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Genesis of the Tianbaoshan Pb–Zn–Cu–Mo polymetallic deposit in eastern Jilin, NE China: Constraints from fluid inclusions and C–H–O–S–Pb isotope systematics

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ABSTRACT

The Tianbaoshan Pb–Zn–Cu–Mo deposit is located in the eastern part of Jilin–Heilongjiang region, NE China which is considered to be the eastern segment of the Central Asian Orogenic Belt. Field and geochronological evidences indicate that this deposit experienced three types of mineralization including Hercynian skarn, cryptoexplosion breccia pipe, and Yanshanian quartz vein. The early stages of the Pb–Zn–Cu mineral systems in skarn and cryptoexplosion breccia pipe are characterized by a high-temperature, high-salinity H_2O–CO_2–NaCl system of hydrothermal fluids that were possibly exsolved from the Hercynian wall-rock granodiorite. These fluids show H–O isotopic compositions similar to those of typical magmatic fluids. By contrast, the low-temperature hydrothermal fluids of the later stages are represented by low-salinity NaCl–H_2O systems with low H–O isotopic values. The skarn and cryptoexplosive breccia pipe types of Pb–Zn–Cu mineralization tend to have weakly negative $\delta^{34}S$ values of −4.0‰ to −0.8‰ (mean values of −2.31‰ and −2.16‰, respectively), indicating that the sulfur was sourced from the Hercynian magma. Therefore, the early stage ore-forming fluids of the skarn and cryptoexplosive breccia pipe were most likely sourced from high-temperature and high-salinity fluids closely related to the cooling and fractional crystallization of the Hercynian granodiorite, while the later stages changed to NaCl–H_2O meteoric water influx. Whereas the ore-forming fluids of the quartz vein type of Mo mineralization were high-temperature, high-salinity NaCl–H_2O systems that differed from those of the skarn and cryptoexplosion breccia pipe, but their H–O isotopic compositions also indicate a magmatic fluid. The weakly enriched $\delta^{34}S$ values of molybdenite from the quartz vein type Mo mineralization ($\delta^{34}S$ = 0.2–2.8‰, average of 1.65‰) are comparable with those of other Mesozoic Yanshanian Mo deposits ($\delta^{34}S$ = 0.4‰–4.1‰, with an average of 1.39‰–3.15‰), but differ significantly from those of the Hercynian Pb–Zn–Cu skarn and cryptoexplosion breccia pipe. This indicates that the sulfur of quartz vein type of Mo originated from Mesozoic Yanshanian magmatism and that the ore-forming fluids were derived from Yanshanian magmatic rocks rather than being a product of the Hercynian activity. The $\delta^{13}C$ values of the fluid inclusions in quartz from the skarn, cryptoexplosion breccia pipe and quartz vein types are in a narrow range of −19.5‰ to −9.3‰, similar to those of the Shanxiuling Group, which indicates that the carbon of the three types of mineralization had the same primary origin in the Shanxiuling Group. The lead isotope compositions of ores from the skarn and cryptoexplosion breccia pipe types of mineralization ($^{206}Pb/^{204}Pb$ = 18.0725–18.3627, $^{207}Pb/^{204}Pb$ = 15.3721–15.5694 and $^{208}Pb/^{204}Pb$ = 37.5542–38.8208) overlap with those of the Hercynian granodiorite and Shanxiuling Group marble, suggesting that the lead was probably derived from a mix of two different sources, the Shanxiuling Group and the Hercynian granodiorite. Whereas the lead isotope compositions of ores from the quartz vein type of Mo mineralization ($^{206}Pb/^{204}Pb$ = 18.3837–18.6949, $^{207}Pb/^{204}Pb$ = 15.6824–15.7293 and $^{208}Pb/^{204}Pb$ = 39.1009–39.1889) are significantly higher than those of the Shanxiuling Group marble and the Hercynian granodiorite. This indicates that the lead may be a product of Yanshanian magmatic activity instead of the nearby Hercynian granodiorite.

1. Introduction

The Jilin–Heilongjiang region, located on the continental margin of northeast China, is an important metallogenic province which hosts a range of large gold, molybdenum, lead, zinc and tungsten deposits.

