

Magmatic to Hydrothermal Evolution of Bianjiadayuan Ag-Pb-Zn-Sn Deposit, Northeast China: A Quartz Texture and Trace Elements Study

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ABSTRACT: Quartz trace elements are extensively employed in studying magmatic evolution, fluid evolution, and metal enrichment. The Bianjiadayuan Ag-Pb-Zn-Sn deposit is a typical magmatic-hydrothermal system in northeastern China, however, studies on its complex magmatic-hydrothermal evolution are limited. This study investigates the quartz from the Bianjiadayuan deposit to gain insight into the physicochemical evolution of mineralization using cathodoluminescence (CL) textures and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) of quartz. Five types quartz (Q1 to Q5) were identified. From Q1 in quartz porphyry to Q5 in Ag-Pb-Zn veins, the CL intensity and Ti content gradually decreases, and Ge, Ge/Ti, and Al/Ti ratios increase, indicating a temperature decline from magmatic to hydrothermal stages. The Sb content shows an opposite trend to Ti content, correlating positively with Ge content in quartz, suggesting that Sb content could also be temperature-dependent. These trace elements in quartz indicate cooling is critical for Ag mineralization. Furthermore, quartz phenocryst (Q1) from the quartz porphyry shows low Al/Ti (mostly < 4) and Ge/Ti ratios (< 0.04), suggesting a low degree of magmatic evolution. The Sb content in Q5 from Ag-Pb-Zn-quartz veins (> 1 ppm, mostly tens of ppm) is notably higher compared to quartz in other lithologies including Sn-bearing quartz veins (< 1 ppm), suggesting that Sb contents can serve as an effective indicator of Ag mineralization.

KEY WORDS: quartz, trace elements, Ag mineralization, Ag-Pb-Zn-Sn deposit, Bianjiadayuan.

0 INTRODUCTION

Quartz is prevalent in magmatic-hydrothermal ore-forming systems and serves as a key recorder of fluid evolution and mineralization processes (Rusk, 2012). Numerous studies based on CL texture and concentrations of trace elements in quartz to determine magmatic evolution, fluid evolution, and metal enrichment processes (Jiang and Wang, 2022; Hong et al., 2021; Zhang et al., 2019; Breiter et al., 2017, 2013; Mao et al., 2017; Jacamon and Larsen, 2009; Rusk et al., 2008). For example, previous studies show that the Al/Ti and Ge/Ti ratios can indicate the degree of magma differentiation (Breiter et

al., 2013; Jacamon and Larsen, 2009). Moreover, Ti content in quartz is positively correlated with temperature (Breiter and Müller, 2009; Larsen et al., 2004) and accordingly, Ti in quartz geothermobarometer was established (Huang and Audétat, 2012; Thomas et al., 2010; Wark and Watson, 2006). However, there have been few studies of metal enrichment mechanisms for relevant trace elements in quartz, especially for complex Ag-bearing magmatic-hydrothermal systems.

The Bianjiadayuan deposit is a typically magmatic-hydrothermal type Ag-Pb-Zn-Sn deposit based on previous studies, such as the geological, geophysical, and structural (Liu et al., 2016; Wang et al., 2014), origin and evolution of the ore-forming fluids (Zhai et al., 2018; Ruan et al., 2015), petrology and geochemistry of ore-related intrusions (Wang et al., 2022; Jiang et al., 2020; Ruan et al., 2015; Wang et al., 2013), mineralogical geochemistry of pyrite, freibergite, pyrrargyrite, and boulangierite (Zhai et al., 2019; Song et al., 2019) and geochronological of mineralization (Gu et al., 2017; Zhai et

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Manuscript received July 25, 2024.

Manuscript accepted November 8, 2024.

al., 2017; Wang et al., 2014; Ruan et al., 2013). Fluid inclusions and C-H-O isotopic analyses indicate that the ore-forming fluids are dominated by magmatic-hydrothermal fluids with the addition of meteoric water (Zhai et al., 2018; Ruan et al., 2015). Despite detailed fluid inclusions studies, there remains a gap in understanding the transition from the magmatic to the hydrothermal stage. Reconstruction of magmatic to hydrothermal evolution contributes to better analysis of metal precipitation mechanisms.

Thus, we focus on the Bianjiadayuan Ag-Pb-Zn-Sn deposit to enhance comprehension of magmatic-hydrothermal fluids evolution and the mechanisms driving Ag enrichment. A detailed textural and geochemical analysis of various quartz types has been conducted, including the quartz porphyry (Q1), greisen (Q2), breccia (Q3), Sn-Cu-Mo quartz vein (Q4), and Ag-Pb-Zn quartz vein (Q5) from the Bianjiadayuan magmatic-hydrothermal system.

1 REGIONAL GEOLOGY

The Central Asian Orogenic Belt (CAOB), which originated during the Neoproterozoic to Phanerozoic, is bordered by the Siberian, Tarim, and North China Cratons. It

was formed through successive accretion of arc complexes, accompanied by the emplacement of extensive volumes of granitic magmas (Jahn et al., 2000). This geological belt is considered one of the largest accretionary orogens formed in the Phanerozoic (Shi et al., 2010; Jahn, 2004).

The eastern part of the CAOB is referred to as the Xing'an-Mongolia Orogenic Belt, spanning Inner Mongolia and Northeast China (Xu et al., 2015). The southern Great Hinggan Range is of particular interest in terms of tectonic importance. The southern Great Hinggan Range forms a wedge-shaped zone, delineated by the Xar Moron fault to the south, separating it from the North China Craton; the Erlian-Hegenshan fault to the northwest, bordering the Erguna-Xing'an Block; and the Nenjiang fault to the northeast, adjacent to the Songliao Basin.

The Xilinhot Massif is the oldest formation in the southern Great Hinggan Range. It is a Paleozoic metamorphic complex including biotite-plagioclase gneiss, plagioclase-amphibole gneiss, plagioclase-amphibole schist, and leptynite. Additionally, remnants of Ordovician, Silurian, Devonian, and Carboniferous detrital metasedimentary units and volcanic formations are locally scattered across the area. Permian volcano-sedimentary for-

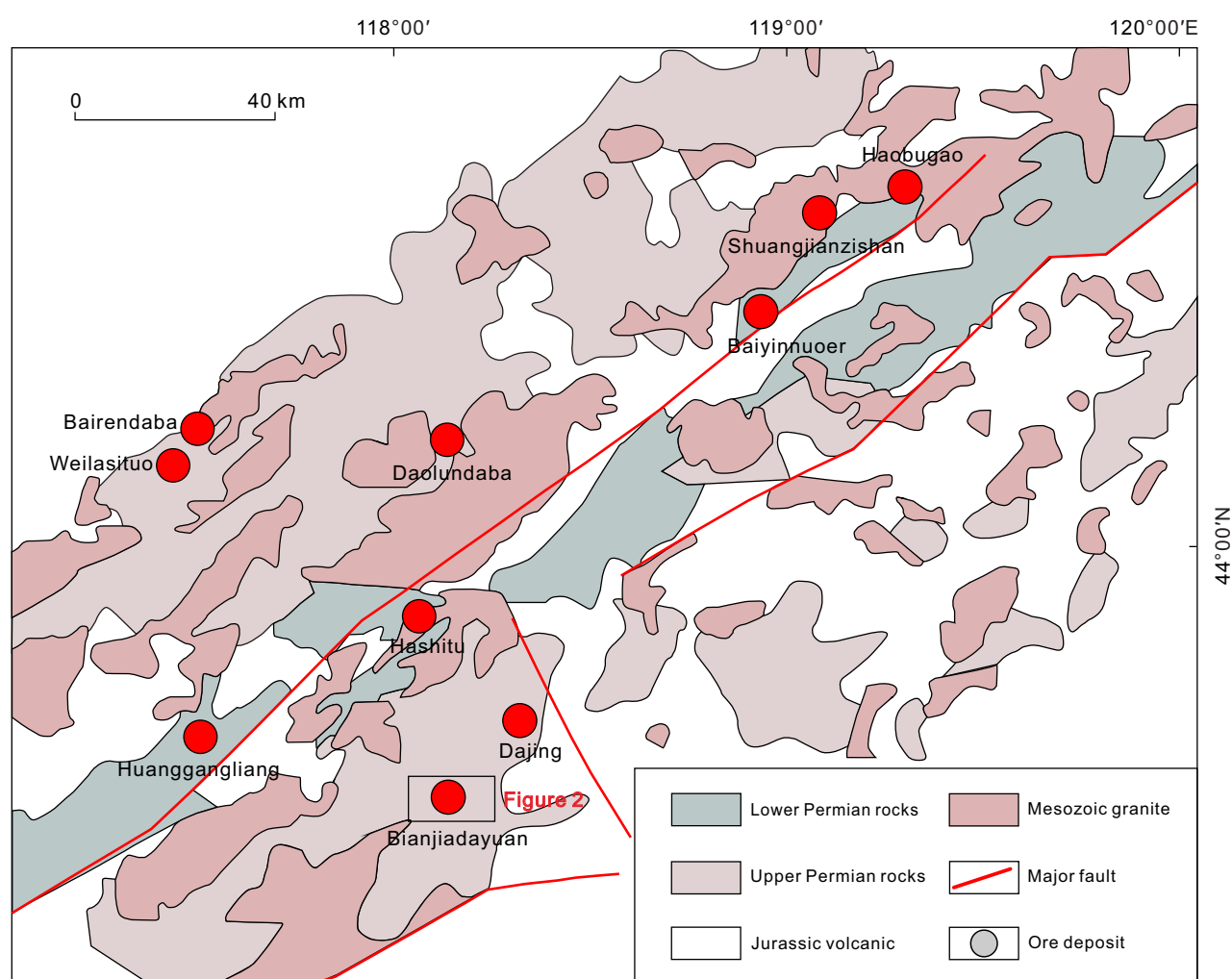


Figure 1. Geological map of the southern of the Great Xing'an Range (modified after Zhai et al., 2019).

mations are widespread, extending further northeast and serving as the predominant host rocks for numerous ore deposits (Chen et al., 2022; Zhai et al., 2014; Shu et al., 2013; Qin et al., 2001). The dominant rock types in this domain include carbonaceous clastic rocks, carbonate rocks, and mafic to intermediate volcanic rocks.

