New insights on the formation of the Jingchong Cu-Co-Pb-Zn deposit, South China: Evidence from sphalerite mineralogy and muscovite

40Ar-39Ar dating

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https://doi.org/10.1016/j.oregeorev.2023.105667
Received 23 June 2023; Received in revised form 24 August 2023; Accepted 12 September 2023
Available online 25 September 2023
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1. Introduction

Sphalerite is the most important zinc mineral in a variety of zinc sulfide deposits (Cook et al., 2009; Ye et al., 2011). Significant amounts of minor and trace elements like Mn, Fe, Co, Ni, As, Cu, Ga, Ge, Se, Mo, Ag, Cd, In, Sn, Sb, Hg, TI, Pb and Bi are incorporated into sphalerite as...
The Yanshanian (150–120 Ma) is an important period of large-scale Au, Cu, Co, Pb and Zn mineralization in South China (Hua et al., 2005; Mao et al., 2011; Chen, 2014; Deng et al., 2017, 2020; Xu et al., 2017, 2022; Zou et al., 2018). The northeastern Hunan Province, located in the central segment of the Jiangnan Orogen, South China, hosts different types of Pb-Zn deposits, such as the hydrothermal vein-type Jingchong and Hengdong Cu-Co-Pb-Zn deposits (Wang et al., 2017, 2022; Zou et al., 2018), hydrothermal vein-type Taolin and Lishan Pb-Zn deposits (Yu et al., 2020, 2021; Guo et al., 2018) and skarn-porphyry type Qibaoshan and Aoyushan Cu-Pb-Zn deposits (Liu, 2017; Yuan et al., 2018). Particularly, these deposits are accompanied by some critical metal resources, as represented by Co in the Jingchong and Hengdong deposits (Wang et al., 2017, 2022; Zou et al., 2018), Ga and Se in the Taolin and Lishan deposits, and In in the Qibaoshan deposit (Liu, 2017). These hydrothermal vein-type deposits share similar ore-forming features such as orebodies controlled by fracture zones or faults and the close tempo-spatial correlation with the Jurassic-Cretaceous granitoids (i.e., orebodies either occurring within or approaching the Jurassic-Cretaceous granitoids) (Wang et al., 2017; Yu et al., 2020, 2021). However, there are still differences in ore geology. For example, fluorite and barite are the main gangue minerals in the Taolin and Lishan Pb-Zn deposits (Yu et al., 2020, 2021), instead, the Jingchong Cu-Co-Pb-Zn deposit has quartz as the main gangue mineral (Wang et al., 2017, 2022). As a result of little attention to the Pb-Zn mineralization in the Cu-Co-Pb-Zn system, it is unclear about the discrepancy among these deposits.

The Jingchong Cu-Co-Pb-Zn deposit with reserves of 0.24 Mt Cu, 3718 t Co, 12250 t Pb and 72831 t Zn, is characterized by lower Cu-Co and upper Pb-Zn orebodies (Wang et al., 2017, 2022). Previous studies focus on the Cu-Co metallogeny and interpreted that the deposit has a magmatic-hydrothermal provenance according to sulfur, lead, helium and argon isotopic analyses (Ning, 2002; Yi et al., 2010; Wang et al., 2017). Field investigation and detailed mineralogy reveal that cobaltiferous pyrite (up to 13.66 wt% Co) and cobaltite-alloclasite are responsible for Co mineralizing stage which follows the Cu stage and, in turn, followed by the Pb-Zn stage (Wang et al., 2022). However, little is known about the formation conditions of Pb-Zn ores and its correlation with Cu-Co mineralization, which limit understanding of the Cu-Co-Pb-Zn mineralizing process.

Sphalerite in the Jingchong deposit exhibits various mineralogical characteristics (e.g., diverse color, texture and mineral inclusions), indicating complex growth mechanisms and varying ore-forming...
conditions during Pb-Zn mineralization. Here, we present data on sphalerite texture and chemical composition determined by in-situ electron probe microanalyzer (EPMA) and Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), with special attention to the elemental distribution of Fe, Mn, Cd, Cu, Ag, In and Ga. Principal component analysis, sphalerite geothermometry and $f_{O_2}$ calculation are used to describe element substitution mechanisms and the formation conditions associated with sphalerite generations. Furthermore, in-situ sulfur isotope data of sphalerite are used to constrain the source of ore-forming fluids. In combination with muscovite $^{40}$Ar/$^{39}$Ar dating, the Pb-Zn mineralizing process and its correlation with the Jingchong Cu-Co mineralization are elaborated.

2. Regional geology

The South China Block is composed of two tectonic units: the Cathaysia Block to the southeast and the Yangtze Block to the northwest (Fig. 1a). These two continental blocks collided in the Neoproterozoic and formed the Jiangnan Orogen (Charvet et al., 1996, 2010; Li, 1999; Zhou et al., 2002a, 2002b; Wang et al., 2007, 2014a; Yao et al., 2014; Zhao, 2015). The Neoproterozoic successions include the early to middle Neoproterozoic Lengjiaxi Group and the middle Neoproterozoic Banxi Group (Zhao and Cawood, 2012; Wang et al., 2016). The Lengjiaxi Group is a suite of flysch turbidites mainly composed of sandstone, siltstone and pelite in protolith intercalated with volcanic rocks deposited in retro-arc foreland basins or in the back-arc at ca. 860–820 Ma (Wang et al., 2007, 2014a; Wang et al., 2010, 2012, 2013; Gao et al., 2011). The Banxi Group overlying the Lengjiaxi Group by an angular unconformity is mainly composed of sandstone, conglomerate and pelite with subordinate carbonate and volcanic rocks formed at ca. 800–760 Ma in a rift and passive margin environment (Wang et al., 2007, 2010).

