

Formation of the Mountain Pass Rare-Earth Deposit: Insights from Mineralogy, Trace Elements, and Isotopic Geochemistry

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The Mountain Pass deposit is a globally significant rare earth element (REE) resource, yet its formation mechanisms remain unclear. REE mineralization is primarily hosted within the Sulphide Queen Stock, occurring in diverse lithologies, including bastnäsite-barite rocks (BB), monazite-calcite rocks (MC), bastnäsite-calcite-barite rocks (BC), mineralized dolomite-calcite-barite rocks (DC), and breccia. This study integrates detailed mineralogical investigations with in-situ trace element and isotope geochemistry in an effort to unravel the deposit's formation and evolution.

Monazite-calcite rocks are equigranular in texture and include silicate wall-rock fragments, indicating a magmatic origin. Calcites in MC display concave-downward REE patterns, likely influenced by monazite crystallization, and low C-O isotopic values clustering below the Primary Igneous Carbonate (PIC) field, potentially due to degassing. In contrast, calcite in BC is inequigranular with concave-upward REE profiles, suggesting post-recrystallization REE redistribution. Strontium isotopes in BC overlap with those of MC, but exhibit a wider range, while its C-O isotopic compositions plot within the PIC field. Dolomite in DC shows concave-upward REE patterns with low trace element concentrations, whereas intergrown calcite exhibits two distinct REE signatures: LREE enrichment and strong negative Ce anomalies, the latter resembling calcite in the breccia matrix. Elevated Sr-C-O isotope values in dolomite imply a sedimentary origin, while calcites with Ce-anomalies record the highest Sr isotopic compositions, indicating external oxidized fluids. These geochemical variations suggest a complex evolution involving magmatic crystallization, recrystallization, and fluid-mediated overprinting.

The widespread occurrence of sulfate-carbonate-REE minerals throughout the deposit highlights the crucial role of sulfate-carbonate-fluorine-REE-rich melts in REE mineralization. Bastnäsite-barite rocks provide direct mineralogical evidence of crystallization from such melts, exhibiting the most primitive Nd isotopic compositions. The heterogeneous Sr-C-O isotopic compositions of carbonate minerals rule out a simple accumulation origin. Instead, we propose that high-salinity melts—likely generated by liquid-liquid immiscibility—concentrated and preserved REE in sulfate-rich stocks while leaving nearby sulfate-poor carbonatite dikes barren of REE mineralization. These melts further interacted with pre-existing igneous and sedimentary rocks, driving REE mineralization across various lithologies at shallow crustal levels.