

Textural, Compositional, and Sulfur Isotope Variations of Sulfide Minerals in the Red Dog Zn-Pb-Ag Deposits, Brooks Range, Alaska: Implications for Ore Formation

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Abstract

The Red Dog Zn-Pb deposits are hosted in organic-rich mudstone and shale of the Mississippian Kuna Formation. A complex mineralization history is defined by four sphalerite types or stages: (1) early brown sphalerite, (2) yellow-brown sphalerite, (3) red-brown sphalerite, and (4) late tan sphalerite. Stages 2 and 3 constitute the main ore-forming event and are volumetrically the most important. Sulfides in stages 1 and 2 were deposited with barite, whereas stage 3 largely replaces barite. Distinct chemical differences exist among the different stages of sphalerite. From early brown sphalerite to later yellow-brown sphalerite and red-brown sphalerite, Fe and Co content generally increase and Mn and Tl content generally decrease. Early brown sphalerite contains no more than 1.9 wt percent Fe and 63 ppm Co, with high Mn (up to 37 ppm) and Tl (126 ppm), whereas yellow-brown sphalerite and red-brown sphalerite contain high Fe (up to 7.3 wt %) and Co (up to 382 ppm), and low Mn (<27 ppm) and Tl (<37 ppm). Late tan sphalerite has distinctly lower Fe (<0.9 wt %) and higher Tl (up to 355 ppm), Mn (up to 177 ppm), and Ge (426 ppm), relative to earlier sphalerite. Wide ranges in concentrations of Ag, Cu, Pb, and Sb characterize all sphalerite types, particularly yellow-brown sphalerite and red-brown sphalerite, and most likely reflect submicroscopic inclusions of galena, chalcopyrite and/or tetrahedrite in the sphalerite. In situ ion microprobe sulfur isotope analyses show a progression from extremely low $\delta^{34}\text{S}$ values for stage 1 (as low as -37.2‰) to much higher values for yellow-brown sphalerite (mean of 3.3‰ ; $n = 30$) and red-brown sphalerite (mean of 3.4 ; $n = 20$). Late tan sphalerite is isotopically light (-16.4 to -27.2‰).

The textural, chemical, and isotopic data indicate the following paragenesis: (1) deposition of early brown sphalerite with abundant barite, minor pyrite, and trace galena immediately beneath the sea floor in unconsolidated mud; (2) deposition of yellow-brown sphalerite during subsea-floor hydrothermal recrystallization and coarsening of preexisting barite; (3) open-space deposition of barite, red-brown sphalerite and other sulfides in veins and coeval replacement of barite; and (4) postore sulfide deposition, including the formation of late tan sphalerite breccias. Stage 1 mineralization took place in a low-temperature environment where fluids rich in Ba mixed with pore water or water-column sulfate to form barite, and metals combined with H_2S derived from bacterial sulfate reduction to form sulfides. Higher temperatures and salinities and relatively oxidized ore-stage fluids (stages 2 and 3) compared with stage 1 were probably important controls on

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the abundances and relative amounts of metals in the fluids and the resulting sulfide chemistry. Textural observations and isotopic data show that preexisting barite was reductively dissolved, providing a source of H_2S for sulfide mineral formation. In stage 3, the continued flow of hydrothermal fluids caused thermal alteration of organic-rich mudstones and a build-up of methane that led to fluid overpressuring, hydrofracturing, and vein formation. Barite, red-brown sphalerite, and other sulfides were deposited in the veins, and preexisting barite was pervasively replaced by red-brown sphalerite. Hydrothermal activity ceased until Jurassic time when thrusting and large-scale fluid flow related to the Brookian orogeny remobilized and formed late tan sphalerite in tectonic breccias.