The northeastern Hunan Province is located at the central segment of the Jiangnan Orogen. The Neoproterozoic successions (dominantly including the Lengjiaxi and Banxi groups metamorphosed in the greenschist facies) and Mesozoic to Cenozoic red-bed rocks together with minor Archean to Paleoproterozoic crystalline basement rocks (the Lianyunshan and Jianxichong groups) and Paleozoic sedimentary rocks constitute the lithostratigraphic units in this region (Wang et al., 2017; Zhou et al., 2021). Magmatism from the Neoproterozoic to the Jurassic-Cretaceous occurred in this area (Li, 2000; Mao et al., 2011; Lin et al., 2022), of which the Jurassic-Cretaceous granitoids are the most widespread (Fig. 1), including the Mufushan pluton (ca. 154–127 Ma; Wang et al., 2014b; Xu et al., 2022), Wangxiang pluton (ca. 160–140 Ma), Jinjing pluton (ca. 160–145 Ma) and the Lianyunshan pluton (ca. 155–140 Ma; Wang et al., 2016; Ji et al., 2017; Deng et al., 2017). The structural framework is characterized by two horsts and three grabens, namely the Miluo graben, the Mufushan–Wangxiang horst, the Changsha–Pingjiang graben, the Liuyang–Hengdong horst and the Liling–Youxian graben, from northwest to southeast (Xu et al., 2009). Several NE-trending, crustal-scale faults, represented by the Xinning–Huitang and the Changsha–Pingjiang fault zones form the major structures (Fig. 1b). Abundant Au-, Cu-Co-Pb-Zn- and Nb-Ta-Li deposits occur in the Mufushan–Wangxiang and Liuyang–Hengdong horsts (Fig. 1b).
3. Deposit geology

The Jingchong Cu-Co-Pb-Zn deposit, situated at the contact of the Changsha–Pingjiang graben and the Liuyang–Hengdong horst, is controlled by the regional Changsha–Pingjiang fault zone (Fig. 1b). This fault zone stretches for nearly 680 km and experienced the transform from transpression to transtension during the Jurassic to the Early Cretaceous (Zhou et al., 2021). It consists of numerous NE-trending parallel faults labeled by F1–5, of which F2 is the main fault with a width of 10–100 m, a strike of N30°E and 40°NW dip (Fig. 2a).

The lithostratigraphic units comprise the Neoproterozoic Lengjiaxi Group, the Middle Devonian Tiaomajian and Qiziqiao formations, the upper Devonian Shetianqiao Formation, the Cretaceous Daijiaping Formation and the Quaternary sediments (Fig. 2a). Due to the intrusion of the Lianyunshan granitoid, the Lengjiaxi Group to the east of the mining area occurs as the migmatization zone with the width of 15–240 m which consists of grey to dark-green banded migmatites and migmatitic gneiss. Fragments of the Lengjiaxi Group form as inclusion in the Lianyunshan granitoid. With the unconformity or fault contact with the Neoproterozoic Lengjiaxi Group, the Devonian Tiaomajian Formation with the lithological protolith of argillaceous limestone, shale, sandy shale, quartz sandstone and conglomerate occur at the footwall of F2. The Devonian Qiziqiao Formation occurs in the hanging wall of F2 and comprises limestone, dolomite, dolomitic limestone and calcareous slate. Due to faulting and hydrothermal activity, the Tiaomajian and Qiziqiao formations have been modified to the hydrothermal alteration zone and fracture zone, respectively (Fig. 2a). The hydrothermal alteration zone is characterized by silicified and/or chloritized breccia and quartzite. The fracture zone is comprised of cataclasite and gouge. The Devonian Shetianqiao Formation occurs in the centre of the mining area and mainly consists of slate and minor sandstone lenses. To the west, the Cretaceous Daijiaping Formation consists of purple-red sandstone, slate and sandy conglomerate. Quaternary sediments cover all other lithologies unconformably.

Magmatism is represented by the Late Jurassic to the Early Cretaceous Lianyunshan granitoid. It is mainly composed of biotite monzogranite, two mica monzogranite and granodiorite. In addition, minor granite porphyry occurs along F5 (Ning, 2002), although no age data are available.

Orebodies mainly occur as lenticular veins surrounded by the hydrothermal alteration zone, with Pb-Zn orebodies at the upper part of the hydrothermal alteration zone and Cu-Co orebodies in the lower segment (Fig. 2b). The Cu-Co orebodies are described by Wang et al. (2022), thus only Pb-Zn orebodies are introduced here. They are mainly present as veins and have a strike parallel to that of the hydrothermal alteration zone. Locally, it can be observed that Pb-Zn veinlets crosscut...
the Cu-Co ores (Fig. 3a-d), and the barren quartz veinlets crosscut Pb-Zn ores (Fig. 3e and f). The Pb-Zn ores have euhedral to anhedral granular, cataclastic and replacement textures, with vein, veinlet and massive structures (Fig. 3e-f). The ore mineral assemblage includes sphalerite and galena, with minor chalcopyrite, pyrite and pyrrhotite. The gangue minerals dominantly consist of quartz, with minor chlorite and siderite (Fig. 4).

4. Sampling and analytical methods

Nine representative Pb-Zn ore samples were collected from underground at 50 m and 0 m elevations (Table ESM 1). These samples include four samples from vein ores (05-B1, 05-B2, 05-B3, 05-B4) and five samples from massive ore (5SB-B1, 5SB-B2, 5B-4-1-18, 5B-6-4-18). They were prepared as polished thin sections for mineral chemistry analyses. A total of 54 LA-ICP-MS spot analyses were carried out for the three sphalerite generations (Table ESM 3).

4.1. Electron probe microanalyzer (EPMA)

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Major and selected trace elements of sphalerite were determined using the SHIMADZU EPMA-1720 electron microprobe equipped with four wavelength-dispersive spectrometers (WDS) at the School of Geosciences and Information Physics, Central South University, China. EPMA uses an accelerating voltage of 20 kV, a beam current of 10 nA and a beam diameter of 1 μm (Table ESM 2). The following elements, analytical lines, standards and monochromators were used for spot analysis: S (Kα), ZnS, PET, Zn (Kα, ZnS, LIF), Fe (Kα, FeS2, LIF), Co (Kα, Co, LIF), Ni (Kα, Ni, LIF), Cu (Kα, Cu, LIF), Cd (Lx, Cd, PET), Ga (Lx, GaAs, TAP), Ge (Lx, Ge, TAP), Sn (Lx, Sn, PET) and Pb (Ma, PbS, PET). The 2AF method (Duncumb and Reed, 1968) was used for the correction of matrix effects. In addition, Fe (Kα, LIF), Zn (Kα, LIF) and Cu (Kα, LIF) were selected for EPMA element mapping, with an accelerating voltage of 20 kV, beam current of 50 nA, sampling time for each point ranging from 30 to 80 ms, beam size of 1 μm and pitch of 1.1 μm. A total of 143 EPMA spot analyses were carried out for the three sphalerite generations (Table ESM 3).

