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Ore geology and fluid evolution of the giant Caixiashan carbonate-hosted Zn–Pb deposit in the Eastern Tianshan, NW China

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ABSTRACT

The Caixiashan giant carbonate-hosted Zn–Pb deposit (~131 Mt@ 3.95% Zn + Pb) formed by replacement of dolomitized marble, with stratiform massive and breccia bodies is located near the base of the Proterozoic Kawabulake Group limestone and marble. It is one of the largest carbonated-hosted massive sulfides Zn–Pb ore deposits in Northwest China to have been discovered in recent years.

Abundant pyrite occurs in dolomitized marble, along fractures in dolomitized clasts in the host rocks and filling cracks in the host rock. Locally, colloform or framboidal pyrites are observed in the early period and sometimes replaced by the later sphalerite. The sulfide assemblage of the main ore stage is characterized by massive or disseminated sphalerite and galena, with less pyrite than the earlier stage, and minor pyrrhotite. Galena occurs as small veins cutting the early-formed sphalerite. Dolomite and calcite are the main gangue minerals that co-precipitated with these sulfides. Tremolite and quartz alteration commonly overprints the orebodies. According to the crosscutting relationships and the different mineral associations within the host rocks and ore bodies, three stages are recognized at Caixiashan, i.e., syn-sedimentary pyrite (stage I), pyrite alteration, sphalerite–carbonate and galena–pyrite–carbonate (stage II-1, stage II-2 and stage II-3, respectively) and magmatic/metamorphic reworking (stage III).

Calcite and quartz crystals are important host minerals among the three hypogene stages (stages I–III, although quartz mainly occurred in stage III). Stage I contains only aqueous inclusions (W-type), which were homogenized from 110 to 236 °C (main range of 138–198 °C and average at 168 °C; main range = average ± σ) and the salinities are from 0.5 to 16.5 (main range of 5.1–15.1 with average of 10.1) wt.% NaCl eqv. In the pyrite alteration of stage II-1 the W-type fluid inclusions homogenized from 175 to 260 °C (main range of 210–260 with average of 235) and the salinities range from 8.5 to 22.4 (main range of 16.7–20.1 with average of 18.4) wt.% NaCl eqv. In the main Zn–Pb mineralization stage (stage II-2–3), four types of fluid inclusions were identified an aqueous phase (W-type), a pure carbon phase (PC-type), a carbon phase containing (C-type) and mineral bearing inclusions (S-type). The W-type fluid inclusions of stage II-2–3 homogenized at 210 to 370 °C (main range of 253–323 and average at 270) and the salinities range from 5.9 to 23.1 (main range of 13.3–20.3 with average at 16.8) wt.% NaCl eqv.; C-type homogenized at 237 °C to 371 °C and the salinities range from 6.4–19.7 wt.% NaCl eqv.; S-type fluid inclusions homogenized at 211 to 350 °C and daughter minerals melted between 340 and 374 °C during heating, indicating a salinity range of 42 to 44 wt.% NaCl eqv. PC-type fluid inclusions with homogenization temperatures of CO_2 phase show large variation from 7.4 °C to 21.2 °C. Laser Raman analyses show that CH_4, CO_2 and SO_4^{2-} coexist in the main mineralization stage fluids. The magmatic/metamorphic reworking stage only contains W-type fluid inclusions which yield homogenized between 220 and 360 °C (main range of 251–325 and average at 288), with salinities ranging from 1.7 to 23.0 (main range of 14.3–20.0 and average at 18.8) wt.% NaCl eqv.

The textural features, mineral assemblages and fluid geochemistry suggest that the Zn–Pb ores were formed through hydrothermal convection of hot marine waters along the faults and fractures resulting in metal (Zn,

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Pb and Fe) enriched stratiform orebodies. Subsequent rapid precipitation of sulfides was triggered by sulfate (SO_4^{2-}) thermal reduction with the CH_4 preserved in sedimentary rocks and early stage I pyrite bodies. This process occurred at moderate temperatures (*ca.* 270 °C). Higher-temperature magmatic hydrothermal alteration overprinted the orebodies, but only provided a minor contribution to the mineralization.

1. Introduction

Carbonate-hosted Zn–Pb deposits play a significant role in the world's supply of Pb and Zn (Kucha et al., 2010; Leach et al., 2005). The Caixiashan Zn–Pb deposit is one of the largest carbonate-hosted Zn–Pb ore deposits in the Eastern Tianshan Terrane, NW China (Fig. 1). Mining of the Caixiashan deposit has focused on four major areas, namely Zones I to IV. Exploration began in 2002, and production commenced two years later. The Caixiashan Zn–Pb deposit has current reserves of 131 Mt at 3.95% Pb + Zn (Zn > Pb; cut off by 0.5% Pb + Zn; Cao et al., 2013).