The faults in the southern Great Hinggan Range are mainly NE- and EW-trending. These faults control the distributions of Jurassic–Cretaceous intrusions and polymetallic deposits (Figure 1). Phanerozoic magmatic intrusions are prevalent along an NE-trending belt across the southern Great Hinggan Range. Late Paleozoic granitoids, including diorite, tonalite, and granodiorite, are predominantly found on the western slope of the southern Great Hinggan Range, with ages ranging from 321 to 237 Ma (Wu et al., 2011). Mesozoic granitic plutons, particularly from the Yanshanian, consist of granodiorite, monzogranite, and syenogranite aged from 150 to 131 Ma (Pei et al., 2018; Ouyang et al., 2015). Most polymetallic deposits of vein-, porphyry-, and skarn-type are hosted primarily by Permian volcanic-sedimentary rocks and Mesozoic strata and plutons (Figure 1). According to previous geochronological studies, these deposits formed mainly during the Early Cretaceous Period (120–155 Ma; Wang et al., 2017; Ouyang et al., 2015), coinciding with the period of granitic magmatism (Chen et al., 2017).

2 DEPOSIT GEOLOGY

The Bianjiadayuan Ag-Pb-Zn-Sn deposit is situated within the southern Great Hinggan Range metallogenic

belt (Figure 1; Zhai et al., 2018). The orebodies are mainly hosted by the Permian Zhesi Formation, which includes slates and siltstones (Figure 2a). The dominant igneous rocks include gabbro (133.2 ± 0.9 Ma; Wang, 2014), quartz porphyry (141–139 Ma, Zhai et al., 2017; Wang, 2014) and numerous granite dikes (Figure 2a; 129.6–130.5 Ma, Wang et al., 2016). The gabbro hosts minor Cu-Pb-Zn veins (Figure 2a), exhibiting a typical gabbroic texture and is characterized by a dominance of plagioclase (55%–60%), pyroxene (30%), hornblende (5%), and biotite (5%) (Wang et al., 2013). Quartz porphyry predominantly outcrop in the western region of the deposit, with a minor occurrence in the southeastern area (Figure 2a). It is composed of quartz (45%–50%), K-feldspar (40%–45%), plagioclase (5%–10%), and minor biotite (Figures 3a–3b; Wang et al., 2014). Quartz porphyry is regarded as a metallogenic geological body (Jiang et al., 2020; Zhai et al., 2017). The ore types at the Bianjiadayuan deposit include porphyry-type Sn-Cu-Mo (Pb-Zn) mineralization, breccia-type Ag-Pb-Zn, and vein-type Ag-Pb-Zn mineralization (Song et al., 2019). The porphyry-type mineralization mainly occurs as veins, stockworks, and veinlets within the quartz porphyry (8 936 tons, 0.35% Sn; 724 tons, 1.187% Cu; 551 tons, 0.109% Mo; 505 tons, 1.98% Pb; 805 tons, 1.48% Zn). In a vertical profile from the porphyry core upward, the distribution of ore metals shows a zonation of tin (Sn), copper (Cu), and molybdenum (Mo) (Zhai et al., 2017). The ore minerals are mainly cassiterite and stannite, with lesser amounts of molybdenite, chalcopyrite, arsenopyrite, galena, and sphalerite. Cassiterite commonly occurs with

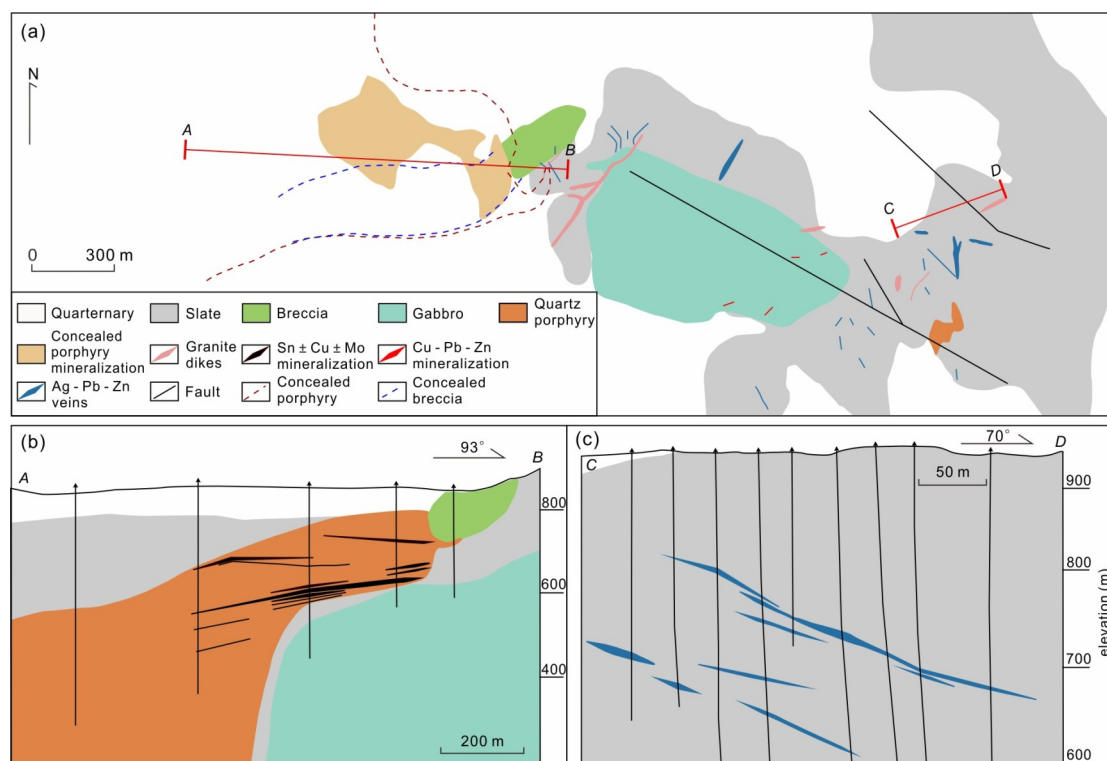


Figure 2. (a) Simplified geological map of the Bianjiadayuan deposit; (b)–(c) representative cross-sections of the Bianjiadayuan Ag-Pb-Zn-Sn deposit (modified after Zhai et al., 2019).

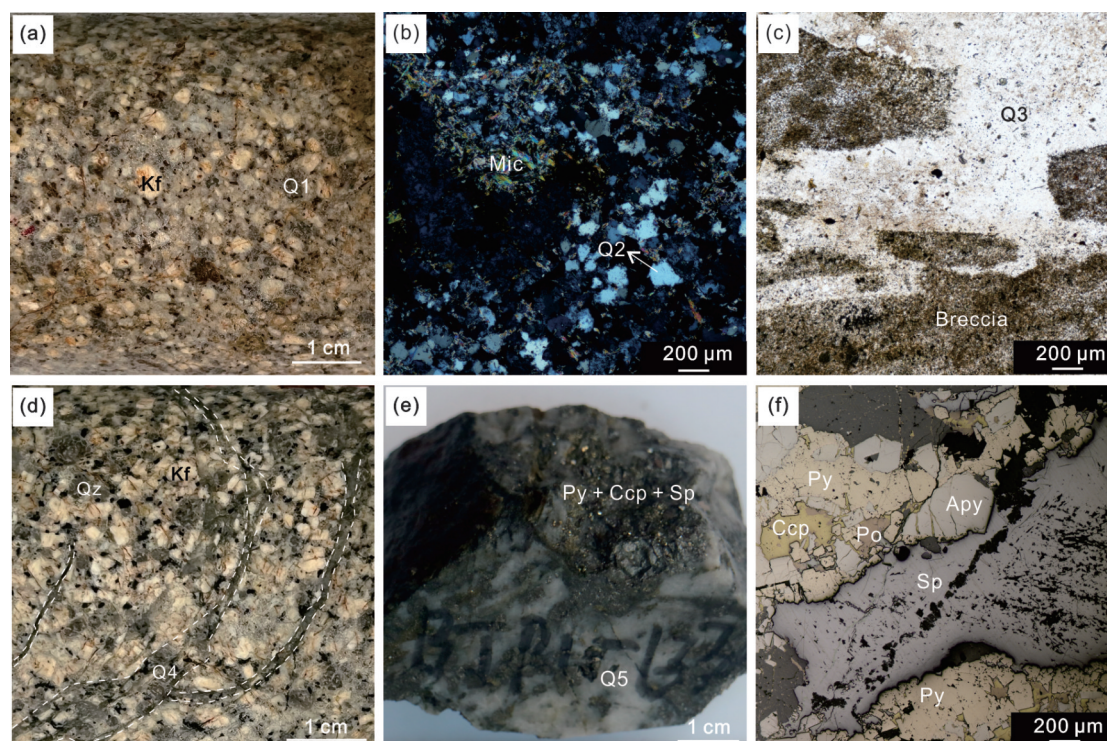


Figure 3. Photographs and photomicrographs of quartz porphyry, greisen, breccia, Sn-Cu-Mo quartz vein, and sulfides quartz vein in the Bianjiadayuan Ag-Pb-Zn-Sn deposit. (a) Hand specimen showing typical occurrences of quartz phenocryst (Q1) in quartz porphyry; (b) Photomicrograph of quartz (Q2) in greisen; (c) photomicrographs of hydrothermal breccia, with quartz cement (Q3); (d) the quartz (Q4) occurs in veins, stockworks, and veinlets within the quartz porphyry; (e) hand specimen showing quartz-sulfide veins; (f) photomicrograph of quartz-sulfide veins, showing that the later sphalerite crosscuts the earlier pyrite-chalcocopyrite-pyrrhotite-arsenopyrite. Ccp. Chalcocopyrite; Apy. arsenopyrite; Kf. K-feldspar; Mic. mica; Po. pyrrhotite; Qz. quartz; Sp. sphalerite.