4.2. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)

Minor and trace element concentrations in sphalerite were determined by a Teledyne CETAC Technologies Analyte Excite laser-ablation system in conjunction with a Nu Instruments Nu Plasma II MC-ICP-MS. Spot measurements were performed using a 30 μm beam size for pyrite and a 40 μm beam size for sphalerite, a pulse rate of 5 Hz, and a laser energy of 100 mJ. After four spot analyses, natural pyrite Wenshan (WS-1; 84Sr/87Sr = 0.7033 ± 0.0003; Zhu et al., 2017) was measured as an external standard. The pressed powder pellets of pyrite GBW 07267 (δ57Fe = +2.6%o ± 0.3‰; Fu et al., 2016) and chalcopyrite GBW 07268 (δ57Fe = -0.3%o ± 0.3‰; Fu et al., 2016) from China’s National Research Center for Geoanalysis as well as fine-grained sphalerite NBS 123 (δ34S = 0.2‰ ± 0.2‰; Bao et al., 2017) from the United States National Institute of Standards and Technology were used for quality control. In-situ sulfur isotopic studies on sphalerite and coexisting pyrite were performed at Nanjing FocuMS Technology Co. Ltd. (China) utilizing a Teledyne CETAC Technologies Analyte Excite laser-ablation system in conjunction with a Nu Instruments Nu Plasma II MC-ICP-MS. Spot measurements were performed using a 30 μm beam size for pyrite and a 40 μm beam size for sphalerite, a pulse rate of 5 Hz, and a laser energy of 100 mJ. After four spot analyses, natural pyrite Wenshan (WS-1; 84Sr/87Sr = 0.7033 ± 0.0003; Zhu et al., 2017) was measured as an external standard. The pressed powder pellets of pyrite GBW 07267 (δ57Fe = +2.6%o ± 0.3‰; Fu et al., 2016) and chalcopyrite GBW 07268 (δ57Fe = -0.3%o ± 0.3‰; Fu et al., 2016) from China’s National Research Center for Geoanalysis as well as fine-grained sphalerite NBS 123 (δ34S = 0.2‰ ± 0.2‰; Bao et al., 2017) from the United States National Institute of Standards and Technology were used for quality control. Sulfur isotopic compositions are expressed in terms of Canyon Diablo Troilite in conventional notation (CDT). The repeatability of the results was better than 0.6% (1σ). Results are given in the electronic supplementary material (Table ESM 6). Twenty-eight in-situ sulfur isotope analyses of sphalerite and associated pyrite were summarized in Fig. 11 and Table ESM 6.

4.4. Statistical analysis

Principal component analysis (PCA) as multivariate statistical analysis is commonly used to reveal the most relevant trends based on a geochemistry dataset without external supervision (Belissont, 2014; Frenzel et al., 2016; Bauer et al., 2019; Yu et al., 2020). Here, we apply PCA to determine the relevance of important minor and trace elements.
in sphalerite. Raw trace element data are log-transformed to ensure the approximate normality required for statistical treatment and are processed by the ioGAS software through the PCA function. Only the elements in more than half of all cases with concentrations above the detection limit were selected for calculation, and the concentrations below the detection limits in the dataset were replaced by random numbers in the normal distribution with a mean and standard deviation equal to the corresponding detection limit (Frenzel et al., 2016).

4.5. Muscovite $^{40}$Ar/$^{39}$Ar dating

After crushing and sieving to 250 to 500 μm size, muscovite was

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Fig. 5. Photomicrographs showing mineral assemblages of Pb-Zn ores and sphalerite textures from the Jingchong deposit. a Sph-I comprises reddish-brown Sph-Ia bands alternating with dark Sph-Ib bands. The honey-brown Sph-IIa replaces Sph-I, in turn is overgrown by white Sph-IIb. The black Sph-III crosscuts other sphalerite types. The white round and square-shaped dots are pits after laser ablation; transmitted light. b Sph-IIa formed along the grain boundaries (in white dash line) of Sph-I relics; transmitted light. c-d Sph-Ib are characterized by zoned chalcopyrite inclusions which are distributed along the crystal plane. Sph-IIa contains chalcopyrite blebs distributed unevenly and has sharp contact with Sph-I. e, transmitted light; d, reflected light. e Aligned pyrrhotite, chalcopyrite and pyrite inclusions in Sph-I. Noting Sph-III with dusting chalcopyrite inclusions cutting Sph-I; reflected light. f White Sph-IIb postdates Sph-IIa as the outer rim in an epitaxial texture; transmitted light. g Sph-IIb locally occurs as fine-grained aggregates; transmitted light. h Sph-III veins cutting Sph-I and Sph-II along fractures; transmitted light. i Corresponding zoomed area of h. Sph-III is rich in submicron chalcopyrite inclusions which are present as typical “dusting” or “watermelon” texture; reflected light. j Transmitted light of i. k Galena and pyrite coexisting with Sph-III; reflected light.
then washed with deionized water. After drying in an oven at 105 °C for 15 h, muscovite separates and the monitor sample ZBH-2506 (Beijing Fangshan granodiorite biotite, ca. 132.7 ± 0.5 Ma; Wang, 1983) were irradiated together in the 49-2 reactor at the atomic reactor of the Research Institute of Atomic Energy (Beijing, China) for an irradiation time of 23 h and 44 min. After cooling, the samples were placed in a sample holder, sealed and degassed, and then analyzed by the 40Ar/39Ar step-heating method by an Argus VI static vacuum mass spectrometer at the Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education, University of Geosciences (Wuhan), China. The correction factors include 39Ar/37Ar = 0.000852, 40Ar/37Ar = 0.000278 and 40Ar/39Ar = 0.001147. The 40Ar/39Ar results were processed and plotted using the ArArCALC Version 2.40 software (Koppers, 2002), and the decay constant used for calculations was λ = (5.54 ± 0.01) × 10−10 a−1 (Steiger and Jäger, 1977). The detailed analytical procedure is described by Qiu et al. (2010) and Zhang et al. (2014). The 40Ar/39Ar data are summarized in Table ESM 7.

5. Results

5.1. Sphalerite mineralogy and paragenesis

Based on the texture and distribution pattern of mineral inclusions, three sphalerite generations and five sphalerite subtypes are distinguished in the Jingchong deposit (Fig. 5a-d).

The first sphalerite generation (Sph-I) forms idiomorphic grains and is characterized by oscillatory zoning that consists of reddish-brown (Sph-Ia) alternated with dark (Sph-Ib) zones (Fig. 5i, j). Nano- to submicron-sized zoned chalcopyrite inclusions are widespread in Sph-III, which is commonly referred to as a “dusting” or “watermelon” texture (Fig. 5i, j) (Bortnikov et al., 1991; Bente and Doering, 1995; Seifert and Sandmann, 2006; Cook et al., 2009). Noticeably, these inclusions become gradually denser and smaller in size as they are closer to fractures (Fig. 5i, k). Locally, anhedral galena and pyrite occur with Sph-III (Fig. 5k).

