

Investigating REE Mineralization Processes Using μ XRF Elemental Mapping: A Case Study of the Nkalonje Carbonatite, Chilwa Alkaline Province, Malawi

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Understanding the rare earth element (REE) enrichment mechanism in carbonatites remains a key challenge in economic geology. This study evaluates the application of micro-X-ray fluorescence (μ XRF) mapping to investigate the light REE (LREE) mineralization process in the understudied Nkalonje Carbonatite, Chilwa Alkaline Province, Malawi. Elemental maps were acquired from carbonatite thin sections ($\sim 4.5 \times 2.5$ cm) using a Bruker Tornado μ XRF scanner at 20 μ m spatial resolution. Data were processed with Bruker M4 Tornado and ESPRIT software programs employing standardless, fundamental parameter quantification. The Nkalonje Carbonatite comprises five lithologies: calcio-carbonatite, feldspathic breccia and agglomerate, fenite, syenite, and quartz-fluorite dykes. Coexistence of carbonatite and syenite has been suggested to indicate genesis via silicate-carbonate melt immiscibility. LREE mineralization in the Nkalonje Carbonatite occurs predominantly as synchysite-(Ce) and bastnäs site-(Ce), with minor apatite. Elemental maps reveal a heterogeneous Ce distribution concentrated in open spaces and along cleavage planes, spatially associated with Sr- and Si-rich zones. Textural evidence shows replacement between synchysite-(Ce), strontianite, and Ca-carbonate, as well as quartz- and Fe-carbonate veinlets crosscutting primary cleavage planes in calcite. In the quartz-fluorite dyke, Ce-rich zones heterogeneously coat the silicate matrix and are spatially associated with P-rich areas, indicating late-stage hydrothermal Ce enrichment. However, primary calcite contains up to 0.2 wt% Ce_2O_3 , suggesting the initial melt was already LREE-enriched. These observations indicate a two-stage mineralization process: (1) primary enrichment through melt immiscibility, followed by (2) hydrothermal redistribution. Compared to scanning electron microscopy, which provides limited spatial coverage, and bulk geochemistry, which masks fine-scale heterogeneity, μ XRF mapping provides a rapid, comprehensive visualization of mineral-element relationships, offering an effective tool for deciphering REE mineralization in carbonatite systems.