

How Do Hydrothermal Fluids Transport and Fractionate Rare Earth Elements in Critical Mineral Deposits?

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The rare earth elements (REE) are included in the 2025 list of Critical Minerals released by the USGS because of their importance in the high-tech, defense, and energy industries, and their high supply risks. The REE include the lanthanides (La-Lu) and Y, which generally occur in the trivalent state and can be subdivided into the larger light (L) and smaller heavy (H)REE. Despite the chemical similarities, the REE display important fractionation in geological systems, particularly in association to magmatic-hydrothermal systems. Carbonatites and alkaline igneous complexes host many of the largest REE deposits where extreme enrichment and fractionation of light from heavy REE are recorded. Igneous processes are undeniably important to enrich and emplace the REE to crustal levels where these mineral deposits form. However, hydrothermal alteration and veining are commonly pervasive in these deposits and can result in significant mobilization, fractionation and enrichment of LREE/HREE. Remaining questions include the significance, spatial scales, and mechanisms by which hydrothermal fluids transport REE. Addressing these questions is important because exploration models for subsurface high-grade targets commonly rely on bulk rock geochemistry, drill core logging, and lithogeochemical vectors associated with alteration footprints. In this keynote, I will present insights from more than a decade of research on magmatic-hydrothermal REE deposits, including examples from different deposit types (e.g. Strange Lake peralkaline granite, Lemitar Mountains carbonatite, and Gallinas Mountains alkaline igneous-hosted hydrothermal breccia). I will also discuss new hydrothermal laboratory experiments designed to determine the solubility of monazite and xenotime and the speciation of REE as a function of temperature, pressure and fluid chemistry (pH and ligand activity) to supercritical conditions, as well as our current progress on geochemical modeling of fluid-rock interaction and REE behavior in hydrothermal fluids. This research is supported by DOE-BES grant DE-SC0026161 and NSF CAREER EAR-2039674.