Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.35928

Rare Earth enrichment in carbonatite-forming magmatic systems

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Most currently mined rare earth element (REE) deposits are hosted in carbonatites and their alteration products, yet carbonatitic melts and hence carbonatite rocks may form through several magmatic pathways with vastly different potentials for economic REE enrichment. With an economic threshold of ≥4-5 wt% REE_2O_3 a 3000-fold enrichment is required compared to an e.g. primitive mantle (15 ppm REE), the ultimate mantle origin of carbonatites being undisputed based on isotopic values.

In this study, we demonstrate that the magmatic processes capable of generating carbonate melts produce primary REE-concentrations in carbonatites spanning three orders of magnitude, in excellent agreement with calculated $[REE]^{melt}$ concentrations from $[REE]^{apatite}$ (1). Based on partition coefficients, partial melting of carbonated lithospheric mantle to carbonate melts yields only a 10-20 fold enrichment and hence barren carbonatites, irrespective of whether a depleted, primitive or metasomatizes lithsopheric mantle source is employed. Partial melting of the asthenospheric mantle to kimberlitic melts, followed by their differentiation to carbonatites may yield a ~200 fold enrichment, yet, such occurrences are scarce and typically small. In contrast, the three-step pathway involving partial asthenospheric melting to form alkaline, heavily Si-undersaturated melts, differentiation to nephelinites or phonolites, and subsequent carbonatite-silicate liquid immiscibility can produce up to 3.5 orders of magnitude enrichment. This latter threestep process increases mantle REE-concentrations of ~10 ppm to 1-2 wt% REE in carbonatites exsolved from phonolitic magmas.

Further, and in contrast to most silicate melts, any magmatic differentiation of carbonatitic magmas decreases REE contents, as REE are compatible in calcite and apatite. Thus, final enrichment to economic concentrations must arise from fluid-mediated processes, and in all likelyhood, these fluids scavange their REE from already REE-rich carbonatites. As H_2O and REE are similarly incompatible, the three-step pathway inherently leads to H_2O enrichment and ultimately to fluid saturation, providing opportunity for fluid-mediated enrichment of REE. Consequently, the highest likelihood of forming economic REE deposits arises from carbonatites immiscible to highly evolved phonolitic silicate magmas. In contrast, single stage partial melting processes or carbonatite differentiation are ineffective.

(1) Guo et al. (2024), *EPSL* 642, 118863.