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Metallogenic age and hydrothermal evolution of the Jidetun Mo deposit in central Jilin Province, northeast China: Evidence from fluid inclusions, isotope systematics, and geochronology

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ABSTRACT

The Jidetun deposit is a large porphyry Mo deposit that is located in central Jilin Province, northeast China. The Mo mineralization occurs mainly at the edge of porphyritic granodiorite, as well as the adjacent monzogranite. Field investigations, cross-cutting relationships, and mineral paragenetic associations indicate four stages of hydrothermal activity. To determine the relationships between mineralization and associated magmatism, and better understand the metallogenic processes in ore district, we have undertaken a series of studies including molybdenite Re–Os and zircon U–Pb geochronology, fluid inclusions microthermometry, and C–H–O–S–Pb isotope compositions. The molybdenite Re–Os dating yielded a well-defined isochron age of 168.9 ± 1.9 Ma (MSWD = 0.34) that is similar to the weighted mean $^{206}Pb/^{238}U$ age of 173.5 ± 1.5 Ma (MSWD = 1.8) obtained from zircons from the porphyritic granodiorite. The results lead to the conclusion that Mo mineralization, occurred in the Middle Jurassic (168.9 ± 1.9 Ma), was spatially, temporally, and genetically related to the porphyritic granodiorite (173.5 ± 1.5 Ma) rather than the older monzogranite (180.1 ± 0.6 Ma). Fluid inclusion and stable (C–H–O) isotope data indicate that the initial H_2O–NaCl fluids of mineralization stage I were of high-temperature and high-salinity affinity and exsolved from the granodiorite magma as a result of cooling and fractional crystallization. The fluids then evolved during mineralization stage II into immiscible H_2O–CO_2–NaCl fluids that facilitated the transport of metals (Mo, Cu, and Fe) and their separation from the ore-bearing magmas due to the influx of abundant external CO_2 and heated meteoric water. Subsequently, during mineralization stage III and IV, increase of pH in residual ore-forming fluids on account of CO_2 escape, and continuous decrease of ore-forming temperatures caused by the large accession of the meteoric water into the fluid system, reduced solubility and stability of metal clathrates, thus facilitating the deposition of polymetallic sulfides.

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1. Introduction

Central Jilin Province, located on the continental margin of northeast China, is important for its Mo resources. Numerous porphyry Mo deposits have been discovered in the area, and they are temporally and spatially related to widespread Mesozoic granitoids. Recently, extensive research has been undertaken on the Mo deposits, and the timing of Mo mineralization has now been constrained to Middle Jurassic (ca. 168 Ma) by zircon U–Pb and molybdenite Re–Os dating (eg., Zhang et al., 2013; Shao, 2014; Yu et al., 2012; Liu, 2014; Wang et al., 2009a; Zhou et al., 2014; Ge et al., 2007; Wang et al., 2011). However, other important characteristics of these Mo deposits, including Jidetun, Fuan'pu, Chang'anpu, and Houdaomu, have not received in-depth discussions, including metallogenic T–P condition, transportation and precipitation mechanisms of ore-froming materials, as well as relationship between mineralization and magmatism.

The Jidetun deposit is a large porphyry Mo deposit in central Jilin Province, which contains Mo metal reserves of 400,000 t with an average grade of 0.087% Mo. As an important Mo producer in NE China, the ore-forming ages of the Jidetun ore district have now been constrained to the Middle Jurassic (160.5–180.2 Ma) by precise zircon U–Pb and molybdenite Re–Os dating (Zhang et al., 2013; Liu, 2014; Lu et al., 2016; Wang et al., 2016). Given that