5.2. Sphalerite chemical compositions and geothermometry and sulfur fugacity

Sph-I has a relatively broad compositional spectrum due to the oscillatory zoning. Generally, Sph-Ia has higher Zn (54.97–85.70 wt%) contents than Sph-Ib (56.16–57.77 wt%) and lower Fe (3.57–11.32 wt%) contents than Sph-Ib (6.82–7.38 wt%). The average formulae are (Zn0.940, Fe0.060)S for Sph-Ia and (Zn0.981, Fe0.017)S for Sph-Ib. Besides, Sph-Ia has higher Mn (127–312 ppm) and Cu (175–1530 ppm) contents than Sph-Ib (82.4–223 ppm Mn, 40.0–858 ppm Cu). The In (1.27–128 ppm) and Ga (0.35–15.1 ppm) contents in

Fig. 6. Box-and-whisker plots of the major and trace element contents of different sphalerite species from the Jingchong deposit. Iron (wt%) is from EPMA analyses and other trace elements (ppm) are from LA-ICP-MS analyses.

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Sph-IIa vary greatly relative to that of Sph-IIb (10.9–42.2 ppm In, 1.15–8.72 ppm Ga). The concentrations of Cd and Ge show no significant differences between the two sub-types (Fig. 6 c, i). The Sph-III contains moderate amounts of Fe (2.36–7.20 wt%), with the average formula of (Zn\(^{0.915}\), Fe\(^{0.078}\))S. In contrast to Sph-I and Sph-II, Sph-III has the highest contents of Cd (454–794 ppm), Cu (259–2748 ppm) and Ag (11.6–60.3 ppm). The concentrations of Sn and In are variable, ranging from 0.82 to 218 ppm and 0.47–181 ppm, respectively. The contents of Mn, Ga and Ge are 89.6–321 ppm, 0.42–13.8 ppm and 1.22–3.67 ppm, respectively (Fig. 6). The Ni, As, Se, Mo, Sb, Te, Au and Tl contents are generally low (Table ESM 4). Binary plots are used to discriminate the correlation between elements in Jingchong’s sphalerite. In Fig. 7, a clear negative correlation is seen between the element groups of Zn and Fe\(^{+}+\)Mn\(^{+}+\)Cd\(^{+}+\)Sn, whereas positive correlations are observed in the plots of Cu\(^{+}+\)Ag vs. In, Cu\(^{+}+\)Ag vs. In\(^{+}+\)Sn, Cu\(^{+}+\)Ag vs. Sn, and In vs. Sn. The In content, however, tends to increase with decreasing Fe content in sphalerite (Fig. 7 f).

The GGIFis geothermometer is employed to estimate the formation temperature of sphalerite varieties according to the Ga, Ge, Fe, Mn and In contents (Frenzel et al., 2016). The calculated formation temperature for the five sphalerite varieties is given in Table 1. Specifically, the GGIFis geothermometer gives average temperatures of 334 ± 56 °C for Sph-Ia, 346 ± 58 °C for Sph-Ib, 289 ± 55 °C for Sph-IIa, 254 ± 60 °C for Sph-IIb, and 286 ± 55 °C for Sph-III (Table 1). Based on GGIFis

![Fig. 7. Bivariate plots of Zn vs. Fe + Mn + Cd + Sn (a), Cu + Ag vs. In (b), Cu + Ag vs. In + Sn (c), Cu + Ag vs. Sn (d), In vs. Sn (e), and In vs. Fe (f).](image-url)

<table>
<thead>
<tr>
<th>Generation</th>
<th>PC1</th>
<th>T(_{GGIFis}) (°C)</th>
<th>2 (\sigma)(_{external}) (°C)</th>
<th>log(_{10})(FeS) (mol.%)</th>
<th>log(<em>{10})(f(</em>{S2}))</th>
<th>2 (\sigma)(<em>{external}) (f(</em>{S2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sph-Ia</td>
<td>-2.32 ± 0.14</td>
<td>334 ± 7</td>
<td>±56</td>
<td>-0.58 ± 0.01</td>
<td>-9.03 ± 0.01</td>
<td>±0.03</td>
</tr>
<tr>
<td>Sph-Ib</td>
<td>-2.54 ± 0.12</td>
<td>346 ± 6</td>
<td>±58</td>
<td>-0.49 ± 0.01</td>
<td>-8.26 ± 0.02</td>
<td>±0.06</td>
</tr>
<tr>
<td>Sph-IIa</td>
<td>-1.50 ± 0.12</td>
<td>289 ± 7</td>
<td>±55</td>
<td>-0.76 ± 0.03</td>
<td>-10.63 ± 0.07</td>
<td>±0.19</td>
</tr>
<tr>
<td>Sph-IIb</td>
<td>-0.84 ± 0.18</td>
<td>254 ± 10</td>
<td>±60</td>
<td>-1.05 ± 0.1</td>
<td>-11.77 ± 0.20</td>
<td>±0.38</td>
</tr>
<tr>
<td>Sph-III</td>
<td>-1.44 ± 0.09</td>
<td>286 ± 5</td>
<td>±55</td>
<td>-0.73 ± 0.04</td>
<td>-10.82 ± 0.08</td>
<td>±0.29</td>
</tr>
</tbody>
</table>

Note: Uncertainties provided here for PC1*, T\(_{GGIFis}\), log\(_{10}\)(FeS), and log\(_{10}\)(f\(_{S2}\)) in the corresponding columns are internal uncertainties. External uncertainties described by 2 \(\sigma\)\(_{external}\) in separate columns contain all sources of uncertainty. The uncertainty levels correspond to ±2 standard errors in all cases.
estimated temperatures (Frenzel et al., 2016; 2022) and FeS contents in sphalerite (Table ESM1), the sulfur fugacity is calculated. The results revealed that Sph-Ia has the mean sulfur fugacity ($\log_{10}f_{S_2}$) of $-9.03 \pm 0.03$ and Sph-Ib of $-8.26 \pm 0.06$. In contrast, Sph-IIa and Sph-IIb have a decreasing sulfur fugacity with $\log_{10}f_{S_2}$ values of $-10.63 \pm 0.19$ and $-11.77 \pm 0.38$, respectively. Sph-III gives mean $\log_{10}f_{S_2}$ values of $-10.82 \pm 0.29$ (Table 1).