stannite in varying proportions, predominantly in deeper sections. Moving upward, it transitions into zones containing chalcocopyrite, arsenopyrite, molybdenite, pyrrhotite, galena, and sphalerite as secondary minerals. The alteration in the porphyry system includes early weak potassic alteration at the core characterized by K-feldspar and biotite, widespread phyllic alteration with quartz and sericite extending outward, propylitic alteration forming a halo with abundant chlorite and epidote, and rare argillic alteration that is not commonly identified (Zhai et al., 2017). The breccia Ag-Pb-Zn zones are found at relatively shallow depths ($\leq \sim 160$ m; Zhai et al., 2019, 2017). The breccia dominantly comprises fragments of slate and quartz porphyry with a cement composed of fine rock fragments and sulfides, i. e., pyrite, sphalerite, galena, and minor chalcocopyrite (Figure 3c). Hydrothermal alteration in breccia-type mineralization features a mineral assemblage of quartz, chlorite, epidote, sericite, and kaolinite. The vein-type Ag-Pb-Zn orebody is primarily hosted in Permian slates (91 669 tons, 1.98% Pb; 92 061 tons, 1.98% Zn; 66.35 tons, 157.4 g/t Ag). It is controlled by NW-trending faults and is located several hundred meters east of the porphyry-type Sn-Cu-Mo mineralization zones (Figure 2c). Ore minerals include galena, sphalerite, chalcocopyrite, pyrrhotite and arsenopyrite (Figures 3e–3f), and Ag-bearing minerals are mainly antimonite, freibergite and pyrargyrite (Zhai et al., 2019). Hydrothermal alterations

are characterized by sericitization, chloritization, epidotization, kaolinization, and carbonatation (Song et al., 2019).

3 QUARTZ OCCURRENCE

Five types of quartz have been identified from the magmatic to hydrothermal stage at the Bianjiadayuan deposit (Table S1; Figure 3). (1) Quartz phenocryst in quartz porphyry: the quartz phenocryst (Q1) occurs as subhedral to anhedral granular, measuring 0.4–1 mm, frequently coexisting with K-feldspar and plagioclase (Figure 3a), and occasionally with biotite, chalcocopyrite, and cassiterite. (2) Quartz in greisen: the quartz (Q2) occurs as anhedral granular aggregates, and commonly coexists with mica, minor galena, and molybdenite (Figure 3b). (3) Quartz in breccia: the quartz cement (Q3) in the breccia appears as anhedral granular aggregates (Figure 3c), coexisting with mica, pyrite, sphalerite, galena, and minor chalcocopyrite. (4) Quartz in Sn-Cu-Mo-Quartz veins: the Sn-Cu-Mo veins are present as veins, stockworks, and veinlets within the quartz porphyry. The quartz (Q4) in the Sn-Cu-Mo veins coexists with cassiterite and stannite, with less amounts of pyrite, molybdenite, chalcocopyrite, arsenopyrite, galena, sphalerite, magnetite, and hematite. (5) Quartz in Ag-Pb-Zn-Quartz veins: the quartz (Q5) coexists with calcite, galena, sphalerite, pyrite, chalcocopyrite, pyrrhotite, arsenopyrite (Figures 3e–3f), pyrargy-

rite, and freibergite.

4 SAMPLES AND METHODS

The samples used in this study were obtained from surface outcrops, underground tunnels, and boreholes within the Bianjiadayuan deposits (Table S1). Upon collection, rigorous cleaning and classification processes were conducted, followed by photographic documentation. Representative samples were selected for the preparation of thin sections and slices to facilitate further analysis. Detailed petrographic and mineralogical examinations were carried out on various rocks and ores using microscopy. Double-polished thin sections underwent scrutiny using a combination of microscopy, scanning electron microscope-cathodoluminescence (SEM-CL), and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). The LA-ICP-MS analysis protocol utilized in this research was designed to minimize the inadvertent ablation of mineral and fluid inclusions within the quartz samples. This method integrated CL images and transmitted light images to guide the laser ablation process effectively.

Quartz cathodoluminescence (CL) images were captured using a cross-insert CL detector connected to a TI-MA GMS system at the Laboratory of Mineralization and Dynamics, Chang'an University, China. The imaging procedure involved applying a 15 kV electric field voltage and a 15 nA current during the acquisition process.

The agilent 7900 ICP-MS with an NWRfemto was employed for *in-situ* LA-ICPMS analysis at the State Key Laboratory of Ore Deposit Geochemistry, Chinese Academy of Sciences. Laser ablation system parameters, ICP-MS operational settings, and data reduction methods followed those described in Lan et al. (2018). A 44 μm laser spot size was used, and trace elements were calibrated against NIST SRM612 and GSE-1G glass standards. Data

processing for trace element analysis was conducted using ICPMSDataCal as outlined in Liu et al. (2008).

5 RESULTS

5.1 Internal Textures of Quartz

In the Bianjiadayuan deposit, the Q1 in the quartz porphyry occurs as subhedral-anhedral granular with gray-white CL with CL-dark fractures and spiders (Figure 4a). The Q2 in the greisen has weak luminescent streaks with gray-white CL (Figure 4b) and the Q3 in the breccia show a consistent homogeneous gray-black CL (Figure 4c), respectively. Moreover, Q4 in the Sn-Cu-Mo veins displays gray-white CL (Figure 4d). Q5 in the Ag-Pb-Zn veins demonstrates gray-black CL with spider and cobweb texture (Figure 4e). From Q1 in the quartz porphyry to Q5 in the Ag-Pb-Zn veins, CL of quartz shows a gradual decrease in brightness.

5.2 Chemical Composition of Quartz

Audétat et al. (2015) and Götze et al. (2004) observed that Na, K, and Ca are notably scarce in quartz compared to other minerals and fluid inclusions. Hence, these elements could be the monitors of contamination from accidental ablation of other mineral and fluid inclusions (Mao et al., 2017). For instance, an abundance of albite grains within quartz could lead to anomalous spectra or spikes in Al and Na concentrations. Similarly, the presence of minerals like K-feldspar, often found alongside quartz, could elevate levels of K and Al. Furthermore, the reliability of B and P values was questioned due to challenges in analysis (Audétat et al., 2015). To eliminate these issues of contamination and uncertainty, any analysis data are available in Table S2 and S3, with specific trace element concentrations provided in Table S4.

Quartz in the Bianjiadayuan deposit generally has lower SiO_2 concentrations, with quartz from quartz por-

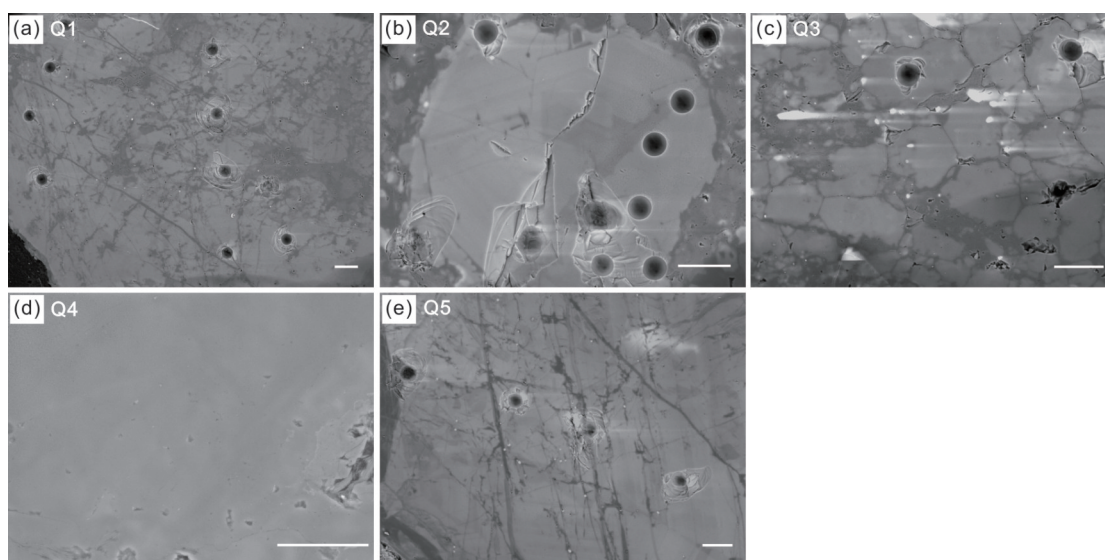


Figure 4. Representative images showing SEM-CL textures of quartz types from the Bianjiadayuan Ag-Pb-Zn-Sn deposit. (a) Q1 in quartz porphyry; (b) Q2 in greisen; (c) Q3 of breccia; (d) Q4 of Sn-Cu-Mo-bearing quartz veins; (e) Q5 of Ag-Pb-Zn-bearing quartz veins. Scale bars in these cases equal 100 μm .

phyry, greisen, and breccia ranging from 99.91 wt.% to 99.96 wt.%, 99.93 wt.% to 99.96 wt.%, and 99.86 wt.% to 99.90 wt.%, respectively. Quartz samples show variations in SiO_2 content, ranging from 99.86 wt.% to 99.97 wt.% in the Sn-Cu-Mo vein and from 99.79 wt.% to 99.97 wt.% in the Ag-Pb-Zn vein.