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the Jidetun Mo mineralization occurs along the contact zone between the porphyritic granodiorite and monzogranite, Shao (2014) proposed that the Mo mineralization was closely related to the monzogranite, whereas Zhang (2013) considered the porphyritic granodiorite as the source of Mo. The ore-forming fluids of the Jidetun deposit were constrained by fluid inclusions and stable H–O–S isotopes (Zhang, 2013; Shao, 2014; Wang et al., 2016); however, Shao (2014) and Wang et al. (2016) classified the ore-forming fluids as NaCl–H_2O–CO_2 system, whereas Zhang (2013) suggested NaCl–H_2O fluids. Recently, Lu et al. (2016) attributed the Middle Jurassic magmatism associated with the Jidetun Mo mineralization to subduction of the Pacific Plate based on geochemical research, which has been widely accepted by many geologists. Taken together, although much work on the ore-forming ages, fluids, and genesis of the Jidetun deposit has been carried out, some discrepancies such as ore-forming fluids and metal sources remain unclear and controversial. Moreover, the question of whether the Mo mineralization sourced from different intrusions has not been resolved as yet.

In this study, we present new molybdenite Re–Os and zircon U–Pb geochronological data, as well as fluid inclusions and stable (H–O–C–S) and radiogenic (Pb) isotope systematics to fully discuss the metallogenic processes, and in particular, to explain the relationship between Mo mineralization and associated intrusions by combining the views of ore-forming age, mineralization space, and material source.

2. Geological background

Located in the eastern segment of the Central Asian Orogenic Belt (CAOB, Fig. 1A), NE China has been divided into five blocks, which from west to east are the Ergun, Xinggan, Songnen, Jiamusi, and Khanka blocks separated by the Tanyuan–Xiguitu, Hegenshan–Heihe, Mudanjiang, Xar Moron–Changchun, and Dunhua–Mishan faults, respectively (Sengör et al., 1993; Jahn et al., 2000). It is generally considered that NE China has undergone three distinct stages of evolution under different tectonic regimes (Wu et al., 2002; Xu et al., 2013): (1) a Paleozoic tectonic evolution that was dominated by the progressive subduction of the Paleo-Asian oceanic lithosphere; and (2) a Mesozoic–Cenozoic tectonic evolution that was controlled mainly by the closure of the Mongol-Okhotsk Ocean (Pei et al., 2011; Xu et al., 2013) and (3) oblique subduction of the Paleo-Pacific oceanic plate beneath the Eurasian continent (Miao et al., 2003; Li et al., 2004; Zhang et al., 2008; Feng et al., 2012; Ge et al., 2012; Zhou et al., 2015). Major events in the Paleozoic tectonic evolution of NE China can be summarized as follows. Multiple microcontinental terranes, such as the Ergun, Xinggan, Songnen, Jiamus and Khanka, were amalgamated to form a unified continent named as Burean–Jiamusi block or Jia–Meng block before the late Paleozoic (Sengör and Natal'in, 1996; Wang et al., 2008, 2009b; Xu et al., 2013; Fig. 1B); subsequently, this block collided with the North China Plate along the Xra Moron–Changchun–Yanji Suture Zone during the late Permian to Middle Triassic, when the intervening Paleo-Asian Ocean closed in a scissor-like manner from west to east due to bidirectional subduction of the Paleo-Asian Ocean Plate (Chen et al., 2009; Cao et al., 2013; Liu et al., 2013; Xu et al., 2013; Wang et al., 2017). In the period of Late-Permian to Middle Jurassic, after the closure of the Mongol-Okhotsk oceanic plate (Wu et al., 2011; Xu et al., 2013), NE China was gradually subjected to a syn- to post-collisional orogenic regime between the North China-Songliao and Siberia-Mongolia continental plates (Johnson et al., 2001; Chen et al., 2017; Zeng et al., 2013). In addition, NE China witnessed the transition from the Paleo-Asian Ocean regime to the circum-Pacific tectonic regime during Late Triassic to Early Jurassic (Wu et al., 2011; Xu et al., 2013), which is evidenced by both the calc-alkaline rocks in the eastern Heilongjiang–Jilin region and a bimodal volcanic rock association in the Lesser Xing'an–Zhangguangcai Ranges in Early–Middle Jurassic (Xu et al., 2013). The subduction of the Paleo-Pacific Plate resulted in development of extensive Early–Middle Jurassic and Cretaceous granitoids, andesitic–rhyolitic volcanic rocks and numerous hydrothermal mineral systems in the southeastern part of NE China (Chen et al., 2009; Wu et al., 2011), e.g. porphyry Au, Cu and Mo (Zhang et al., 2013; Wang et al., 2016a), skarn Cu–Au (Zhang et al., 2015), and hydrothermal vein Pb–Zn–Au–Ag (Zhou et al., 2016; Chai et al., 2016).