5.3. Element distribution in sphalerite

In EPMA maps, the areas with higher Fe and Cu contents are characterized by relatively lower Zn content (Fig. 8b-d). Fe and Cu element maps display chalcopyrite inclusions with the most widespread in Sph-IIa and subordinate in Sph-Ib (Fig. 8c, d). After excluding the element anomalies from mineral inclusions, Sph-Ib has the highest Fe contents in all the sphalerite varieties, while Fe tends evenly distributed within Sph-Ia (Fig. 8c).

LA-ICP-MS trace element maps (Fig. 9) reveal composite sphalerite consisting of oscillatory-zoned Sph-I in the core, Sph-IIa in the rim and Sph-III veinlets. The dark Sph-Ib bands generally have high Fe, Cd, Mn, Cu, Ag and In but relatively low Zn concentrations (Fig. 9b-i). Specifically, the Fe-, Mn- and Cd-rich zones are mainly overlapped in Sph-Ib (Fig. 9c-e), while the Cu- and Ag-rich zones are generally consistent (Fig. 9g, h) but antithetical to the zoning patterns of Fe, Mn and Cd. The In map displays the best-developed rhythmic zoning, which overlaps with Cu- and Ag-rich zones in Sph-I (Fig. 9g-i). In contrast, Ga has a distinct distribution pattern in the element maps, i.e., local sector zoning. Sph-IIa and Sph-III have different element distribution patterns compared to Sph-I (Fig. 9g, h).

5.4. Principal component analysis

In the PCA loading biplot (Fig. 10), the arrow angles of two elements are determined by the covariance of element concentration (Bauer et al., 2019), and thus indicate the correlation of elements as well as similarities of geochemical behavior. The PCA results based on the log-transformed trace element concentration dataset yield a total variance of 72.3% explained by the first principal component (PC1, 55.1%) and the second principal component (PC2, 17.2%) for Sph-I (Fig. 10b). Manganese, Fe, Cu, Ag, Cd, In and Sn are mainly measured by PC1 to PC4. The scoring and loading biplot demonstrate that the data points of Sph-Ia and Sph-Ib are separate into two clusters (Fig. 10a, c), and two distinct element groups were identified: group-1 is composed of Ag, Cu and In, group-2 comprises Fe, Mn, Cd and Sn.

Principal components of PC1 (37.1%) and PC2 (23.2%) account for 60.3% of the total variance of Sph-II (Fig. 10e). The Sph-IIa and Sph-IIb populations appear to divide into two distinct clusters, showing minimal overlap (Fig. 10d). Based on the element correlation, three groups of elements are observed (Fig. 10d): Fe + Mn, Ag + Cu + Sn + Cd and In. As for Sph-III, PC1 (51.8%) and PC2 (18.2%) have a combined variance of 70% (Fig. 10h), and three major element groups are identified: Fe + Mn (group-1), Cu + Ag + Cd + Sn (group-2) and In (group-3). In general, In exhibits distinct geochemical behavior as indicated by the negative or unrelated correlation with other elements in Sph-II and Sph-III. In contrast, Cu and Ag are highly correlated and described by the same principal component.
5.5. Sulfur isotopes

Sph-I has $\delta^{34}$S$_{V-CDT}$ values from $-3.0$ to $-1.7\%$ (n = 15), Sph-II has $\delta^{34}$S$_{V-CDT}$ values varying between $-2.7$ and $-1.7\%$ (n = 12), and Sph-III yields $\delta^{34}$S$_{V-CDT}$ values between $-2.8$ and $-2.0\%$ (n = 5), indicating a relatively uniform sulfur isotopic composition. In contrast, pyrite has a relatively large $\delta^{34}$S$_{V-CDT}$ variation ranging from $2.1$ to $3.5\%$ (n = 6) (Fig. 11 and Table ESM 6).

5.6. Muscovite 40Ar/39Ar geochronology

The corresponding plateau, isochron and inverse isochron age diagrams are presented in Fig. 12. The 40Ar/39Ar data exhibited a flat distribution in plateaus indicating no disturbance by late thermal events. The plateau date in the range of 4.8% to 30% laser energy is ca. 121.4 $\pm$ 1.2 Ma (MSWD = 0.52, Fig. 12b), which accounts for 85.09% of the total 39Ar released. The corresponding isochron date is ca. 121.8 $\pm$ 1.2 Ma (MSWD = 0.54, Fig. 12b) and the inverse isochron date is ca. 121.7 $\pm$ 1.2 Ma (MSWD = 0.52, Fig. 12d). The initial 40Ar/36Ar ratios of 282.2 $\pm$ 8.5 and 283.8 $\pm$ 8.5 for the isochron and inverse isochron plots are close to the atmospheric value (295.5; Marty et al., 1989; Burnard et al., 1999). The plateau date is in good agreement with the isochron and inverse isochron dates, indicating that hydrothermal muscovite alteration occurs at ca. 121.1 $\pm$ 2 Ma.

6. Discussion

6.1. Element distribution and substitution mechanism

Micro-scale inclusions are often identified as peaks in LA-ICP-MS ablation profiles, and conversely, flat signal spectra indicate that elements are present in solid solution or evenly distributed nano-particles (Cook et al., 2009; Ye et al., 2011). Generally, time-resolved depth profiles of the Jingchong sphalerite exhibit smooth signal patterns of Mn, Co, Ni, Ga, Ge and Cd (Fig. 13). Most Fe and Cu profiles exhibit relatively flat features for all sphalerite varieties, indicating they are mainly present as solid solutions. However, a few peaks of Fe and Cu signals are observed in Sph-Ib and Sph-IIa ablation profiles (Fig. 13b, c). Their compatible trends further imply that these anomalous peaks are caused by chalcopyrite inclusions. This is consistent with bleb-shaped anomalies in EMPA maps (Fig. 8a, c, d). In addition, some Fe peaks unparallel with Cu signals in Sph-I profiles may be attributed to the presence of pyrite and/or pyrrhotite inclusions (Fig. 5e). Besides, the spiky spectra of Ag, In and Sn in Sph-IIa and Sph-III presented similar trends which are compatible to Fe and Cu signals (Fig. 13c, e), indicating that Ag, In and Sn occur in both solid solution and chalcopyrite inclusions. Noticeably, only the smooth signal sections in the time-resolved depth profiles were selected for data processing, i.e., the interference of micro-scale mineral inclusions on the trace element compositions of sphalerite are negligible.

