

Applications of Mineral Chemistry to Petrogenesis and Exploration in the Borralan Carbonatite Complex and Associated Alkaline Silicate Rocks

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The Loch Borralan Carbonatite Complex (LBC) and associated alkaline silicate rocks in NW Scotland provide insights into the interplay between mineral chemistry, petrogenesis, and rare earth element (REE) enrichment in carbonatite systems. Mineral chemistry (LA-ICP-MS, EMPA), stable isotopes (C, O, N and Ar), radiogenic isotopic tracers (Sr-Nd-Hf-Pb) and geochronology (U-Pb, Ar-Ar) were used to investigate the LBC rocks. Mineral chemistry revealed that multistage REE mobilisation and deposition was driven by fluorine- and carbonate-rich magmatic-hydrothermal fluids. Early magmatic phases (apatite, perovskite, chevkinite) sequestered REEs via carbonate complexation, while later oxidising-hydrothermal events triggered remobilisation into secondary assemblages (bastnäsite, monazite, ancylite). Redox contrasts are revealed by coexisting sulphides (pyrite, pyrrhotite) and sulphates (barite, celestine) that localised REE deposition along structural conduits (e.g., fenite veins with high REE). Phlogopite zoning and replacement textures (perovskite→chevkinite→fluorocarbonates; perovskite→menite, calcite and ancylite; monazite→britholite) chronicle episodic fluid influx and evolving REE availability. Geochronology links LBC emplacement (~424–438 Ma) to Caledonian subduction with inherited zircons (480–553 Ma) and enriched mantle isotopic signatures (ϵNd_{430} : -1 to -2), suggesting that subduction of oceanic crust modified mantle sources and controlled formation of the carbonatite-associated REE system. Radiogenic isotope data and analysis of abundance and isotopic composition of C, O, N and Ar revealed that formation of carbonatite and initial enrichment was linked to fluids from recycled marine sediments, although primary mantle signatures are preserved. Mineral chemistry defines key vectors to guide extraction strategies: (1) fluorite-rich fenites mark fluid pathways, (2) sulphide-sulphate redox interfaces with high REE-rich zones, and (3) refractory vs. leachable REE phases (zirconolite vs. fluorocarbonates). The complex mineralogy necessitates advances in beneficiation tailored to mineral speciation. This work demonstrates that interpreting mineral-scale processes can bridge the gap between petrogenetic models and orebody knowledge, emphasizing the role of ligand-driven fluid evolution and tectonic fluid histories in targeting carbonatite-hosted REE deposits.