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Origin of the Red Dog Zn-Pb-Ag Deposits, Brooks Range, Alaska: Evidence from Regional Pb and Sr Isotope Sources

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Abstract

Pb and Sr isotope data were obtained on the shale-hosted Zn-Pb-Ag Red Dog deposits (Qanaiyaq, Main, Aqqaluk, and Paalaaq), other shale-hosted deposits near Red Dog, and Zn-Pb-Ag sulfide and barite deposits in the western and central Brooks Range. The Red Dog deposits and other shale-hosted Zn-Pb-Ag deposits near Red Dog are hosted in the Mississippian Kuna Formation, which is underlain by a sequence of marine-deltaic clastic rocks of the Upper Devonian to Lower Mississippian Endicott Group. Ag-Pb-Zn vein-breccias are found in the Endicott Group. Galena formed during the main mineralization stages in the Red Dog deposits and from the Anarraaq and Wulik deposits have overlapping Pb isotope compositions in the range $^{206}Pb/^{204}Pb$ = 18.364 to 18.428, $^{207}Pb/^{204}Pb$ = 15.553 to 15.621, and $^{208}Pb/^{204}Pb$ = 38.083 to 38.323. Galena and sphalerite formed during the main ore-forming stages in the Red Dog deposits define a narrow field on standard uranogenic and thorogenic Pb isotope diagrams. Lead in sulfides of the Red Dog district is less radiogenic ($^{238}U/^{204}Pb$: μ = 9.51–9.77) than is indicated by the average crustal lead evolution model (μ = 9.74), a difference consistent with a long history of evolution at low ratios of μ before the Carboniferous. The homogeneous regional isotopic reservoir of Pb may indicate large-scale transport and leaching of minerals with various μ ratios and Th/Pb ratios. Younger and genetically unrelated fluids did not significantly disturb the isotopic compositions of galena and sphalerite after the main mineralization event in the Red Dog district. Some pyrite shows evidence of minor Pb remobilization. The overall lead isotope homogeneity in the shale-hosted massive sulfide deposits is consistent with three types of control: a homogeneous regional source, mixing of lead during leaching of a thick sedimentary section and fluid transport, or mixing at the site of deposition. Isotopic variability of the hydrothermal fluids, as represented by galena in the Red Dog district, appears to be consistent with a simple mixing system. Evidence indicates that galena was deposited from largely similar hydrothermal solutions throughout the Red Dog district. A shared regional isotopic reservoir is also supported by the correspondence of Pb isotope compositions of galena in deposits of the Red Dog district and galena in clastic rocks (vein-breccias). Leaching of metals and progressive extraction of radiogenic lead from the clastic rocks in the Endicott Group may account for the trend of increasing $^{206}Pb/^{204}Pb$ in galena of the Red Dog district. Galena in the Red Dog deposits is unlikely to have been derived entirely from the same isotopic reservoir as that represented by the lead in the Kuna Formation or from the igneous rocks in the Red Dog district.

Sr isotope data for barite, calcite, and witherite from the Red Dog deposits are compared with data from regional barite that is associated with sulfides and from barite in sulfide-poor occurrences. Fluids with heterogeneous Sr isotope signatures are indicated. Barite in the Main deposit extends to higher ratios of $^{87}Sr/^{86}Sr$ (0.709034–0.709899) than barite in the Anarraaq deposit (0.708615–0.709256). All barite is more radiogenic than Carboniferous seawater. Other Mississippian(?) shale-hosted deposits and mineral occurrences containing barite in the Red Dog district and barite in regional occurrences east of Red Dog in the western and central Brooks Range also have heterogeneous $^{87}Sr/^{86}Sr$ ratios. Carbonate ($^{87}Sr/^{86}Sr$ = 0.710319–0.713637) and witherite ($^{87}Sr/^{86}Sr$ = 0.710513) in the Main deposit are more radiogenic than barite. In contrast, carbonate ($^{87}Sr/^{86}Sr$ = 0.708196–0.709740) intergrown with massive sulfides at Anarraaq has isotopic compositions similar to that of barite.

Paragenetic and isotopic studies suggest that early barite is similar to barite typically formed in cold seeps along continental margins. This early fine-grained barite formed before the main mineralization event at Red Dog, contains Sr that is more radiogenic than Carboniferous seawater, and suggests two possible sources of Sr: fluid-rock reactions involving radiogenic clastic minerals derived from ancient continental crust in strata underlying the Kuna Formation and/or mixing with radiogenic pore fluids in the Ikalukrok unit. The Sr isotope

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data do not show compelling differences between coarse-grained barite, related to the influx of metalliferous fluids, and the early barite. Higher ratios of $^{87}Sr/^{86}Sr$ in barite in the Red Dog deposits compared with massive barite at Anarraaq that is not directly associated with massive sulfides probably resulted from superposition of the metal-bearing hydrothermal fluid. Leachates (acetic acid and HCl) of whole-rock samples from the clastic rocks in the Endicott Group, as well as samples from the ore-hosting Ikalukrok unit of the Kuna Formation distal to the mineralization, indicate variable and more radiogenic Sr than that in barite and carbonate of the Red Dog district. In contrast, the calcareous radiolarites and lithic turbidites in the Ikalukrock unit may have contributed Sr to the barite and carbonate in the deposits. Comparison of Sr isotope compositions in barite in deposits and occurrences in the Red Dog district and elsewhere in the Brooks Range indicate that no single fluid was responsible for their isotopic signature.