Ore genesis and hydrothermal evolution of the Baiyinnuo’er zinc-lead skarn deposit, northeast China: evidence from isotopes (S, Pb) and fluid inclusions*

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The Baiyinnuo’er zinc-lead deposit (BZLD) is located in the south segment of the Great Xing’an Range. It is the largest Zn-Pb deposit in northern China, with a resource of 32.74 Mt averaging 5.44% Zn, 2.02% Pb, and 31.36 g/t Ag. Skarn and orebodies mainly occur between the different units of the Huanggangliang Formation, or within the contact zone between the intrusions and Permian marble.

Several phases of igneous rocks exposed in the mining areas, and among them the Yanshanian plutonic rocks are interpreted to be the sources of ore, since their Pb isotope compositions ($^{206}\text{Pb}/^{204}\text{Pb} = 18.25–18.35$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.50–15.56$ and $^{208}\text{Pb}/^{204}\text{Pb} = 38.14–38.32$) are highly consistent with the sulfides including sphalerite, galena and chalcopyrite ($^{206}\text{Pb}/^{204}\text{Pb} = 18.23–18.37$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.47–15.62$ and $^{208}\text{Pb}/^{204}\text{Pb} = 37.93–38.44$). Sulfur isotope values of the sulfides give a narrow $\delta^{34}\text{S}$ interval from -6.1 to -4.6‰ (mean = -5.4‰, n = 15), suggesting the ore-forming fluid is magmatic.

Three main paragenetic stages of skarn formation and ore deposition have been recognized based on petrographic observation, namely the pre-ore stage (garnet – clinopyroxene – wollastonite – magnetite ± sulfides), the syn-ore stage (sulfides – epidote – quartz – calcite ± garnet), and the post-ore stage (calcite – chlorite – quartz - fluorite). Several fluid evolution episodes can be inferred from microthermometric results at the BZLD: (1) Immiscibility. Pre-ore stage coexistence of halite-bearing brine inclusions (S1-type, ~44 wt% NaCl eqv) and vapor-rich fluid inclusions (V-type) sharing the same homogenization temperatures (~470 °C) confirms that fluid unmixing occurred under lithostatic pressures of ~400 bars (~1.5 km), and the brine is considered to related to the formation of most prograde skarn minerals (e.g., clinopyroxene); (2) Over pressure trapping. Pre-ore stage brine inclusions homogenized by halite dissolution (S2-type) postdated the immiscible assemblages. This type of inclusions are characterized by high but variable (minimum) trapping pressures (150–3000 bars) relative to S1-type inclusions, and can be explained as a result of entrapment under overpressuring condition; (3) Boiling. The presence of both vapor and liquid inclusions (i.e., V-type and L-type) in the same assemblages within syn-ore stage quartz, calcite and sphalerite indicates the occurrence of fluid boiling (~350 °C, hydrostatic pressures of ~150 bars and depth of ~1.5 km), which resulted in large scale mineralization in the BZLD; and (4) Mixing with external fluids. Fluid inclusions scattered in post-ore stage calcite or secondary trails.
in syn-ore stage minerals show low homogenization temperatures (<260 °C) and both decreasing (for L-type) and increasing (for CaCl₂-bearing inclusions, i.e., Lc-type) trends for salinities as homogenization temperatures decrease, implying addition of both meteoric water (low temperature, low salinity) and basinal brines (low temperature, Ca-rich), respectively.

Systematic fluid inclusion studies also indicate that the mineralizing fluid is of magmatic origin. Prograde minerals formed during the pre-ore stage fluid immiscibility and then the sulfide deposition occurred during the syn-ore stage fluid boiling. Mixing with external fluid began as the hydrothermal system cooled to <300 °C, after the main metal precipitation.