

Isotopic Fingerprints of REE-mineralizing Fluids in the Mountain Pass Carbonatite

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Carbonatites, which host over 50% of global rare earth element (REE) projects, initially form as volatile-rich melts in the mantle. During crystallization, they evolve to or exsolve H₂O- and/or CO₂-rich fluids that are increasingly linked to high-grade REE mineralization. The carbonatite stock at Mountain Pass hosts a world-class REE deposit where mineralization has historically been considered magmatic. However, isotopic and textural evidence indicate fluids were critical in the genesis of high-grade mineralization. Isotope geochemistry and petrography support at least two fluids of varying fO₂ in the Mountain Pass carbonatite. Primary barite phenocrysts frequently exhibit fine-grained, Sr-rich rims texturally associated with disseminated sulfides. Sulfur isotope geothermometry indicates these sulfides precipitated from a late-stage, low-temperature (~250-300 °C) fluid. The presence of hydrothermal sulfides in an oxidized primary mineral assemblage (carbonates + sulfates) indicates this fluid was more reduced than the initial parental melt. Another population of barite, which appears phenocrystic in hand sample, in thin section consists of porous grain aggregates that lack Sr enrichment. This population of barite is not associated with sulfide minerals, suggesting precipitation from a more oxidized fluid. The two fluids indicated by sulfur minerals are supported by calcite carbon and oxygen isotopes. Two isotopically distinct, late-stage calcite populations are observed in textural association with late-stage REE minerals: one with $\delta^{13}\text{C} = -3$ to 1‰ ; $\delta^{18}\text{O} = 8$ to 10‰ and one with $\delta^{13}\text{C} = -6$ to -3‰ and $\delta^{18}\text{O} = 15$ to 25‰ . Isotopic modeling indicates the first calcite population precipitated from an H₂O-dominant fluid, whereas the second population, which exhibits strong negative Ce anomalies, precipitated from an oxidized, CO₂-dominant fluid. Fluid-linked mineralization in carbonatite systems is complex; this study documents isotopic and textural evidence for hydrothermal REE mineralization under different redox states. Whether the transition in redox state was a driver of mineralization remains under investigation.