

Alteration Vectors for Hydrothermal Mobilization of REE, U, Ti, Nb, and Zr in the Lemitar Mountains Carbonatite, New Mexico

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Carbonatites host the world's largest rare earth elements (REE) deposits and commonly undergo extensive hydrothermal alteration that redistributes REE and other high-field strength elements (HFSE). However, the processes controlling HFSE mobilization and fluid evolution during hydrothermal overprinting are poorly understood. The Lemitar Mountains carbonatite in New Mexico consists of hundreds of carbonatite dike exposures (calcio- to ferro-carbonatites) that intrude Proterozoic basement rocks. Hydrothermal veins and/or extensive multi-stage alteration overprints these lithologies. In this study, we investigate the hydrothermal evolution of the Lemitar carbonatite and present the alteration mineralogy, vein mineral paragenesis and major/trace elements in chlorite, apatite, calcite, and quartz using SEM-BSE, CL, EPMA, and LA-ICP-MS analysis. Three main vein generations are distinguished from petrographic observations. Type I quartz-albite veins are associated with Na-K fenitization and silicification with the Ti-in-quartz geothermometer recording $465 \pm 22^\circ\text{C}$. Type II (hematite)-chlorite-quartz-calcite veins are associated with silicification, carbonatization, and chloritization/hematization and host REE fluorocarbonates, Nb-rutile, coffinite, and zircon with Ti-in-quartz and chlorite geothermometers recording $\sim 270\text{--}369 \pm 6^\circ\text{C}$. Type III (barite)-fluorite-quartz-calcite veins crosscut earlier alteration styles and contain REE fluorocarbonates associated with Ca-F metasomatism and silicification. Primary HFSE-bearing minerals in the carbonatites include pyrochlore, columbite, aesynchite, baddeleyite, and apatite. Localized replacement of HFSE minerals occurs; however, widespread HFSE mobilization is evidenced by vein-hosted mineralization. In addition to REE fluorocarbonates, apatite occurs as another REE-bearing phase spanning multiple generations from the carbonatite (Ap 1) to the hydrothermal stages in Type I-II veins (Ap 2). Ap 1 occurs in the carbonatite and displays high L/HREE fractionation, whereas Ap 2-3 in the hydrothermal veins and fenites have up to one order of magnitude higher HREE. Overall, the hydrothermal stage shows a progression from high- to low-temperature fluid-rock interaction, with minerals such as apatite and calcite being important alteration vectors in the Lemitar Mountains carbonatite.