Divalent cations such as Fe, Mn, Cd and Co commonly substitute Zn$^{2+}$ directly, while monovalent cations like Cu$^{+}$ and Ag$^{+}$ are favored to be incorporated into sphalerite lattice by coupled substitution with trivalent and/or tetravalent cations such as In$^{3+}$, Ga$^{3+}$, Sn$^{3+}$, Sn$^{4+}$ and...
direct substitutions are proposed in Sph-I: $\text{Zn}^{2+} \leftrightarrow (\text{Fe, Mn, Cd, Sn})^{2+}$. Given that $\text{Fe}^{3+}$ commonly exists in Fe-rich sphalerite with more than 10 mol.% FeS at high sulfur fugacity (Lepetit et al., 2003), the incorporation of $\text{Fe}^{3+}$ in the Jingchong sphalerite was not considered. In Sph-I, a coupled substitution of $2\text{Zn}^{2+} \leftrightarrow (\text{Cu, Ag})^{+} + \text{In}^{3+}$ is proposed based on the relatively narrow angles between In, Cu, and Ag in the PCA biplot and the positive correlation of Cu + Ag and In in Fig. 7b. Besides, the positive correlations in Cu + Ag vs. In + Sn, Cu + Ag vs. Sn and In vs. Sn plots (Fig. 7c-e) show that the data points are generally distributed along the lines of $(\text{Cu} + \text{Ag})/(\text{In} + \text{Sn}) = 1:1$, $(\text{Cu} + \text{Ag})/\text{Sn} = 1:2:1$, In/ Sn = 1/1. These observations suggest the coupled substitution of $4\text{Zn}^{2+} \leftrightarrow 2(\text{Cu, Ag})^{+} + \text{Sn}^{2+}$, $3\text{Zn}^{2+} \leftrightarrow 2(\text{Cu, Ag})^{+} + \text{Sn}^{2+}$ and $3\text{Zn}^{2+} \leftrightarrow \text{Sn}^{2+} + \text{In}^{3+} + [\text{vacancy}]$ may exist in Sph-I at Jingchong.

Different from Sph-I, PCA reveals different groups of Fe + Mn, Cu + Ag + Cd + Sn and In in Sph-II and Sph-III. This is consistent with the results that Sph-II and Sph-III generally show higher Cd, Cu, Ga, and Ge but lower Fe and Mn contents with variable In concentration compared to Sph-I (Figs. 6, 10). Thus, the following direct substitution may be incorporated into Sph-II and Sph-III: $\text{Zn}^{2+} \leftrightarrow (\text{Fe, Mn})^{2+}$. Besides, the weak negative correlation between Fe and Cd in PCA plots and their opposite distribution patterns in Sph-II and Sph-III (Fig. 9e, d and Fig. 10d, g) indicate that there is elemental competition between Fe and Cd, which can be described as $\text{Fe}^{3+} \leftrightarrow \text{Cd}^{2+}$. Notably, In tends to decouple from Cu and Ag in Sph-II and Sph-III (Fig. 7g-i) and exhibits uncorrelated or negative correlations with Cu, Ag and Fe in PCA (Fig. 10d, g). This is further confirmed by the irrelevance of Cu + Ag and In and the weak negative correlation between Fe and In as shown in Fig. 7b and f. These findings contradict many previous research studies in which In is commonly coupled with Cu and Ag and incorporated into sphalerite as solid solution or mineral inclusions, e.g., chalcopyrite (CuFeS$_2$), stannite (Cu$_2$FeSnS$_4$), roquesite (Cu$_2$SnS$_3$) and sakuraiite (Cu$_2$In$_x$Sn$_{3-x}$) (Cook et al., 2009; Pavlova et al., 2015; Bauer et al., 2017; Xu et al., 2020). Here, we infer that the following substitution could also exist in Sph-II and Sph-III: $3(\text{Zn, Fe})^{2+} \leftrightarrow 2\text{In}^{3+} + [\text{vacancy}]$.

6.2. Sphalerite formation mechanism

Oscillatory zoning as a common texture could be caused either by fluctuations of the physicochemical conditions under open systems or by the internal diffusion-limited self-organization process in closed systems (Reeder et al., 1990; Shore and Fowler, 1996; Holten et al., 1997; L’Heureux and Jamtveit, 2002; Di Benedetto, 2005). In the Jingchong deposit, no significant variations of the physicochemical conditions between Sph-Ia and Sph-Ib bands (Fig. 14) preclude the external mechanism caused by environmental fluctuations. Instead, the altered Fe + Cd + Mn-rich and Cu + Ag + In-rich zones in Sph-I (Fig. 9g) reveal the competition among these elements for incorporation into the crystal structure. Such element competition mechanisms are referred as self-organized non-equilibrium processes during crystal growth (Patrick et al., 1993; L’Heureux, 2000, 2013; Katsev and L’Heureux, 2001; Di Benedetto, 2005). The presence of sector zoning of Ga in Sph-I (Fig. 9f) which implies the slow crystallization growth, further supports a kinetically-induced process (Watson and Liang, 1995). Therefore, the self-organized mechanism is a possible explanation for the formation of Sph-I and its oscillatory and sector zoning patterns.

The intimate intergrowth of sphalerite with pyrite, pyrrhotite and chalcocopyrite has been interpreted as the products of exsolution, epitauxial growth, co-precipitation, or replacement (Wiggins and Craig, 1980). As for pyrite and pyrrhotite inclusions, they appear as oriented rows of blebs, ellipsoids or lamella, and are distributed discretely within Sph-I grains (Fig. 5e). This seems to preclude the likelihood of replacement (Wiggins and Craig, 1980), and instead exsolution formed the lamellar and ellipsoid intergrowths given the high Fe contents in Sph-I. It is supported by the partial overlap of the Sph-I ranges with the mineral reaction line of pyrite and pyrrhotite in Fig. 14 at relatively high...
temperature and sulfur fugacity conditions. The separation of pyrite and pyrrhotite inclusions most likely occurred from the Fe-rich ZnS meta-stable solid solution due to cooling or decompression (Wiggins and Craig, 1980; Bortnikov et al., 1991; Einaudi et al., 2003). However, exsolution is not an alternative formation mechanism for chalcopyrite inclusions due to the limited Cu-solubility in sphalerite (Kojima and Sugaki, 1985; Sugaki et al., 1987; Barton and Bethke, 1987; Kojima, 1990; Cook et al., 2009; Govindarao et al., 2018). The relatively high Fe contents in the dark Sph-Ib bands (av. 9.24 wt%), combined with the abundance of coexisting chalcopyrite inclusions, verified the potential of local supersaturation of Fe$^{2+}$ and Cu$^{+}$ at the mineral-fluid interfaces. Consequently, chalcopyrite inclusions parallel to the growth zones of Sph-I are most likely formed by co-precipitation (Mizukami and Ohmori, 1989; Kojima, 1990; Bortnikov et al., 1991; Kojima et al., 1995).

