Goldschmidt 2024 Abstract
https://doi.org/10.46247/gold2024.22685

# Insights into pegmatite evolution and Li mineralization through tourmaline geochemistry and B isotope analysis

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Pegmatite-related deposits represent one of the most important types of deposits containing rare-metal elements such as Li, Be, Nb, and Ta. Despite nearly two centuries of extensive study, the mechanism governing the rare-metal mineralization of pegmatites remains contentious. Alongside the enrichment of rare-metal elements in the source region, differentiation processes after emplacement may have also contributed to the concentration and mineralization of rare-metal elements. However, compared to fractional crystallization, limited attention has been directed toward the role of liquid immiscibility in pegmatite mineralization. In this study, the element and boron (B) isotope compositions of tourmalines from various textural zones (Zones I–VIII) of the Koktokay No.3 pegmatite were analyzed to assess the influence of liquid immiscibility in the formation of Li-mineralized pegmatites. Tourmalines in Zones I–III and VII–VIII show less variable $\delta^{11}$B values (–15.07‰ to –12.21‰ and –14.16‰ to –13.10‰, respectively), indicating minimal B isotope fractionation resulting from fractional crystallization during pegmatite evolution. By contrast, tourmalines in Zones IV–VII demonstrate more significant variations in $\delta^{11}$B values (–14.83‰ to –8.09‰) than those in Zones I–III and VII–VIII. The high $\delta^{11}$B tourmalines in Zones IV–VII were likely crystallized from fluids exsolving from the highly evolved pegmatite-forming magma. Their presence suggests fluid exsolution occurring between zones IV and V, where Li mineralization was initiated in the Koktokay No. 3 pegmatite. Thus, the mineralization of rare-metal elements appears closely tied to the evolution of magma into a coexisting magma-fluid system. In addition, Li-mineralized pegmatites are characterized by tourmalines with $Fe^{3+}Al_{-1}$ substitution and higher Zn, Li, Li/Sr, and V/Sc compared to barren pegmatites. These distinctions are thought to stem from the elevated $fO_2$ and more extensive magmatic evolution in Li-mineralized pegmatites relative to the barren ones. These findings provide new insights into utilizing the geochemical compositions of tourmalines as a guide for exploring Li-mineralized pegmatites.