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Recently, numerous gold and molybdenum deposits such as Jinchang, Wufeng, Naozhi, Daheishan, Fuanpu and Jidetun have been discovered in this region, and extensive research has been undertaken on the gold and molybdenum deposits with the goal of documenting their geologic characteristics, isotopic ages, genesis of ores and fluid inclusions (Sun et al., 2006; Li et al., 2009, 2013; Chen et al., 2012; Zhang et al., 2013a,b; Zhao, 2013; Zhou et al., 2014, 2015; Chai et al., 2016). In contrast, the Pb–Zn deposits have received less attention; systematic isotope and fluid inclusion studies on the Pb–Zn deposits are relatively scarce for limited Pb–Zn deposits that have been discovered from the Jilin–Heilongjiang region.

The Tianbaoshan deposit is a large and unique Pb–Zn–Cu–Mo polymetallic deposit in the central-southern of the Jilin–Heilongjiang region, which contains total metal reserves of 74,0000 t Pb, Zn and Cu, with an average grade of 0.31% Cu, 1.72% Pb and 2.56% Zn, and 74,5200 t Mo, with an average grade of 0.21% Mo (Li and Li, 1991; Sun, 1994). As an important Pb–Zn–Cu–Mo-producer in NE China, crystallization and ore-forming ages of the Tianbaoshan ore district attracted much attention, and the timing of Pb–Zn–Cu and Mo mineralization has now been constrained to the Permian (264.6–273.6 Ma) and Jurassic (192.0–196.6 Ma) by precise zircon U–Pb and molybdenite Re–Os dating, respectively (Zhang et al., 2013a,b; Sun et al., 2014; Yang et al., 2015b). These results have revealed the fact that Pb–Zn–Cu mineralization was temporally much earlier than Mo mineralization in the Tianbaoshan deposit. So far, however, the genetic relationships between Pb–Zn–Cu and Mo mineralization, origin and evolution of the deposit and the metallogenic processes involved, remain unclear and controversial. (Li and Li, 1991; Sun, 1994; Zhang et al., 2013a,b; Sun et al., 2014; Yang et al., 2015b).

In this study, we present a detailed study of fluid inclusions, stable (H–O–C–S) and radiogenic (Pb) isotope systematics of the Tianbaoshan deposit. Our fluid inclusion results combined with isotopic data provide clear constraints on the genesis of this deposit, and in particular explain the origin and evolution of the ore-forming fluids. We hope that this study can provide a scientific basis for further mineral prospecting and future prospecting of new Pb–Zn deposits in this area.

