High-Pressure Behaviour and REE Enrichment in Carbonatite Systems – Sources of Critical Elements

Introduction: Rare earth elements (REEs) are critical for modern technologies, including renewable energy, electronics, and advanced materials. Understanding the geological mechanisms responsible for concentrating rare earth elements (REE) in the Earth's crust is essential to meeting growing global demand. The principal sources of economically viable REE deposits include carbonatite and peralkaline intrusive complexes—such as nepheline syenites and granitic suites—as well as their derivative alteration and weathering products, including fenites, placers, and ion adsorption clays. These systems exhibit distinct REE fractionation trends, with carbonatite-related deposits typically enriched in light rare earth elements (LREE: La to Sm), whereas peralkaline silicate intrusions and syenites often contain higher concentrations of heavy rare earth elements (HREE: Eu to Lu, +Y) (Jin et al., 2025).

REE enrichment in primary magmatic systems results from processes such as extreme fractional crystallization and liquid–liquid immiscibility, leading to the formation of REE-bearing minerals. Depending on melt composition, these may include apatite, pyrochlore, monazite, xenotime, REE-fluorocarbonates, or eudialyte. In many cases, late-stage magmatic-hydrothermal fluids mobilize REEs from crystallized phases and facilitate their re-deposition in secondary hydrothermal minerals like monazite, xenotime, fluorapatite, or fluorcarbonates (bastnäsite, parisite, synchysite). This hydrothermal reworking is frequently regarded as a critical step in the development of ore-grade deposits in both peralkaline granite and carbonatite systems (Mororó et al., 2024, Louvel et al., 2022, Yuan et al., 2024). Despite these insights, the detailed high-pressure behavior of these systems remains poorly understood, particularly in terms of mineral stability, reaction pathways, and fluid-melt interactions at deep crustal and upper mantle conditions. This project aims to bridge this gap through high-pressure experimental synthesis, in situ spectroscopic techniques, and synchrotron X-ray analysis. It tackles the fundamental processes associated with the formation of REE deposits, particularly carbonatite derived material.

Research Objectives: Experimental petrology, High-Pressure materials science and mineral physics can significantly advance our understanding of the processes leading to the economic mineralization of REEs and niobium (Nb) in carbonatite systems. Here, the student will:

1. Synthesize REE-bearing carbonatite compositions under controlled high-pressure and high-temperature (P-T) conditions (1–4 GPa, 600–1200°C) using piston-cylinder experiments to simulate deep crustal and upper mantle environments.
2. Investigate the stability and transformation mechanisms of REE minerals during high-pressure crystallization, metasomatism, and hydrothermal alteration.
3. Perform in situ Raman spectroscopy on experimental run products in a diamond anvil cell (DAC) to track structural and bonding changes under high-P/T conditions.

4. Use synchrotron X-ray diffraction (XRD) and X-ray fluorescence (XRF) to determine phase transitions, crystallographic changes, and REE partitioning across different mineral phases.

Methodology: *High-Pressure Experimental Synthesis* will be conducted using piston-cylinder apparatus and large volume presses (Paris-Edinburgh and multi-anvils) to synthesize REE-bearing carbonatites at pressures up to 4 GPa and temperatures between 600°C and 1200°C. The starting materials will be high-purity carbonate-silicate mixtures doped with controlled amounts of REE oxides (La, Ce, Nd, Eu, Y). Rapid quenching techniques will be used to preserve metastable phases, and recovered samples will be characterized using electron microscopy and microprobe analysis to confirm phase compositions.

In Situ High-Pressure Raman Spectroscopy (DAC) will be used to help track phase transitions, molecular speciation, and hydration/decarbonation reactions relevant to deep Earth processes. Raman spectra will be compared with natural samples to assess the geochemical relevance of experimental products.

Synchrotron X-Ray Diffraction and XRF will be employed to determine structural controls, phase stabilities, and compression mechanisms of synthesized REE-bearing carbonates and silicates at high pressures. XRF mapping will be used to evaluate REE partitioning and redistribution among these mineral phases, to understand the controls on REE mobility in deep carbonatite systems.

Anticipate Outcomes: This project will provide insights into the role of high-pressure hydrothermal fluids in REE redistribution, with implications for ore formation and the deep carbon cycle. It will lead to an enhanced understanding of REE mobility in geodynamic settings, informing exploration strategies for economic deposits. This will contribute to both mineral physics and economic geology by advancing knowledge on REE behaviour in high-pressure environments to provide experimentally derived constraints on the formation of REE-rich carbonatite systems.

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