Some aspects of the Caixiashan Zn–Pb deposit including the major and trace element geochemistry of the host rocks (Liang et al., 2008; Peng et al., 2007), the general isotope compositions and the fluid inclusion studies were initially constrained. Whole rock sulfur isotopes range from −21.1 to 19.1‰ with the majority of the values being positive whereas carbon and oxygen isotopic compositions range from −2.4 to 0.1‰ and 5.9 to 19.1‰, respectively (Cao et al., 2013; Gao et al., 2007). Published fluid inclusion homogenization temperatures vary from 180 °C to 310 °C with salinity range from 1.4 to 23.1 wt.% NaCl eqv. (Gao et al., 2006) or homogenized at 190 °C to 240 °C with salinity range from 0 to 6.0 wt.% NaCl eqv. (Sun et al., 2013). However, these results were not constrained by detailed paragenetic studies as the detailed geology, especially the paragenetic relationships of mineralization and alteration, and the corresponding ore forming processes of Caixiashan are poorly understood. One of the most commonly discussed but least well-understood aspects of the deposit is the source of the ore-forming fluid with previous studies proposing either magmatic hydrothermal fluids (Cao et al., 2013) or sedimentary brines (Peng et al., 2008). Other aspects that still remain controversial include the pressure, volume and temperature (*PVT*) variations of ore-forming fluids from the multiple paragenetic stages, the precipitation mechanism of metals and the preservation regime of ore bodies. These parameters are critical to defining the metallogenesis of carbonated-hosted deposits (Appold and Wenz, 2011).

To help clarify these questions, this paper characterizes the ore petrology and ore-forming fluids in the various paragenetic stages present in the Caixiashan deposit. We provide a detailed documentation of the temporal and spatial evolution of the mineralizing system for this newly discovered giant Zn–Pb deposit in NW China. Based on this information, the mechanisms that control the precipitation of Zn and Pb sulfides and the genetic link between dolomite and tremolite alteration and mineralization will be discussed.

2. Regional geology

The Caixiashan Zn–Pb mining district is located between the Central Asian Orogenic Belt (CAOB) and Tarim (Fig. 1A), and hosted in the northern margin of the Central Tianshan Terrane, about 200 km south of Hami city in the Xinjiang Uygur Autonomous Region, NW China. The Central Tianshan Terrane is located in the southern part of the Eastern Tianshan, between the Junggar Basin in the north and Tarim Basin in the south (Fig. 1B). The Eastern Tianshan was affected by the collision of the Junggar and the Tarim plates during the Ordovician to the Carboniferous (Allen and Natal'in, 1995; Pirajno et al., 2008) and is usually classified into four parts from north to south, i.e., Dananhu–tousuquan, Kanggurtag–huangshan shear zone, Aqishan–Yamansu volcanic belt and Central Tianshan Terrane, separated by a series of E-trending faults from north to south, including the Kanggurtag, Yamansu, Aqikekuduke and Tuokexun faults (Fig. 1C).

The Caixiashan Zn–Pb deposit is hosted in Precambrian platform carbonates of the Kawabulake Group. Smaller Pb–Zn deposits such as the Jiyuan, Hongxishan, Hongyuan and Shaquanzi occur in the same rocks in the eastern section of the Central Tianshan Terrane. The Mesoproterozoic Kawabulake Group is well exposed in the Central Tianshan Terrane and located in the area south of Aqikekuduke Fault and northeast of Tuokexun Fault (Fig. 1C), unconformably overlain by the Lower Cambrian Huangshan Formation (fault contact with mid-Carboniferous Matoutan Formation in the study area) and conformably underlain by the Mesoproterozoic Xingxingxia Group in the Eastern Tianshan area (Cai et al., 2013; Xiu et al., 2002). The depositional age of the Kawabulake Group is therefore after the Xingxingxia Group but before the Lower Cambrian Huangshan Formation, as confirmed by the occurrence of stromatolite (e.g., *Conophyton cylindrical*; Dong, 2005) and a single zircon grain U–Pb age of 1141 ± 60 Ma (Xiu et al., 2002). The brief outline given here is largely based on the previous studies (Cai et al., 2013; and references therein). The Kawabulake Group is comprised of two lithologic sections (Fig. 2), from bottom to top: the basal unit (section I) comprises siltstones with chert interlayers overlain by slate with siliceous rock interlayers and sandstone lenses, followed by sandstone and slate with quartz veins and capped by slate after a layer of siltstone. Section II comprises a basal package of sandstone with dolomitized marble overlain by a narrow carbon-bearing-shale within the siliceous rock layer conformably roofed by a massive layer of sandstone, then a very thin layer of carboniferous shale with siltstone lenses capped by a phyllite interbedded with siltstone and chert, among which there are some small layers of carbon-bearing-shale, chert and andesite (Fig. 2). The formation of a carbonate platform suggests that the Eastern Tianshan formed in a stable sedimentary environment during the Precambrian (Cai et al., 2013).

Combined with the available geochemical and chronological data from the Central Tianshan Terrane and the Tarim Craton (Cai et al., 2013; Xia et al., 2012), the subduction and accretion processes of the Tarim Craton and Tianshan area are described as below: (1) from the Mesoproterozoic to Middle Neoproterozoic, a continental rift or a passive continental margin formed at the northern margin of the Tarim, accompanied by an ancient ocean basin (proto-Paleoasian Ocean) formed at least before 890 Ma (Zheng et al., 2010). During that time the basement of the Central Tianshan Terrane was formed along passive continental margins. (2) The Central Tianshan Terrane drifted northwards to the active southern margin of the Siberian Craton in the Late Paleozoic; resulting in the termination of the Paleoasian Ocean during the Late Carboniferous and Permian (Xiao et al., 2009). The presence of high-Mg diorite and adakite in the northern and southern margins of the Central Tianshan Terrane suggests the closure of the Northern and Southern Tianshan Ocean (Tang et al., 2012; Yin et al., 2010). (3) The overlapping of the plates eventually led to the initiation of subduction on both the northern and southern margins of the Central Tianshan Terrane no later than ~350 Ma, forming active arcs and back (intra)-arc systems (Xiao et al., 2009).