

Mantle Source Enrichment and Volatile Recycling Controls on Rare Earth Element Fertility in the Loch Borralan Carbonatite, Scotland

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Carbonatites host the world's most important rare earth element (REE) resources, yet the processes controlling their fertility remain poorly understood, particularly the role of mantle source enrichment. This study integrates radiogenic (Sr-Nd-Hf-Pb) and volatile (N-Ar) isotope systematics to constrain the mantle source characteristics and enrichment history of the Loch Borralan Carbonatite (LBC), northwest Scotland. Carbonatites and associated rocks exhibit negative $\epsilon\text{Nd(i)}$ (-0.65 to -1.79) and $\epsilon\text{Hf(i)}$ (-8.0 to -10.6), elevated initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70570-0.70602), and Pb isotope compositions plotting below the mantle array in the EM1 field, indicating derivation from an enriched subcontinental lithospheric mantle containing subducted recycled oceanic crust components. Trace element and isotopic relationships overlap with ocean island basalt (OIB) fields and extend toward compositions characteristic of fluids derived from altered oceanic crust and sediments, supporting metasomatic enrichment prior to carbonatite generation. Stepwise crushing analyses of fluid inclusions reveal coupled N and Ar release patterns with elevated $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (>5000), indicating a mantle-derived volatile component distinct from atmospheric contamination. Nitrogen isotope compositions ($\delta^{15}\text{N} = 0$ to +9.4‰) and mixing relationships between mantle, atmospheric and devolatilised sedimentary end-members demonstrate significant incorporation of recycled sedimentary N into the mantle source. These data define a modified OIB-like mantle reservoir enriched in volatiles and incompatible elements through subduction-related metasomatism. Although the LBC shows geochemical signatures consistent with many REE-fertile carbonatites, economic deposits typically exhibit substantially higher REE concentrations. Stable C-O isotopes signatures indicate minimal hydrothermal overprinting, confirming a mantle-derived origin and suggesting that REE enrichment at Loch Borralan was not fully mobilised into ore-grade concentrations. This implies that LBC inherited its REE content from a metasomatically enriched mantle source modified by subducted recycled oceanic sediments but did not undergo post-magmatic processes necessary to generate economic mineralisation. These results highlight the key role of subduction-related mantle metasomatism in generating REE-fertile carbonatite magmas.