Further, the Al content of the quartz in the quartz porphyry (83.1 ppm–200 ppm, median 101 ppm) and greisen (89.7 ppm–148 ppm, median 108 ppm) are consistently low. The Al contents of quartz in the breccia are significantly above the content of quartz in quartz porphyry and greisen, reaching 265 ppm–365 ppm (median 306 ppm). Further, the Al content of vein-type quartz variation in a broad range, including quartz in the Sn-Cu-Mo veins (53.1 ppm–559 ppm, median 310 ppm) and Ag-Pb-Zn veins (54.3 ppm–906 ppm, median 432 ppm) (Figure 5).

Moreover, the Li content of Q3 from the breccia and Q5 from the Ag-Pb-Zn vein is relatively high, with 36.1 ppm–39.8 ppm (median 39.3 ppm) and 3.59 ppm–58.0 ppm (median 29.2 ppm). However, Q1, Q2, and Q4 have lower Li content, ranging from 2.21 ppm–10.8 ppm (median 7.61 ppm), 6.15 ppm–8.66 ppm, (median 7.53 ppm), and 3.39 ppm–28.7 ppm (median 10.5 ppm), respectively.

The content of Ti in quartz exhibits a decreasing trend from quartz porphyry (Q1) to Sn-Cu-Mo vein (Q4) and increasing from Q4 to Ag-Pb-Zn vein (Q5) (Figure 5), with Ti contents of 20.3 ppm–66 ppm (median 49.3 ppm), 41.5 ppm–55.4 ppm (median 50.0 ppm), 9.82 ppm–36.9

ppm (median 17.2 ppm), 1.74 ppm–5.94 ppm (median 2.20 ppm) and 1.42 ppm–5.03 ppm (median 3.28 ppm) respectively.

In contrast, the content of Ge in quartz follows an increasing trend from quartz porphyry (Q1) to Ag-Pb-Zn vein (Q5) (Figure 5), with Ge contents of 0.40 ppm–0.82 ppm (median 0.60 ppm), 0.45 ppm–0.91 ppm (median 0.59 ppm), 1.73 ppm–1.88 ppm (median 1.73 ppm), 0.96 ppm–3.20 ppm (median 1.70 ppm) and 1.24 ppm–4.93 ppm (median 3.20 ppm) respectively.

The Sb content in quartz follows a decreasing trend from quartz porphyry (Q1) to greisen (Q2) and an increasing trend from greisen (Q2) to Ag-Pb-Zn vein (Q5), with Sb contents of 0.02 ppm–1.45 ppm (median 0.09 ppm), 0.02 ppm–0.08 ppm (median 0.04 ppm), 0.36 ppm–0.50 ppm (median 0.41 ppm), 0.04 ppm–1.56 ppm (median 0.86 ppm) and 0.26 ppm–27.6 ppm (median 7.1 ppm) respectively.

6 DISCUSSION

6.1 Substitution Mechanisms of Trace Elements in Quartz

Previous studies by Larsen et al. (2004), Götte and Ramseier (2012), and Rusk (2012) highlighted that internal lattice defects, mineral composition, and distribution of trace impurities significantly influence the cathodoluminescence (CL) intensity and spectrum of quartz. The trace element composition in quartz is influenced by fac-

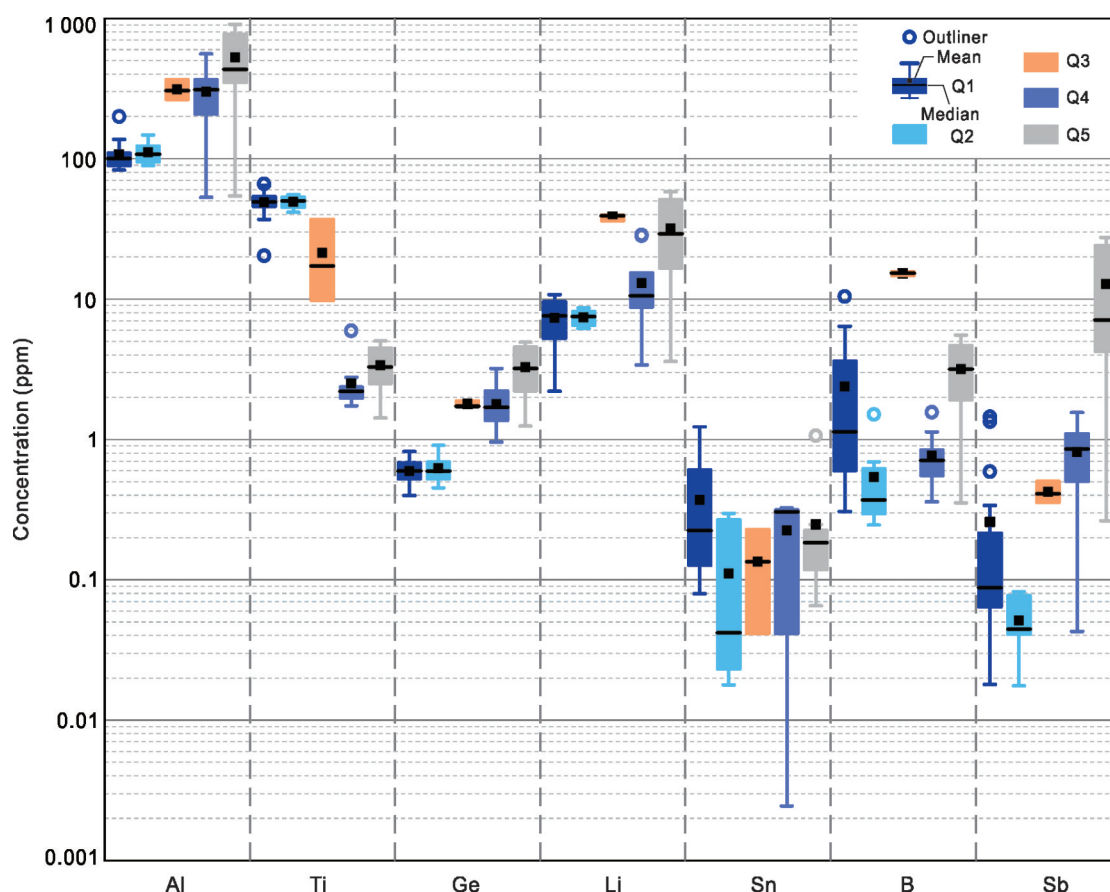


Figure 5. Percentile box and whisker plots showing ranges, averages, and median of representative trace elements in different quartz types.

tors such as pressure, temperature (Thomas et al., 2010), crystallization rate (Lowenstern and Sinclair, 1996), melt/fluid composition (Breiter et al., 2013; Müller et al., 2000; Jacamon and Larsen, 2009), and pH (Rusk et al., 2008). Therefore, a thorough analysis of trace elements in quartz can provide insights into its formation environment.

Notably, aluminum is the most abundant trace element in quartz, with its concentrations varying significantly (Table S2). The substitution of Al^{3+} for Si^{4+} primarily involves combinations with Li^+ , Na^+ , K^+ , Rb^+ , H^+ , Be^{2+} , and P^{5+} ($\text{Si}^{4+} = \text{Al}^{3+} + (\text{Li}^+, \text{Na}^+, \text{K}^+, \text{H}^+)$; $2\text{Si}^{4+} = \text{Al}^{3+} + \text{P}^{5+}$; and $2\text{Si}^{4+} = 2\text{Al}^{3+} + \text{Be}^{2+}$; Yang et al., 2022; Götze et al., 2021; Breiter et al., 2013; Jacamon and Larsen, 2009; Müller et al., 2002). The Li concentrations in the Bianjiadayuan deposit ($R^2 = 0.66$; Figure 6d) correlate positively with Al in quartz, implying Li^+ is the main charge compensator during Al^{3+} substitutes for Si^{4+} . By contrast, there is no obvious linear relationship between P, K, Na, Rb, and Al contents in quartz from the Bianjiadayuan deposit (Figures 6a, 6e, 6f, 6g), implying that P, K, Na, and Rb in quartz do not function as a charge compensator for Al. Notably, the Be concentrations ($R^2 = 0.23$; Figure 6c) correlate positively with Al in quartz, indicating that Be^{2+} may act as a charge compensator when Al^{3+} replaces Si^{4+} .