Sph-IIa occurs along fractures or grain boundaries of Sph-I (Figs. 5 a, b, c, h and 8 a). The sharp contact (Fig. 5 b, c) and remarkable changes in chemical compositions (such as Zn, Fe, Cd, Cu and Ag) between Sph-I and Sph-IIa (Figs. 6–8) indicate that Sph-IIa most likely formed by fluid-mediated coupled dissolution-reprecipitation reaction (CDR) (Altree-Williams et al., 2015). The fractures and grain boundaries of Sph-I can serve as the significant fluid pathway to the CDR reactions (Røyne et al., 2008; Jamtveit et al., 2009) and therefore formed “core (Sph-I)-rim (Sph-IIa)” texture. The higher Cu contents and more chalcopyrite inclusions in Sph-IIa further suggest the fluid is elevated in Cu contents. Thus, the replacement of Sph-I by Sph-IIa is explained by the following reaction: 2Zn$_{0.90}$Fe$_{0.10}$S$_{0.10}$Cu$^{+}$+0.10H$^+$ $\rightarrow$ 1.80Zn$_{0.95}$Fe$_{0.05}$S$_{0.10}$CuFeS$_{2}$+0.10Zn$^{2+}$+0.05H$_2$ (modified from Barton and Bethke, 1987, Eldridge et al., 1988, Bortnikov et al., 1991).

During this reaction, the dissolution of Fe-rich Sph-I provides abundant Zn$^{2+}$, Fe$^{2+}$ and S$^{2-}$, while fluids provide Cu$^{+}$ and H$^+$, which caused the subsequent precipitation of Sph-IIa and chalcopyrite inclusions. According to the GGIMFis geothermometer, Sph-II was formed at the lower temperature and sulfur fugacity conditions relative to Sph-I (Fig. 14). This indicates that the influx of the low-T, -pH and -fS$_2$ fluid with
elevated Cu level significantly facilitated the formation of Sph-IIa. After the extensive precipitation of Sph-IIa and chalcopyrite inclusions, the remaining fluids are depleted in Cu$^+$ and Fe$^{2+}$, and thus formed the Fe-poor Sph-Ib (rare chalcopyrite inclusions) with typical epitaxial texture. Relative to the formation temperature of 289 ± 55 °C for Sph-IIa, Sph-Ib yielded a lower temperature of 254 ± 60 °C, indicating Sph-Ib formed under decreasing temperature (Table 1; Fig. 14).

Sph-III is characterized by the “dusting” or “watermelon”-like chalcopyrite inclusions with uneven sizes and distribution patterns (Fig. 5 h, i), which are commonly regarded as the products of the solid-state diffusion mechanism (Bente and Doering, 1995; Blesgen et al., 2002, 2004, Blesgen, 2005; Bauer et al., 2017, 2019; Kaur et al., 2020). However, in our case, distinct textural and compositional boundaries between Sph-III and Sph-I/ Sph-II (Figs. 5 a, b, h and 8), and the absence of massive Cu-sulfide sources preclude solid-state diffusion. Instead, it favors the formation mechanism of CDR (Putnis, 2009, 2018; Zhao et al., 2013; Altree-Williams et al., 2015). The dissolution of Sph-I, Sph-II and their mineral inclusions can provide abundant Zn$^{2+}$, Fe$^{2+}$ and Cu$^+$ to form chalcopyrite inclusion-rich Sph-III. Nevertheless, given that the chalcopyrite inclusion is more abundant in Sph-III than Sph-I and Sph-II, a fluid pulse with elevated Cu contents may be involved during the Sph-III formation. Finally, a genetic model is built for the evolution of sphalerite varieties during Pb-Zn mineralization in the Jingchong deposit (Fig. 15).

6.3. Correlation of Pb-Zn with Cu-Co mineralization

The $^{40}$Ar-$^{39}$Ar dating of muscovite from the hydrothermal alteration zone gives a plateau age of ca. 121.1 ± 2 Ma (Fig. 12). According to the presence of sphalerite in the altered rock sample, the plateau age could be regarded as the mineralizing time of the Jingchong Cu-Co-Pb-Zn deposit given that the hydrothermal system is not extremely long-lived. The obtained mineralizing age is consistent either with that of the Hengdong Co deposit (ca. 125 Ma, muscovite $^{40}$Ar-$^{39}$Ar method; Zou et al., 2018) or the Taolin Pb-Zn deposit (ca. 121 Ma, muscovite $^{40}$Ar-$^{39}$Ar method; Xu et al., 2022) within error and slightly younger than that of the Lishan Cu-Pb-Zn deposit (ca. 129 Ma, muscovite $^{40}$Ar-$^{39}$Ar method; Xu et al., 2022). These geochronological data indicate that the Early Cretaceous (ca. 130–120 Ma) is an important Cu-Co-Pb-Zn mineralization period in the northeastern Hunan Province.

The abundance of trace elements such as Fe, Mn, Cu, Ga, Ge, Cd, In and Sn in sphalerite can serve as important indicators for its origin (Cook...
et al., 2009; Ye et al., 2011; Belissont, 2014; Yu et al., 2020; Zhao et al., 2023). Generally, magmatic-hydrothermal sphalerite has higher Fe, Mn, Cu, In and Sn compared to those of non-magmatic-hydrothermal deposits (Canet et al., 2009; Murakami and Ishihara, 2013; Belissont, 2014; Bauer et al., 2019; Zhao et al., 2023). The Jingchong sphalerite exhibits Fe (av. 5.87 wt%), Mn (av. 229 ppm), Cu (av. 692 ppm), In (av. 46.5 ppm) and Sn (av. 44.0 ppm) concentrations, which are obviously higher than those in the non-magmatic-hydrothermal deposits (e.g., MVT, Jingding, Irish-type Pb-Zn deposits with generally Fe < 2 wt%, Mn < 100 ppm, Cu < 200 ppm, In < 1 ppm and Sn < 1 ppm; Ye et al., 2011; Bonnet et al., 2016; Zhou et al., 2018; Li et al., 2020; Yu et al., 2020; Song et al., 2020; Doran et al., 2022). Besides, the Cd/Fe and Cd/Mn ratios of the Jingchong sphalerite range from 0.013 to 0.054 and 1.21 to 4.12, respectively, consistent with that of magmatic-hydrothermal origin (Cd/Fe < 0.1, Cd/Mn < 5; Zhao et al., 2007; Cao et al., 2014; Yu et al., 2020).

