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Origin and evolution of granitic pegmatite rare metal deposits in the northern Mufushan batholith, South China: Insights from muscovite chemistry

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Abstract

Granitic pegmatites are renowned as significant sources of rare metals (e.g., Li, Ta, Nb, Be, Cs). However, the origins and mechanisms underlying the enrichment of rare metals in granitic pegmatites remain subjects of intense debate. This study provides comprehensive petrography, major and trace element analyses of muscovites and isotopic data from pegmatite dikes associated with the Early Cretaceous Mufushan composite batholith in South China to elucidate geochemical fractionation processes and the mechanisms responsible for rare metals mineralization. Rare metal-bearing pegmatite and barren pegmatite dikes are found within the metasedimentary strata and the granitoid batholith, respectively. Both types of pegmatite dikes exhibit internal zoning, featuring three distinct structural zones with varied mineral assemblages, where muscovite is ubiquitously present across all zones. Both rare metal pegmatites and barren pegmatites show a limited monazite $\varepsilon_{Nd}(t)$ range between −9.0 and −7.6, which is aligned with the apatite $\varepsilon_{Nd}(t)$ values of −9.8 to −7.8 from the monzogranites. Progressing from the wall zone to the core zone in both pegmatites, muscovite exhibits increasing enrichment in incompatible elements (Li, Rb, Cs, Ta, Mn, and F) but a depletion in Ti, Zr, and Pb, indicative of a gradual differentiation trend. The consistent Nd isotope characteristics but variable fractionation in muscovite chemistry for the pegmatites and monzogranites indicate that they were derived from a similar magmatic source. The most primitive units of both pegmatites show differentiation degrees of muscovite comparable with the two-mica monzogranite but lower than the muscovite monzogranite, implying that the pegmatites and monzogranites might represent evolutionary products independent of two-mica monzogranite and muscovite monzogranite. Melt compositions (Li, Rb, and Cs) in equilibrium with muscovites for pegmatites are quantitatively calculated, evaluated, and aligned with a Rayleigh fractional crystallization model. Our modeling indicates that the formation of barren pegmatite requires merely 50% Rayleigh fractional crystallization degree, whereas the intermediate zone, marking the initial conspicuous occurrence of rare metal minerals in rare metal pegmatites, necessitates ~90% Rayleigh fractional crystallization degree. Notable variations in Li, Rb, and Cs contents across different zones underscore the progressive enrichment of rare metals due to the fractionation of pegmatitic magmas within the cooler metasedimentary rocks. We propose that pegmatites in the Mufushan batholith predominantly concentrate rare metals by evolutionary processes through Rayleigh fractional crystallization and constitutional zone refining (CZR).

Keywords: Muscovite, pegmatite magma evolution, rare metal enrichment mechanism, Rayleigh fractional crystallization, Special Collection: Pegmatites