Moreover, Götze et al. (2021) suggest that Si could

also be replaced by a coupled mechanism through $2\text{Si}^{4+} = \text{B}^{3+} + \text{P}^{5+}$. However, quartz typically has a high phosphorus content especially in breccia (84.4 ppm–112 ppm) and Ag-Pb-Zn veins (20.8 ppm–54.6 ppm) but low B contents (0.25 ppm–15.7 ppm, most below 6; Table S4). Besides, there is no correlation exists between P and B either (Figure 6b), suggesting P^{5+} and B^{3+} did not replace Si^{4+} simultaneously. It is noteworthy that from Q2 to Q5, the Li and B contents in quartz show a positive correlation ($R^2 = 0.48$; Figure 6h), indicating that B^{3+} and Li^+ replace Si^{4+} .

6.2 Implication for Chemical Differences in Quartz

The structural and chemical compositions from quartz porphyry, greisen, and breccia to vein-type quartz in the Bianjiadayuan deposit are significantly different, especially Ti, Ge, Al, Li, and Sb (Table S2; Figure 5). Ti and Ge exhibit distinct compatible and incompatible characteristics in quartz, respectively (Jacamon and Larsen, 2009), Ti contents of quartz is positively correlated with crystallization temperature (Breiter and Müller, 2009; Larsen et al., 2004) whereas Ge contents show opposite trend (Pokrovski and Schott, 1998). Therefore, the decrease in Ti contents and the increase in Al/Ti and Ge/Ti ratio in quartz from the intrusions reflect a higher degree of magma differentiation (Jacamon and Larsen, 2009;

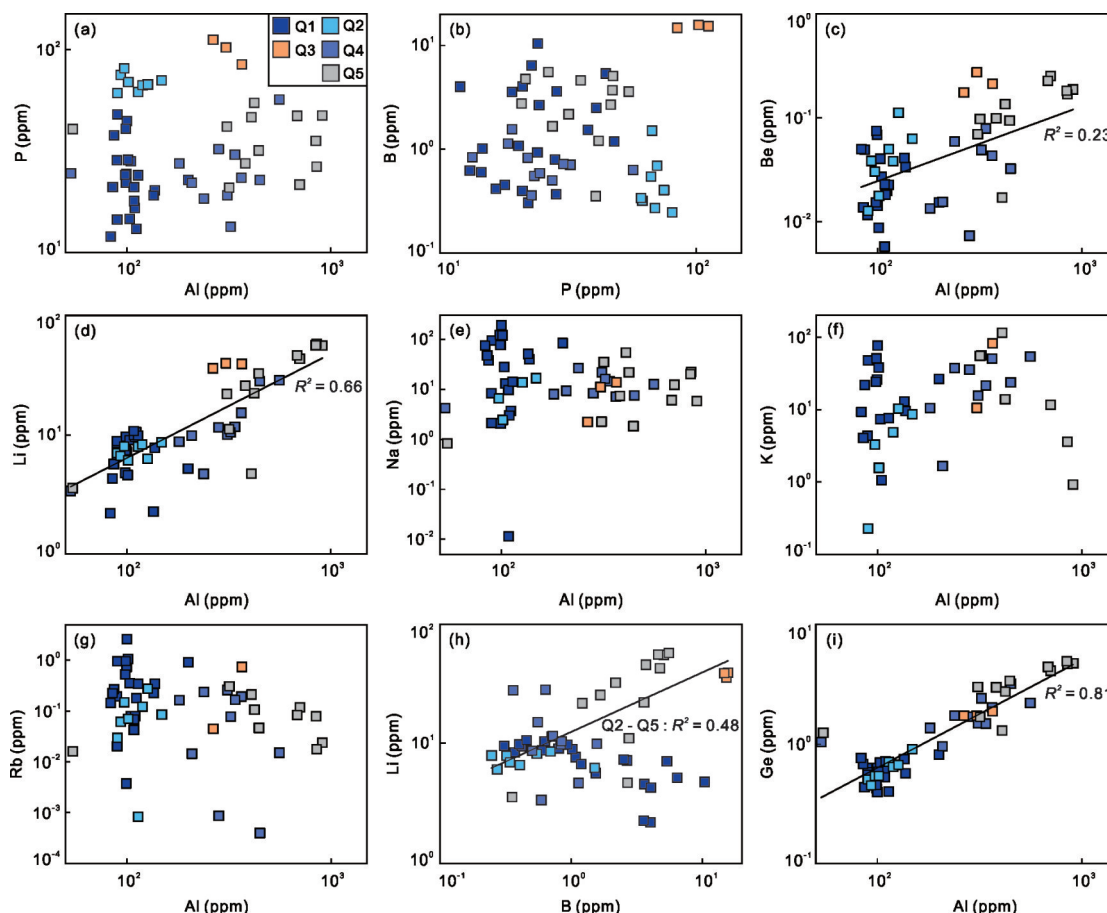


Figure 6. Plots of trace elements in quartz from Bianjiadayuan Ag-Pb-Zn-Sn deposit. (a) P vs. Al; (b) B vs. P; (c) Be vs. Al; (d) Li vs. Al; (e) Na vs. Al; (f) K vs. Al; (g) Rb vs. Al; (h) Li vs. B; (i) Ge vs. Al.

Götze et al., 2004; Larsen et al., 2004). The quartz phenocryst (Q1) of the quartz porphyry in the Bianjiadayuan Sn-Ag-Pb-Zn deposit exhibits low Al/Ti and Ge/Ti ratios, ranging from 1.54 to 9.81 (most are below 4, with only one ratio of 9.81) and 0.01 to 0.04, respectively, indicating a low degree of magmatic evolution. From quartz porphyry (Q1) to Ag-Pb-Zn vein (Q5), the Ti content of quartz decreases and Ge content increases (Figure 5), and the increasing of Ge/Ti and Al/Ti ratios, indicates a relatively clear evolution from magmatic to hydrothermal stage and decrease in temperature (Figures 7a–7b). Interestingly, the titanium content in Q5 (1.42 ppm–5.03 ppm) is notably higher compared to Q4 (1.74 ppm–2.78 ppm, with only one exception) (Figure 5; Figures 7b–7c), which contradicts the discussed temperature variations.

Müller et al. (2018) proposed that rapid quartz growth can lead to elevated trace element concentrations, such as Al, Ti, Ge, Li, and Sb. Furthermore, microthermometry data from the Bianjiadayuan deposit indicates that the homogenization temperature of fluid inclusions decreased from 292–350 °C in early silver-barren quartz veins to 201–262 °C in Ag-Pb-Zn veins (Zhai et al., 2018), hinting the rapid crystallization due to cooling.

From quartz porphyry (Q1) to Ag-Pb-Zn vein (Q5), the Al content of quartz gradually increases. In addition, the Ge concentrations ($R^2 = 0.81$; Figure 6i) correlate positively with Al in quartz, indicating that Al content is affected by temperature. This observation is consistent with quartz forming in aluminum-saturated environments, where the trace aluminum content varies linearly and di-

