

How fluids control beryllium mineralization in a magmatic-hydrothermal system: Evidence from mica geochemistry and quartz-beryl O isotopes

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ABSTRACT

Beryllium (Be) deposits are associated with highly fractionated granites and high-silica rhyolites that record a long and complex magmatic-hydrothermal evolution. However, the genetic link between Be mineralization and magmatic-hydrothermal processes, especially the origin of fluids and their role in enriching and precipitating Be, remains poorly understood. Here we present mica geochemistry and quartz-beryl O isotopes, as well as zircon U-Pb ages and O-Hf isotopes, cassiterite U-Pb ages, and whole-rock geochemistry for two distinct types of Be deposits (i.e., the Nasigatu greisen-type and the Zhujiayingzi quartz vein-type) in the southern Great Xing'an Range (SGXR), NE China. Zircon and cassiterite U-Pb dating results of the Nasigatu alkali feldspar granites (AG) and greisens (144–139 Ma) are nearly coeval with the Zhujiayingzi quartz veins (149–147 Ma), revealing that Be mineralization in the SGXR occurred in a Late Jurassic to Early Cretaceous magmatic-hydrothermal system. Zircon O-Hf isotopes and whole-rock geochemistry suggest that the ore-related AG is a highly differentiated A2-type granite with a complex source involving juvenile lower crustal components with ancient continental and altered oceanic crust. Partial melting, Rayleigh fractionation, and fluid exsolution modeling, along with geological and petrological observations, suggest that Be mineralization could hardly be achieved through partial melting, fractional crystallization and/or fluid exsolution processes. Si, Cl, Ca, Mn, K, and Al contents in muscovite from AG to beryl-bearing greisens and quartz veins are consistent with the evolution trend of A-type granites, which, together with the uniform $\delta^{18}\text{O}$ values recorded by quartz and beryl in both barren and ore fluids, suggests the involvement of magmatic fluids derived from highly differentiated granitic melts at a shallow emplacement depth. These magmatic fluids interacted with the early-stage crystals within granitic melts, extracting Be into the fluids due to the low $D_{\text{mineral/fluid}}$ values for Be in feldspar and biotite. In contrast, the obvious increase in Mg-Ti contents of muscovite from AG to greisens and quartz veins, as well as core-rim zonation of beryl, contradict the normal evolution trend of a closed magmatic-hydrothermal system, indicating the coexistence of deep magmatic fluids exsolved from large deep silicic magmatic reservoirs. Such deep magmatic fluids not only provided heat and promoted fluid-mineral interaction but also efficiently extracted and transported Be enriched in deep crystal mushes at varying depths. The strong linear relationships between Be and F in muscovite suggest that Be-F complexes served as the primary migration model in the fluid system. Thermal and O isotopic variations reveal that the decomposition of Be-F complexes and subsequent beryl precipitation were triggered by the cooling of pure magmatic fluids rather than by mixing with external fluids and/or water-rock interaction. The abrupt decrease in fluid $\delta^{18}\text{O}$ values was solely observed in the barren quartz druse at Nasigatu, indicating that the system ultimately allowed for the infiltration of meteoric water and further cooling. Our findings confirm that fluid cooling is the primary driver of Be deposition in magmatic-hydrothermal systems, and underscore the significant role of interaction between pre-existing minerals and multi-depth magmatic fluids in Be enrichment.

Keywords: Beryllium mineralization, magmatic-hydrothermal system, mica geochemistry, quartz-beryl O isotopes, fluid-mineral interaction, fluid cooling