In general, the measured δ³⁴S_VCDT values of sulfide minerals are regarded as equivalent to those of fluids at low oxygen fugacity and pH conditions (Ohmoto and Goldhaber, 1997). Given the absence of sulfate minerals and Fe-oxides in the Pb-Zn mineral paragenesis and the medium-low formation temperature for different sphalerite types (Fig. 14), the measured δ³⁴S_VCDT values can represent the sulfur isotopic composition of the ore-forming fluid. By comparison, the measured δ³⁴S_VCDT values are obviously distinct from that of the Neoproterozoic Lengjiaxi Group (Fig. 11; Luo, 1990; Liu et al., 1994; Liu et al., 1999), indicating a non-strata sulfur origin. Instead, they are similar to those for the magmatic-hydrothermal vein-type Lishan (5.1 to −0.4‰; Yu et al., 2021) and Taolin (−6.0 to −2.3‰; Yu et al., 2020) Pb-Zn (-Cu) deposits, and the skarn-porphry Qibaoshan (+0.6 to +5.4‰; Liu et al., 2001) and Aoyushan (−2.9 to +3.3‰; Liu et al., 2001) Cu-Pb-Zn deposits in the northeastern Hunan Province. What is more, the measured δ³⁴S_VCDT values (−2.79‰ to +3.47‰) of sulfides from Pb-Zn ores fall in the δ³⁴S_VCDT range of Jingchong Co-Cu ores (−3.57‰; Wang et al., 2017, 2022), indicating a similar sulfur source for both Cu-Co- and Pb-Zn mineralization. Consequently, consistent with the Cu-Co ores (Wang et al., 2022), the Jingchong Pb-Zn ores most likely have a sulfur source predominantly from a magmatic reservoir (0 ± 5‰; Ohmoto and Rye, 1979).

The fluid cooling, boiling and mixing are considered as important metal precipitation mechanisms (Hemley et al., 1992; Hemley and Hunt, 1992). In the Jingchong deposit, no evidence supports that fluid boiling controlled Cu-Co-Pb-Zn deposition according to the available mineralogical and fluid inclusion data (Zhou and Kang, 2017). The integrated

Fig. 14. Sulfur fugacity-inverse temperature plot (adapted from Einaudi et al., 2003; Frenzel et al., 2022) showing the location of different sphalerite species in the Jingchong deposit relative to mineral reaction lines (in black), the S-gas and rock buffers (in grey), and isolines (in blue) describing the variation in sphalerite Fe contents. Ellipses delineating the fields for sphalerite varieties correspond to 95% confidence intervals. Mineral abbreviations: Cv, covellite; Dg, digenite; Py, pyrite; Bn, bornite; Ccp, chalcopyrite; Po, pyrrhotite; Apy, arsenopyrite; Lo, loellingite.

Fig. 15. Schematic diagram for the formation of three sphalerite generations in the Jingchong deposit.
mineralogical and sulfur isotope evidence have disclosed that the Jingchong Pb-Zn and Cu-Co mineralization were formed in a magmatic-hydrothermal system with similar wall rock alteration. The He-Ar isotopes of Cu-Co ores revealed that the mixing of magmatic-hydrothermal fluids with meteoric water was a possible mechanism for metal precipitation (Wang et al., 2017, 2022). In combination with the consistent ore-forming temperature between the Cu-Co stages (256–318 °C, chlorite geothermometry; Wang et al., 2017) and Pb-Zn stage (286–346 °C, sphalerite geothermometry; this study), the mixing process is assumed to dominate the mineralization of Pb-Zn. The placement of Pb-Zn orebodies at the upward zoning of Cu-Co orebodies and the sequent precipitation of Pb-Zn following Cu-Co might be related to the mobility of these metals in hydrothermal fluids (Brügger et al., 2016). According to Soft-Hard Acid-Base theory (Pearson, 1963), chloride complexes are assumed to be the dominant Co, Cu, Pb and Zn species in hydrothermal solutions with the temperature of no more than 400 °C, and their stability is dependent not only on the temperature, salinity, pH and redox of ore-forming fluid but also the coordination chemistry of metals (Migdisov et al., 2011; Zhong et al., 2015; Brügger et al., 2016). As mentioned above, the varying physicochemical conditions are hardly considered as the main factors controlling the discrepant precipitation between Pb-Zn- and Cu-Co metals. Instead, the higher solubility of Pb and Zn complexes relative to Cu complex in hydrothermal fluids could explain the long-distance transportation of Pb-Zn than Cu (Hemley et al., 1992; Emsbo, 2000).

7. Conclusions

(1) Three generations of sphalerite are identified. Sph-I is featured by the oscillatory and sector zonings of Sph-I are formed by the self-organized mechanism. Pyrite and pyrrhotite inclusions in Sph-I are exsolved, while chalcopyrite inclusions are co-precipitated. The Sph-II and Sph-III species and associated mineral inclusions are interpreted to be formed by CDR reactions with the aid of the influx of relatively Cu-elevated fluids and subsequent direct precipitation.

(4) The Jingchong deposit was most likely formed at ca. 121.1 ± 2 Ma based on muscovite 40Ar/39Ar dating, which is in agreement with the ca. 130–120 Ma Pb-Zn mineralizing events in the northeastern Hunan Province. The sulfur isotopic values (−3.0 to +3.5‰) of the Pb-Zn ores plot within the range of Cu-Co ores, indicating a similar sulfur reservoir. Together with the trace element affinity of sphalerite with magmatic-hydrothermal origin, the Jingchong Pb-Zn and Cu-Co mineralization was formed in a magmatic-hydrothermal system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared my data in the appendix at the Attach File step

Acknowledgments

This research was financially co-supported by the National Natural Science Foundation of China (No. 42372106, 41672077), Hunan Provincial Natural Science Foundation of China (No. 2021JJ30817), Jiangxi Provincial Natural Science Foundation of China (No. 2022ACB203008) and China Scholarship Council (CSC). LA-ICPMS facility at LERA KIT is supported by DFG grant INST 121384/213-1 FUGG. The authors sincerely thank Kirsten Drüppel and Qizi Hu for LA-ICP-MS technical support, and Diogo Ribeiro and Matteo Luca Dedda for helpful discussion. A particular thank is given to editors and two anonymous reviewers for constructive reviews.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oregeorev.2023.105667.

References


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