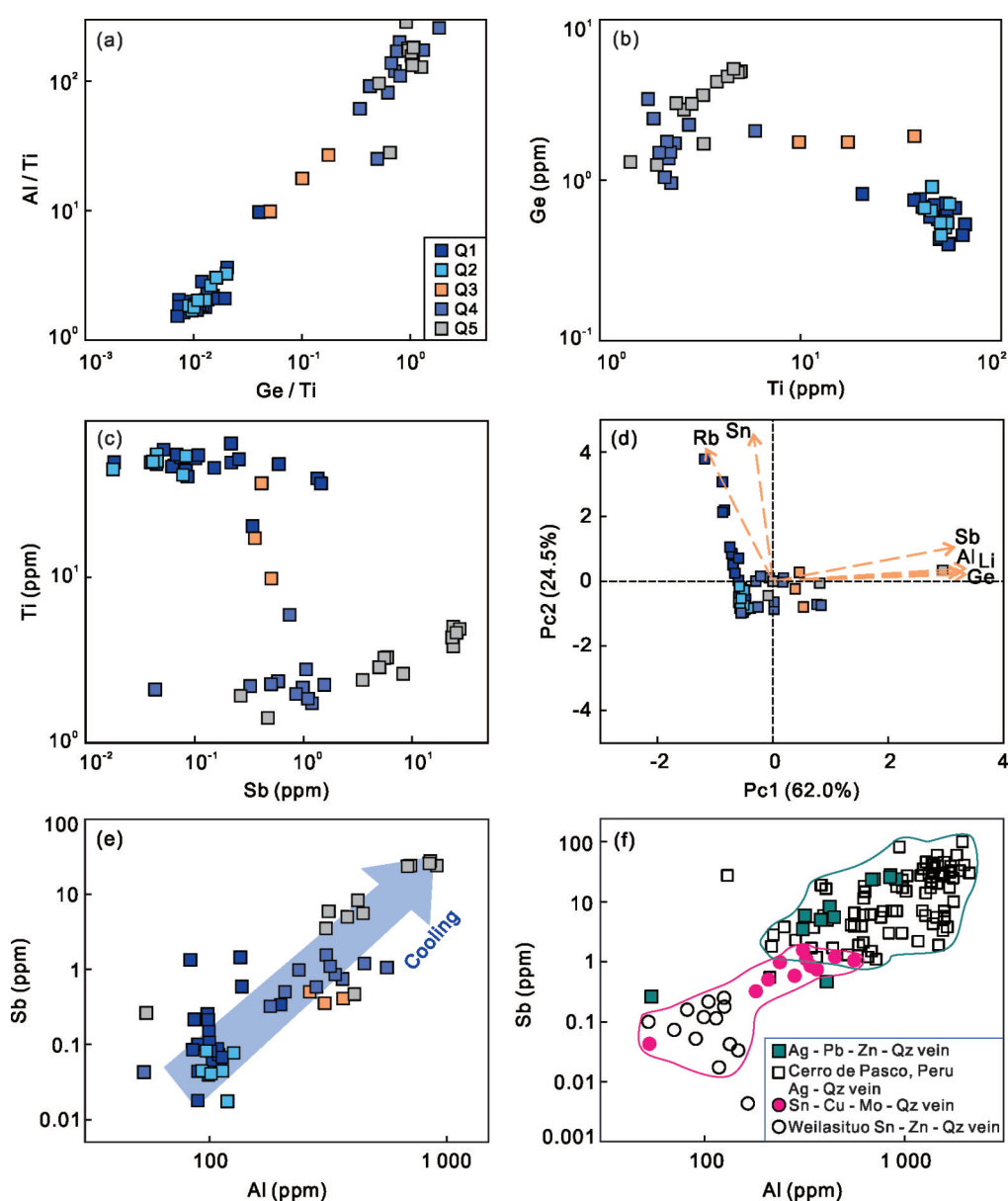


Figure 7. Plots of trace elements in quartz of the Bianjiadayuan Ag-Pb-Zn-Sn deposit. (a) Al/Ti vs. Ge/Ti; (b) Ge vs. Ti; (c) Ti vs. Sb; (d) principal component 1 (PC1) versus principal component (PC2) binary diagram; (e) Sb vs. Al; (f) Sb vs. Al. Color graphics are from this article, black hollow boxes are from Intermediate-sulfidation Ag-Pb-Zn quartz veins in Cerro de Pasco, Peru (Rottier, 2016); black hollow circle data from the Weilasituo tin polymetallic deposit (unpublished data).

rectly with its crystallization temperature (Dennen et al., 1970). The Li content in quartz is mainly controlled by the composition of the melt and the order of crystallization of Li-bearing minerals (Jacamon and Larsen, 2009). However, Li-bearing minerals typically deplete Li content in quartz, which is not the case for Bianjiadayuan deposits. From quartz porphyry (Q1) to Ag-Pb-Zn vein (Q5), the Li content of quartz gradually increases, except for breccia (Q3). Combined with Li concentrations correlate positively with Al in quartz, suggesting that the Li content in quartz is controlled by the crystallization temperature.

The Sb content in quartz decreases from quartz porphyry (Q1) to greisen (Q2) and then gradually increases from Q2 to Q5 (Figure 5). The Sb content was lowest in greisen (Q2) (Figure 5). The variation of Sb content is consistent with the variation of Ge content and Al content in quartz, implying that the Sb content may be temperature dependent (Figure 5; Figure 7e).

6.3 Implication for Ag Mineralization and Metallogenic Model

Principal component analysis was applied to the quartz dataset, which was transformed prior to analysis using centered log-ratio transformation. The data projected onto a biplot of principal component 1 (PC1) versus PC2 shows distinct clusters that discriminate both the lithology and mineralization type (Figure 7d). Quartz from magmatic stage featured by intrusions to the magmatic-hydrothermal stage including greisen and to the hydrothermal stage including breccia, Sn-Cu-Mo-quartz veins and

Ag-Pb-Zn-quartz veins are largely defined by Al + Li + Ge + Sb path, which is positively correlated, indicating a decrease in temperature along with the magmatic-hydrothermal evolution. In the Bianjiadayuan deposit, the quartz from the magmatic stage (Q1) to the hydrothermal stage (Q5) shows a positive Sb-Al correlation (Figure 7e), consistent with porphyry-epithermal systems (Gao et al., 2022). Antimony is abundant in low-temperature quartz and is commonly associated with classic epithermal silver deposits, such as the positive correlation between Al and Sb observed in quartz from the Cerro de Pasco large epithermal polymetallic deposit in Peru (Rottier, 2016). Moreover, it is noteworthy that the Sb content in quartz of Ag-Pb-Zn-quartz veins (> 1 ppm, mostly tens of ppm) is much higher than that in quartz from other lithologies including Sn-bearing Quartz veins (< 1 ppm; Figure 5; Figure 7f). The presence of high Sb content in quartz veins, observed in both the Ag-Pb-Zn quartz vein of the Cerro de Pasco large epithermal polymetallic (Zn-Pb-Ag-Cu-Bi) deposit (Rottier, 2016) and the Bianjiadayuan deposit (Figure 7f), suggests that Sb content in quartz is an effective indicator of Ag mineralization.

Based on the ore geology and quartz trace elements, we propose the following metallogenic model (Figure 8) for the Bianjiadayuan Ag-Pb-Zn-Sn deposit. As magma underwent a low degree differentiation, quartz porphyry crystallized with decreasing temperature. This followed by pressure changes that led to the formation of breccia, with large amounts of sulfide as a cement (Zhai et al., 2017), and the development of early porphyry-style

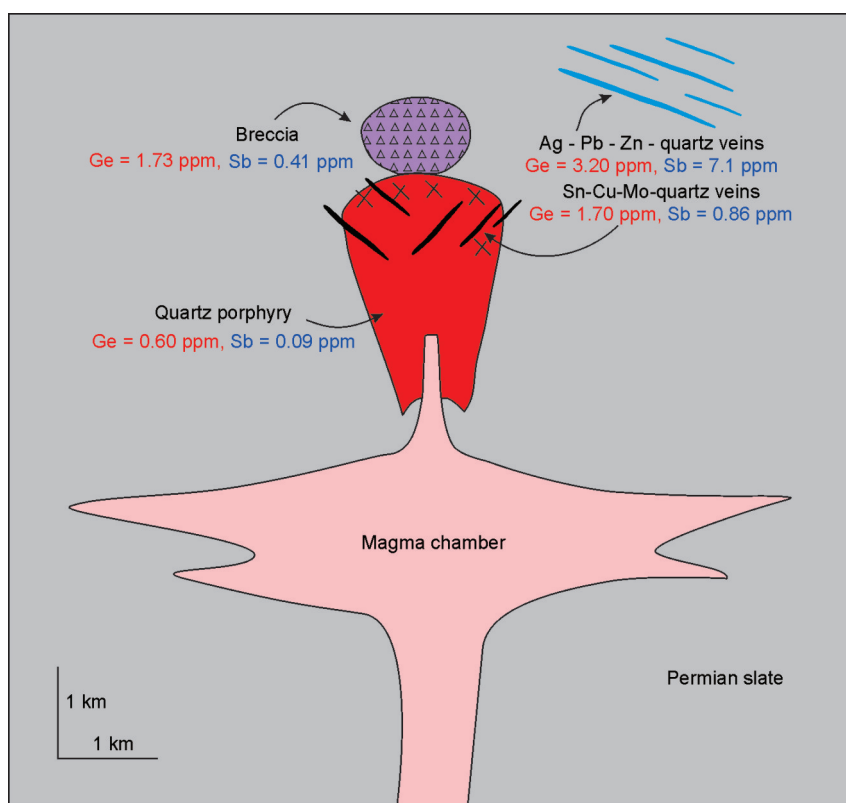


Figure 8. Metallogenic model of the Bianjiadayuan Ag-Pb-Zn-Sn deposit.

veins, stockworks, and veinlets hosting Sn-Cu-Mo mineralization. As temperature continued to decrease, Sb and Ag became concentrated, forming Ag-rich minerals, such as antimonite, pyrrargyrite, and freibergite (Zhai et al., 2019), which were associated with Ag-Pb-Zn mineralization. In conclusion, cooling appears to be a key factor driving Ag mineralization in the Bianjiadayuan Ag-Pb-Zn-Sn deposit.

7 CONCLUSION

The chemical variability and textural features of quartz from the magmatic to hydrothermal stages of the Bianjiadayuan Ag-Pb-Zn-Sn deposit provide insights into the ore-forming process. Quartz evolves from quartz porphyry in magmatic stage to greisen during the magmatic-hydrothermal transition, and then to hydrothermal quartz veins, following a trend characterized by a positive correlation of Al, Li, Ge, and Sb. This correlation suggests Sb enrichment in the ore-forming fluid, accompanied by a decrease in temperature. From quartz porphyry (Q1) to Ag-Pb-Zn veins (Q5), there is a marked decrease in titanium and an increase in Ge and Sb, alongside rising Ge/Ti and Al/Ti ratios, which indicates a transition from magmatic to hydrothermal processes with cooling. Consequently, trace elements in quartz provide a new perspective on the precipitation mechanism, specifically the cooling process, involved in Ag mineralization at the Bianjiadayuan Ag-Pb-Zn-Sn deposit.

ACKNOWLEDGMENTS

This study was financially supported by the National Natural Science Foundation of China (No. 42222205), the National Key Research and Development Program of China (No. 2017YFC0602403), and the Fundamental Research Funds for the Central Universities, CHD (No. 300102273301). Two anonymous reviewers helped the authors improve the manuscript significantly. The final publication is available at Springer via <https://doi.org/10.1007/s12583-024-0110-4>.

Electronic Supplementary Materials: Supplementary materials (Tables S1–S4) are available in the online version of this article at <https://doi.org/10.1007/s12583-024-0110-4>.

Conflict of Interest

The authors declare that they have no conflict of interest.