2. Geological background

As one of the largest and most complex Phanerozoic accretionary orogens worldwide (Sengör et al., 1993; Windley et al., 2007; Fig. 1A), the Central Asian Orogenic Belt (CAOB) (Jahn et al., 2000; Eizenhöfer et al., 2014) is thought to have evolved over a period of some 800 million years, from the latest Mesoproterozoic to the late Paleozoic (Windley et al., 2007; Safonova et al., 2011; Yang et al., 2015a). It extends for more than 5500 km from the European craton to the Pacific Ocean (Jahn et al., 2000; Windley et al., 2007). NE China and adjacent regions have traditionally been considered as the eastern segment of the CAOB and separate the North China Craton from the Siberia Plate. This segment has been divided into five blocks, namely the Ergun, Xinggan, Songnen, Jiamus, and Khanka blocks from west to east (Sengör et al., 1993; Jahn et al., 2000; Fig. 1B). It is thought that this segment of the CAOB mainly underwent three stages of evolution under different tectonic regimes (Wu et al., 2002; Liu et al., 2010; Chen et al., 2012; Xu et al., 2013). In the Paleozoic, the evolution of NE China was controlled mainly by the closure of the Paleo-Asian Ocean (Wu et al., 1999; Ge et al., 2012; Yu et al., 2012a; Cao et al., 2013; Xu et al., 2013). In the Mesozoic–Cenozoic, its evolution was dominated by the closure of the Mongol–Okhotsk Ocean (Pei et al., 2011; Xu et al., 2013) and the subduction of the western Pacific Plate (Miao et al., 2003; Zhang et al., 2008; Feng et al., 2012; Ge et al., 2012; Xu et al., 2013). Major events in the Paleozoic tectonic evolution of NE China can be summarized as follows. Multiple fragments, including the Ergun, Xinggan, Songnen, Jiamus and Khanka blocks, were amalgamated to form a unified Jia–Meng Continental Block before the late Paleozoic (Sengör and Natalin, 1996; Wang et al., 2008, 2009b; Xu et al., 2013); subsequently, this block collided with the North China Plate along the Xra Moron–Changchun–Yanji Suture Zone, resulting in intracontinental slab stacking, crustal shortening and thickening during the late Permian to Middle Triassic (Xiao et al., 2003; Jia et al., 2004; Zhang et al., 2004; Li, 2006; Yang et al., 2006; Chen et al., 2009b; Wu et al., 2011; Liu et al., 2013). This collision occurred 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., 2009b; Cao et al., 2013; Liu et al., 2013; Xu et al., 2013). In the period of end-Permian to Middle Jurassic, with the subduction of the Mongol–Okhotsk oceanic plate (Zorin, 1999; 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, accommodating crustal deformation, shortening, thickening, uplifting, and development of crust-sourced granites (Johnson et al., 2001; Chen et al., 2007, 2016; Zeng et al., 2013). In addition, the presence of calc-alkaline rocks in the eastern Heilongjiang–Jilin region, and a bimodal volcanic rock association in the Lesser Xing'an–Zhangguangcai Ranges in the Early–Middle Jurassic, led Xu et al. (2013) to conclude that the transformation from the Paleo-Asian Ocean regime to the circum-Pacific tectonic regime occurred during the Late Triassic to Early Jurassic.

It was in the three different geodynamic regimes, particularly the regime of the closure of Paleo-Asian, that the metallogenic events discussed in this paper took place, and the result was the development of one of the most important hydrothermal mineral systems in NE China.

3. Ore district geology

3.1. Stratigraphy

The Tianbaoshan deposit, which contains abundant Pb–Zn–Cu–Mo nonferrous metal resources, is located ~1.5 km north of Tianbaoshan town, Yanji city, eastern Jilin–Heilongjiang region (Figs. 1C; 2A). A relatively simple sequence of stratigraphic units is exposed in the ore district, consisting mainly of the Silurian Qinglongcun Supergroup, the lower Carboniferous Shanxiuling Group, the lower Permian Miaoling Group, and the Middle Jurassic Mingyuegou Group (Fig. 2A). The Qinglongcun Supergroup is exposed mainly in the southwestern part of the district over an area of 8 km^2 (Fig. 2A), and it consists of metasediments including a lower amphibole–plagioclase gneiss, a biotite quartzo-feldspathic gneiss, a felsic gneiss, a biotite granulite, and an upper marble and slate with pronounced graphitic–siliceous bands. The Shanxiuling Group in the western part of the ore district trends NW–SE and is made up of a set of crystalline limestone with chert intercalations and marble with thicknesses of 1.5 to 2.5 km (Fig. 2A). This great thickness of carbonate sediments may have provided the appropriate conditions for the skarn type Pb–Zn–Cu mineralization in the Lishan ore block. The Miaoling Group consists of a thick succession (0.8 to 1 km) of well-preserved volcanic rocks that underwent low-grade and low-strain metamorphism, and it overlies the Shanxiuling Group and is unconformably overlain by the Mingyuegou Group. The outcrops of the Mingyuegou Group, which includes pyroxene andesite, basaltic andesite, trachyandesite, rhyolite, and minor sedimentary intercalations and pyroclastic units, are controlled by a series of NW–SE trending faults in the Mingyuegou zone (Fig. 2A).

3.2. Structures

The faults in the ore district include a set of NE–SW-trending tensile shear faults (e.g., F1–F6), a set of NW–SE-trending compressive shear faults (F7–F9), and a set of NNW–SSE-trending tensile shear faults (Fig. 2A). The NE–SW-trending faults formed first, and they control the