The central Jilin Province is located in the southeastern part of NE China (Fig. 1B). Phanerozoic granitoids occur in this region, and the basement consists of Paleozoic–Mesozoic granites and Paleozoic lithologies (Li and Zhao, 1991; Gao et al., 2007; Pei et al., 2007; Wu et al., 2011; Zhou et al., 2015), together with minor Proterozoic granitoids (Wang et al., 2006; Pei et al., 2007). Intense Early–Middle Jurassic magmatism caused by the subduction of Paleo-Pacific Plate occurred in central Jilin Province, producing widespread NE–SW-trending I- and A-type granites along the Yitong–Yilan and Dunhua–Mishan faults (Fig. 1C; Wu et al., 2011). A series of economically significant granitoid-related Mo deposits, such as Jidetun, Fu'anpu, Daheishan, Xinhualong, Liushengdian and Houdaomu, have been discovered (Fig. 1B, C). The principal ore-forming ages of these Mo mineralization has been constrained to Middle Jurassic on the basis of molybdenite Re–Os dating (Zhang et al., 2013), which has been attributed to the subduction of the Paleo-Pacific Plate beneath Eurasia during Early–Middle Jurassic (Chen and Li, 2009; Xu et al., 2013; Zhang, 2013, 2014; Shu et al., 2016).

3. Ore deposit geology

The Jidetun Mo deposit is located ~26 km east of Shulan City in Jilin Province, and northeast of the junction between the Xar Moron–Changchun and Yilan–Yitong faults. Extensive intrusions with different ages and minor late Paleozoic strata are exposed in this ore district (Fig. 2A, B). The intrusions can be placed into two categories according to ages: Early Jurassic granodiorite and Middle Jurassic monzogranite, porphyritic granodiorite and tonalite. Among them, the Early Jurassic granodiorite is mainly distributed in the northern part of the ore district, and the Middle Jurassic granitoids are widespread in the centeral and southern parts of the ore district, with porphyritic granodiorite and tonalite forming small irregular stocks that intrude earlier and larger monzogranite (Fig. 2A). It should be noted that late Paleozoic rocks, including marble, schist, metasandstone and carbonate with a total thicknesses of 0.1 to 0.3 km, form small residual bodies that are sporadically exposed above the Middle Jurassic monzogranite and porphyritic granodiorite (Fig. 2A). Structures in the area are dominated by NW–SE faults that are subsidiary to the Yitong–Yilan Fault (Fig. 2A). In addition, several irregular minor faults caused from intrusive activity developed in the porphyritic granodiorite and its contact zone with the monzogranite (Fig. 2A). Some of these minor faults and their secondary fractures, especially on both sides of the contact zone, were filled with mineralized quartz veins, and hence acted as loci for hydrothermal alteration and Mo mineralization.

At the Jidetun deposit, Mo mineralization mainly occurs at the edge of porphyritic granodiorite, but develops gradually outwards into the monzogranite (Fig. 2B). The deposit consists of a single, stratiform-like orebody with a maximum length of 1210 m and width of 300 m. Its vertical extent in the center is 418 m. Several mineralized quartz veins with relatively high Mo grade are distributed at the outer edges of the stratiform-like ore body, and

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