REFERENCES CITED

- Audétat, A., Garbe-Schönberg, D., Kronz, A., et al., 2015. Characterisation of a Natural Quartz Crystal as a Reference Material for Microanalytical Determination of Ti, Al, Li, Fe, Mn, Ga and Ge. *Geostandards and Geoanalytical Research*, 39(2): 171–184. <https://doi.org/10.1111/j.1751-908X.2014.00309.x>
- Breiter, K., Ackerman, L., Svojtka, M., et al., 2013. Behavior of Trace Elements in Quartz from Plutons of Different Geochemical Signature: A Case Study from the Bohemian Massif, Czech Republic. *Lithos*, 175: 54–67. <https://doi.org/10.1016/j.lithos.2013.04.023>
- Breiter, K., Jana, Ď., Dosbaba, M., 2017. Quartz Chemistry—A Step to Understanding Magmatic-Hydrothermal Processes in Ore-Bearing Granites: Cínovec/Zinnwald Sn-W-Li Deposit, Central Europe. *Ore Geology Reviews*, 90: 25–35. <https://doi.org/10.1016/j.oregeorev.2017.10.013>
- Breiter, K., Müller, A., 2009. Evolution of Rare-Metal Granitic Magmas Documented by Quartz Chemistry. *European Journal of Mineralogy*, 21(2): 335–346. <https://doi.org/10.1127/0935-1221/2009/0021-1907>
- Chen, S. J., Hu, X. Y., Liu, S., 2022. Application Study on High Precision Aeromagnetic Survey in Weilasituo, Inner Mongolia, China. *Earth Science*, 47(6): 2175–2189 (in Chinese with English Abstract)
- Chen, Y. J., Zhang, C., Wang, P., et al., 2017. The Mo Deposits of NorthEast China: A Powerful Indicator of Tectonic Settings and Associated Evolutionary Trends. *Ore Geology Reviews*, 81: 602–640. <https://doi.org/10.1016/j.oregeorev.2016.04.017>
- Dennen, W. H., Blackburn, W. H., Quesada, A., 1970. Aluminum in Quartz as a Geothermometer. *Contributions to Mineralogy and Petrology*, 27(4): 332–342. <https://doi.org/10.1007/BF00389817>
- Gao, S., Zou, X. Y., Hofstra, A. H., et al., 2022. Trace Elements in Quartz: Insights into Source and Fluid Evolution in Magmatic-Hydrothermal Systems. *Economic Geology*, 117(6): 1415–1428. <https://doi.org/10.5382/econgeo.4943>
- Götze, T., Ramseier, K., 2012. Trace Element Characteristics, Luminescence Properties and Real Structure of Quartz. In: Götze, J., Möckel, R., eds., *Quartz: Deposits, Mineralogy and Analytics*. Springer Berlin Heidelberg, Berlin, Heidelberg. 71 – 118. https://doi.org/10.1007/978-3-642-22161-3_12
- Götze, J., Pan, Y. M., Müller, A., 2021. Mineralogy and Mineral Chemistry of Quartz: A Review. *Mineralogical Magazine*, 85(5): 639–664. <https://doi.org/10.1180/mgm.2021.72>
- Götze, J., Plötze, M., Graupner, T., et al., 2004. Trace Element Incorporation into Quartz: A Combined Study by ICP-MS, Electron Spin Resonance, Cathodoluminescence, Capillary Ion Analysis, and Gas Chromatography. *Geochimica et Cosmochimica Acta*, 68(18): 3741–3759. <https://doi.org/10.1016/j.gca.2004.01.003>
- Gu, Y. C., Chen, R. Y., Jia, B., et al., 2017. Zircon U-Pb Dating and Geochemistry of the Syenogranite from the Bianjiadayuan Pb-Zn-Ag Deposit of Inner Mongolia and Its Tectonic Implications. *Geology in China*, 44(1): 101 – 117. <https://doi.org/10.1029/gc20170108> (in Chinese with English Abstract)
- Hong, W., Cooke, D. R., Zhang, L. J., et al., 2021. The Formation of Magmatic-Hydrothermal Features in Sn-Mineralized and Barren Tasmanian Intrusions, Southeast Australia: Insights from Quartz Textures, Trace Elements, and Microthermometry. *Economic Geology*, 116(8): 1917–1948. <https://doi.org/10.5382/econgeo.4853>
- Huang, R. F., Audétat, A., 2012. The Titanium-in-Quartz (TitaniQ) Thermobarometer: A Critical Examination and Re-Calibration. *Geochimica et Cosmochimica Acta*, 84: 75–89. <https://doi.org/10.1016/j.gca.2012.01.009>
- Jacamon, F., Larsen, R. B., 2009. Trace Element Evolution of Quartz in the Charnockitic Kleivan Granite, SW-Norway: The Ge/Ti Ratio of Quartz as an Index of Igneous Differentiation. *Lithos*,

- 107(3/4): 281–291. <https://doi.org/10.1016/j.lithos.2008.10.016>
- Jahn, B. M., 2004. The Central Asian Orogenic Belt and Growth of the Continental Crust in the Phanerozoic. *Geological Society, London, Special Publications*, 226(1): 73–100. <https://doi.org/10.1144/gsl.sp.2004.226.01.05>
- Jahn, B. M., Wu, F. Y., Chen, B., 2000. Granitoids of the Central Asian Orogenic Belt and Continental Growth in the Phanerozoic. *Geological Society of America Special Papers*, 350: 181–193. <https://doi.org/10.1130/0-8137-2350-7.181>
- Jiang, H. Y., Zhao, Z. D., Zhu, X. Y., et al., 2020. Characteristics and Metallogenic Significance of Granite Porphyry and Pyroxene Diorite in the Bianjiadayuan Pb-Zn-Ag Polymetallic Deposit, Inner Mongolia. *Geology in China*, 47(2): 450–471. <https://doi.org/10.12029/gc20200213> (in Chinese with English Abstract)
- Jiang, S. Y., Wang, W., 2022. What are the Super-Enrichment Mechanisms for Strategic Critical Metal Deposits?. *Earth Science*, 47(10): 3869–3871. <https://doi.org/10.3799/dqkx.2022.844> (in Chinese with English Abstract)
- Lan, T. G., Hu, R. Z., Bi, X. W., et al., 2018. Metasomatized Asthenospheric Mantle Contributing to the Generation of Cu-Mo Deposits within an Intracontinental Setting: A Case Study of the ~128 Ma Wangjiazhuang Cu-Mo Deposit, Eastern North China Craton. *Journal of Asian Earth Sciences*, 160: 460–489. <https://doi.org/10.1016/j.jseaes.2017.07.014>
- Larsen, R. B., Henderson, I., Ihlen, P. M., et al., 2004. Distribution and Petrogenetic Behaviour of Trace Elements in Granitic Pegmatite Quartz from South Norway. *Contributions to Mineralogy and Petrology*, 147(5): 615–628. <https://doi.org/10.1007/s00410-004-0580-4>
- Liu, H. J., Yang, Y. Q., Sun, Y. Q., et al., 2016. The Primary Halo Characteristics of Bianjiadayuan Pb-Zn-Ag Polymetallic Deposit in Inner Mongolia, China and Ore Prediction to Depth. *Contributions to Geology and Mineral Resources Research*, 31(2): 245–252 (in Chinese with English Abstract)
- Liu, Y. S., Hu, Z. C., Gao, S., et al., 2008. *In situ* Analysis of Major and Trace Elements of Anhydrous Minerals by LA-ICP-MS without Applying an Internal Standard. *Chemical Geology*, 257(1/2): 34–43. <https://doi.org/10.1016/j.chemgeo.2008.08.004>
- Lowenstern, J. B., Sinclair, W. D., 1996. Exsolved Magmatic Fluid and Its Role in the Formation of Comb-Layered Quartz at the Cretaceous Logtong W-Mo Deposit, Yukon Territory, Canada. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 87(1/2): 291–303. <https://doi.org/10.1017/s0263593300006696>
- Mao, W., Rusk, B., Yang, F. C., et al., 2017. Physical and Chemical Evolution of the Dabaoshan Porphyry Mo Deposit, South China: Insights from Fluid Inclusions, Cathodoluminescence, and Trace Elements in Quartz. *Economic Geology*, 112(4): 889–918. <https://doi.org/10.2113/econgeo.112.4.889>
- Müller, A., Herklotz, G., Giegling, H., 2018. Chemistry of Quartz Related to the Zinnwald/Cínovec Sn-W-Li Greisen-Type Deposit, Eastern Erzgebirge, Germany. *Journal of Geochemical Exploration*, 190: 357–373. <https://doi.org/10.1016/j.gexplo.2018.04.009>
- Müller, A., Kronz, A., Breiter, K., 2002. Trace Elements and Growth Patterns in Quartz: A Fingerprint of the Evolution of the Subvolcanic Podlesí Granite System (Krušné Hory Mts., Czech Republic). *Bulletin of Geosciences*, 77(2): 135–145. <https://www.researchgate.net/publication/280016513>
- Müller, A., Seltmann, R., Behr, H. J., 2000. Application of Cathodoluminescence to Magmatic Quartz in a Tin Granite: Case Study from the Schellerhau Granite Complex, Eastern Erzgebirge, Germany. *Mineralium Deposita*, 35(2): 169–189. <https://doi.org/10.1007/s001260050014>
- Ouyang, H. G., Mao, J. W., Zhou, Z. H., et al., 2015. Late Mesozoic Metallogeny and Intracontinental Magmatism, Southern Great Xing'an Range, Northeastern China. *Gondwana Research*, 27(3): 1153–1172. <https://doi.org/10.1016/j.gr.2014.08.010>
- Pei, Q. M., Zhang, S. T., Hayashi, K. I., et al., 2018. Permo–Triassic Granitoids of the Xing'an-Mongolia Segment of the Central Asian Orogenic Belt, NorthEast China: Age, Composition, and Tectonic Implications. *International Geology Review*, 60(9): 1172–1194. <https://doi.org/10.1080/00206814.2017.1377121>
- Pokrovski, G. S., Schott, J., 1998. Thermodynamic Properties of Aqueous Ge(IV) Hydroxide Complexes from 25 to 350 °C: Implications for the Behavior of Germanium and the Ge/Si Ratio in Hydrothermal Fluids. *Geochimica et Cosmochimica Acta*, 62(9): 1631–1642. [https://doi.org/10.1016/S0016-7037\(98\)00081-7](https://doi.org/10.1016/S0016-7037(98)00081-7)
- Qin, G. J., Kawachi, Y., Zhao, L. Q., et al., 2001. The Upper Permian Sedimentary Facies and Its Role in the Dajing Cu-Sn Deposit, Linxi County, Inner Mongolia, China. *Resource Geology*, 51(4): 293–305. <https://doi.org/10.1111/j.1751-3928.2001.tb00103.x>
- Rottier, B., 2016. Magmatic and Hydrothermal Fluid Processes at the Origin of the Giant Porphyry-Related Epithermal Polymetallic Deposit of Cerro de Pasco (Central Peru): [Dissertation]. University of Geneva, Geneva
- Ruan, B. X., Lü, X. B., Liu, S. T., et al., 2013. Genesis of Bianjiadayuan Pb-Zn-Ag Deposit in Inner Mongolia: Constraints from U-Pb Dating of Zircon and Multi-Isotope Geochemistry. *Mineral Deposits*, 32(3): 501–514. <https://doi.org/10.1611/j.0258-7106.2013.03.003> (in Chinese with English Abstract)
- Ruan, B. X., Lv, X. B., Yang, W., et al., 2015. Geology, Geochemistry and Fluid Inclusions of the Bianjiadayuan Pb-Zn-Ag Deposit, Inner Mongolia, NE China: Implications for Tectonic Setting and Metallogeny. *Ore Geology Reviews*, 71: 121–137. <https://doi.org/10.1016/j.oregeorev.2015.05.004>
- Rusk, B., 2012. Cathodoluminescent Textures and Trace Elements in Hydrothermal Quartz. In: Götze, J., Möckel, R., eds., *Quartz: Deposits, Mineralogy and Analytics*. Springer Berlin Heidelberg, Berlin, Heidelberg. 307–329. https://doi.org/10.1007/978-3-642-22161-3_14
- Rusk, B. G., Lowers, H. A., Reed, M. H., 2008. Trace Elements in Hydrothermal Quartz: Relationships to Cathodoluminescent Textures and Insights into Vein Formation. *Geology*, 36(7): 547–550. <https://doi.org/10.1130/G24580A.1>
- Shi, Y. R., Liu, D. Y., Miao, L. C., et al., 2010. Devonian A-Type Granitic Magmatism on the Northern Margin of the North China Craton: SHRIMP U-Pb Zircon Dating and Hf-Isotopes of the Hongshan Granite at Chifeng, Inner Mongolia, China. *Gondwana Research*, 17(4): 632–641. <https://doi.org/10.1016/j.gr.2009.11.011>
- Shu, Q. H., Lai, Y., Sun, Y., et al., 2013. Ore Genesis and Hydrothermal Evolution of the Baiyinnuo'er Zinc-Lead Skarn Deposit, NorthEast China: Evidence from Isotopes (S, Pb) and Fluid Inclusions. *Economic Geology*, 108(4): 835–860. <https://doi.org/10.2113/econgeo.108.4.835>

