systematics were also implemented for specific deposits (Ni et al., 2012). Mao et al. (2005) reviewed the geodynamic settings of the Mesozoic large-scale mineralization in and around the North China Plate and suggested that the North China Plate and its adjacent regions experienced evolution in three stages: post-collisional orogenesis (200–160 Ma), transition in a tectonic regime (~140 Ma), and lithospheric stretching and thinning (130–110 Ma, peaking at 120 Ma). The vast majority of Mo deposits in the East Qinling area were formed during the transition from an EW-trending tectonic regime to a NNE-trending tectonic regime at approximately 140 Ma.

The Yinjiagou Mo–Cu–pyrite deposit is located in west Henan Province and is typical of deposits in the EQMB. As the largest pyrite deposit in Henan Province, it differs from other Mo deposits because of its large pyrite resource and complex associated elements. However, the Yinjiagou deposit has not been given its due share of research attention recently, except for a small number of geological characterizations and analyses of the deposit genesis (Xu, 1985; Chen and Guo, 1993; Yan et al., 2007; Zhang et al., 2008). The lack of systematic research limits our understanding of the deposit's genesis type and ore-forming mechanism. In this work, we present new data of molybdenite Re–Os ages, sericite ^{40}Ar–^{39}Ar ages, and measurements of fluid inclusions and stable isotopes. The purpose of this study is to classify the genesis type, determine the mineralization age, reveal the characteristics of its ore-forming fluids and its evolution, and discuss the sources of ore-forming fluids and materials of the Yinjiagou deposit. We also incorporate our results with previous studies on the chronology and ore-forming tectonic settings of the EQMB to probe the genesis of the Yinjiagou deposit in a regional tectonic context, providing new clues for fundamental research and prospecting in this area.

2. Regional geology

The Qinling orogenic belt, which is situated in the middle of the Central China Orogen (Fig. 1a), is bounded by the San–Bao, Luanchuan, Shang–Dan, Mian–Lue, and Longmenshan fault zones and is divided from north to south into the Huaxiong block, the North Qinling accretion zone, the South Qinling orogenic belt, and the foreland fold–thrust fault (Deng et al., 2012; Yang et al., 2012) (Fig. 1b). The Mo deposits explored so far in the East Qinling area are distributed primarily in the Huaxiong block and the North Qinling accretion zone along the southern margin of the North China craton (Fig. 1c).

The basement of the Huaxiong block comprises biotite–plagioclase gneiss and amphibolite gneiss of the Neoarchean–Paleoproterozoic Taihua Group, overlain by mafic-intermediate to felsic continental volcanic rocks of the Mesoproterozoic Xiong'er Group and the overlying clastic rocks and carbonates of the Mesoproterozoic and Neoproterozoic Guandaokou, Luanchuan, and Taowan Groups (Wei et al., 2009). The rocks in the North Qinling accretion zone mainly consist of the Qinling, Kuanping, and Erlangping Groups with minor amounts of Lower Paleozoic and Triassic marine clastic rocks and carbonates. The Qinling Group comprises high-grade metamorphic Paleoproterozoic gneiss, migmatite, and amphibolite; the Kuanping Group comprises Mesoproterozoic (1.8–1.4 Ga) ophiolitic melange; the Erlangping Group is composed of medium- to low-grade metamorphic Neoproterozoic bimodal volcanic–sedimentary assemblage; the Lower Paleozoic Cambrian–Ordovician layer is composed of marine clastic rocks and carbonates; and the Triassic layer is composed of clastic rock with local coal seams (Li et al., 2007a) (Fig. 1c). The East Qinling area consists of mainly NWW-trending faults superimposed with NE-NNE-trending faults (Huang et al., 1994). The primary NWW-trending faults include the Shang–Dan, Zhu–Xia, Waxuezi, Luanchuan, and Machaoying fault zones from south to north, all of which dip northward; the NE-NNE-trending fractures were mainly developed in the Huaxiong block (Fig. 1c). The locations at which the NWW-trending fractures and NE-NNE-trending fractures intersect primarily control the formation of Yanshanian deep-sourced hypabyssal granite porphyry and further control the formation of porphyry, porphyry–skarn, and skarn polymetallic Mo deposits in the research area. Magmatic activity is extensive in this area, and pre-Mesozoic granite mainly consists of Mesoproterozoic and Neoproterozoic alkaline granite, Caledonian granite, and Hercynian granite. The Indo-Yanshanian magmatic activity affected all of the Huaxiong block and the North Qinling accretion zone, which mainly consists of acid intrusive rocks and subvolcanics.

3. Ore geology

The Yinjiagou Mo–Cu–pyrite deposit is located in the Yinjiagou area, 40 km south of Lingbao City, Henan Province [geographic coordinates of 110°47′30″–110°49′22″ longitude (east) and 34°11′10″–34°12′55″ latitude (north)]. The deposit was discovered in 1958 as a Mo–Cu–pyrite deposit with associated minerals of, among others, Fe, Au, Pb, Zn, and Ag. Details of the estimated mineral and metal reserves of the Yinjiagou deposit are listed in Table 1 (Chen and Guo, 1993; Yan et al., 2007; Zhang et al., 2008).

The Yinjiagou deposit is located on the north of the NNE-trending Yinjiagou–Yechangping tectonic–magmatic belt (Fig. 2a). The rocks in the mine area consist of dolostone of the Mesoproterozoic