Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.35462

Carbonate–Sulfur Coupling Drives the Formation of Sediment-hosted Zn–Pb Sulfide and Carbonate Ore-Forming Systems

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Sediment-hosted Zn–Pb deposits are a major source of Zn and Pb, and a potentially important source of the critical metals Ga, In, and Ge. In most of these deposits, Zn and Pb occur mainly as the sulfide minerals, sphalerite and galena (sulfide-type), but in a small number of relatively large deposits, the metals occur dominantly as the primary carbonate minerals, smithsonite and cerussite (carbonate-type). Until recently, these two classes of Zn-Pb deposits were assumed to be genetically distinct. However, the discovery of very large hypogene carbonate-type Zn–(Pb) deposits (Huoshaoyun and Angouran) has challenged this assumption. Both deposit-types (sulfide and carbonate) are hosted mainly by carbonate sedimentary rocks and are sulfur-rich (sulfate in carbonate-type deposits), suggesting a potential genetic link between them. Here, we combine the results of hydrothermal experiments and thermodynamic calculations to show that Zn–Pb mineralization in these two deposit types is genetically related via a previously unrecognized coupled dissolution-precipitation process involving calcite and redox-dependent sulfur species (SO_4^{2-} or H_2S). Under oxidized, sulfate-rich conditions, coupling of calcite dissolution with anhydrite precipitation enriches the fluid in HCO_3^-, driving smithsonite and cerussite precipitation. Under reduced, H_2S-rich conditions, however, calcite dissolution buffers the pH to higher values promoting sphalerite and galena precipitation. Together, these analogous pathways establish a unifying framework in which interactions between carbonate and sulfur species at contrasting oxygen fugacity determine both the type (carbonate or sulfide) and the efficiency of Zn–Pb mineralization. This new framework resolves the long-standing issue of the genetic relationship between primary sulfide- and carbonate-type sediment-hosted Zn–Pb deposits, and links metal–sulfur–carbon cycling to Zn–Pb resource development in sedimentary basins.