- Song, K. R., Tang, L., Zhang, S. T., et al., 2019. Genesis of the Bianjiadayuan Pb-Zn Polymetallic Deposit, Inner Mongolia, China: Constraints from *in-situ* Sulfur Isotope and Trace Element Geochemistry of Pyrite. *Geoscience Frontiers*, 10(5): 1863–1877. <https://doi.org/10.1016/j.gsf.2019.02.004>
- Thomas, J. B., Bruce Watson, E., Spear, F. S., et al., 2010. TitaniQ under Pressure: The Effect of Pressure and Temperature on the Solubility of Ti in Quartz. *Contributions to Mineralogy and Petrology*, 160(5): 743–759. <https://doi.org/10.1007/s00410-010-0505-3>
- Wang, F. X., Bagas, L., Jiang, S. H., et al., 2017. Geological, Geochemical, and Geochronological Characteristics of Weilasituo Sn-Polymetal Deposit, Inner Mongolia, China. *Ore Geology Reviews*, 80(Suppl. C): 1206 – 1229. <https://doi.org/10.1016/j.oregeorev.2016.09.021>
- Wang, C. G., Sun, F. Y., Sun, G. S., et al., 2016. Geochronology, Geochemical and Isotopic Constraints on Petrogenesis of Intrusive Complex Associated with Bianjiadayuan Polymetallic Deposit on the Southern Margin of the Greater Khingan, China. *Arabian Journal of Geosciences*, 9(5): 334. <https://doi.org/10.1007/s12517-016-2333-x>
- Wang, S. Q., Xin, H. T., Zhang, Y., et al., 2022. Geochronology and Petrogenesis of Late Carboniferous Alkaline Granites from Erlian-Dongwuqi Region, and Its Geological Significance. *Earth Science*, 47(4): 1295–1315 (in Chinese with English Abstract)
- Wang, X. L., Liu, J. J., Zhai, D. G., et al., 2013. LA-ICP-MS Zircon U-Pb Dating, Geochemistry of the Intrusive Rocks from the Bianjiadayuan Pb-Zn-Ag Deposit, Inner Mongolia, China and Tectonic Implications. *Geotectonica et Metallogenia*, 37(4): 730–742 (in Chinese with English Abstract)
- Wang, X. L., Liu, J. J., Zhai, D. G., et al., 2014. U-Pb Dating, Geochemistry and Tectonic Implications of Bianjiadayuan Quartz Porphyry, Inner Mongolia, China. *Bulletin of Mineralogy, Petrology and Geochemistry*, 33(05): 654–665 (in Chinese with English Abstract)
- Wark, D. A., Watson, E. B., 2006. TitaniQ: A Titanium-in-Quartz Geothermometer. *Contributions to Mineralogy and Petrology*, 152(6): 743–754. <https://doi.org/10.1007/s00410-006-0132-1>
- Wu, F. Y., Sun, D. Y., Ge, W. C., et al., 2011. Geochronology of the Phanerozoic Granitoids in Northeastern China. *Journal of Asian Earth Sciences*, 41(1): 1–30. <https://doi.org/10.1016/j.jseaes.2010.11.014>
- Xu, B., Zhao, P., Wang, Y. Y., et al., 2015. The Pre-Devonian Tectonic Framework of Xing'an-Mongolia Orogenic Belt (XMOB) in North China. *Journal of Asian Earth Sciences*, 97: 183–196. <https://doi.org/10.1016/j.jseaes.2014.07.020>
- Yang, X. Y., Sun, C., Cao, J. Y., et al., 2022. High Purity Quartz: Research Progress and Perspective Review. *Earth Science Frontiers*, 29(1): 231–244. <https://doi.org/10.13745/j.esf.sf.2021.8.1> (in Chinese with English Abstract)
- Zhai, D. G., Liu, J. J., Cook, N. J., et al., 2019. Mineralogical, Textural, Sulfur and Lead Isotope Constraints on the Origin of Ag-Pb-Zn Mineralization at Bianjiadayuan, Inner Mongolia, NE China. *Mineralium Deposita*, 54(1): 47–66. <https://doi.org/10.1007/s00126-018-0804-6>
- Zhai, D. G., Liu, J. J., Zhang, A. L., et al., 2017. U-Pb, Re-Os, and $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology of Porphyry Sn $\pm$ Cu $\pm$ Mo and Polymetallic (Ag-Pb-Zn-Cu) Vein Mineralization at Bianjiadayuan, Inner Mongolia, NorthEast China: Implications for Discrete Mineralization Events. *Economic Geology*, 112(8): 2041–2059. <https://doi.org/10.5382/econgeo.2017.4540>
- Zhai, D. G., Liu, J. J., Zhang, H. Y., et al., 2014. S-Pb Isotopic Geochemistry, U-Pb and Re-Os Geochronology of the Huanggangliang Fe-Sn Deposit, Inner Mongolia, NE China. *Ore Geology Reviews*, 59: 109–122. <https://doi.org/10.1016/j.oregeorev.2013.12.005>
- Zhai, D. G., Liu, J. J., Zhang, H. Y., et al., 2018. A Magmatic-Hydrothermal Origin for Ag-Pb-Zn Vein Formation at the Bianjiadayuan Deposit, Inner Mongolia, NE China: Evidences from Fluid Inclusion, Stable (C-H-O) and Noble Gas Isotope Studies. *Ore Geology Reviews*, 101: 1–16. <https://doi.org/10.1016/j.oregeorev.2018.07.005>
- Zhang, Y., Cheng, J. M., Tian, J., et al., 2019. Texture and Trace Element Geochemistry of Quartz in Skarn System: Perspective from Jiguanzui Cu-Au Skarn Deposit, Eastern China. *Ore Geology Reviews*, 109: 535–544. <https://doi.org/10.1016/j.oregeorev.2019.05.007>