

## **Petrographic, Geochemical, and Isotopic Characteristics of the Early Silurian Miaoya Syenite-Carbonatite Complex, Central China: Implications for the Origin of REE-Enriched Carbonatite Melt**

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Carbonatites are typically associated with alkali silicate igneous rocks. Proposed models for the generation of carbonatites associated with silicate rocks include derivation by immiscible separation from CO<sub>2</sub>-saturated silicate melts or crystal fractionation of a carbonated alkali silicate melt. The Miaoya syenite-carbonatite complex is located in the southern margin of the Qinling orogen in central China. It contains  $\approx$ 1.21 Mt total rare earth oxides (@ 1.72 wt % TREO) and  $\sim$ 0.93 Mt Nb<sub>2</sub>O<sub>5</sub>. The genetic relationship between carbonatites and syenites in this complex is still not well understood. A combined field, petrological, and geochemical study was conducted on this complex to better understand its origin. The fresh syenites are dark gray in color and contain dominantly potassium feldspar, with zircon, rutile, ilmenite, magnetite, and columbite as accessory minerals. Syenites are commonly altered by carbonatitic melts to a slightly gray color. The altered syenites commonly contain ankerite, calcite, apatite, and rare earth minerals interstitial among K-feldspar crystals. The carbonatites are divided into calcite and ferrodolomite carbonatite groups. The former consists mostly of calcite, with subordinate apatite and biotite, and minor allanite, monazite, ilmenite, magnetite, columbite, bastnäsite, and rutile. Locally, K-feldspar phenocrysts and zircons can also be found within the calcite carbonatites, which may be crystallized from the earlier carbonated silicate melt. The ferrodolomite carbonatite is mainly composed of ankerite, calcite, and fluorite, with accessory phases of bastnäsite and monazite.

Both carbonatites and syenites are characterized by the enrichment in Nb, Sr, Ba, U, Th, and LREE, and variable depletion in high field strength elements (such as Ta, Zr, and Hf) and HREE in primitive mantle-normalized patterns. The carbonatites have higher concentrations of REE than syenites. Ferrodolomite carbonatites are obviously richer in REE than calcite carbonatites. Zircon grains separated from a calcite carbonatite sample have a weighted mean U-Pb age of  $428 \pm 3$  Ma (MSWD = 0.44), representing the crystallization age of the carbonatite. The carbonatites have initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios of 0.70390, which are almost identical to those of syenites (0.70325), indicating that carbonatite and syenite are derived from the same magma source (e.g., depleted mantle). This interpretation is also supported by the field relationships of widespread occurrence of altered syenites and presence of K-feldspar phenocrysts in carbonatites. The calcite carbonatites was formed by separation of immiscible carbonate-rich melts from related silicate magmas that formed entirely different mineral assemblages in carbonatites and syenites, respectively; the ferrodolomite carbonatites are interpreted as a more evolved end member of the carbonatitic melts. Furthermore, REE elements are more compatible in carbonatite melt than in silicate melt, and bastnäsite-(Ce) and monazite-(Ce) are the main REE-bearing minerals, while Zr generally partitions into the silicate melt. The REE mineralization is specifically concentrated

largely in the later ferrodolomite carbonatite. A fluoride fluid may play an important role in REE mineralization.