Continuous Be mineralization from two-mica granite to pegmatite: Critical element enrichment processes in a Himalayan leucogranite pluton

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**ABSTRACT**

Beryllium is a critical metal typically concentrated in highly fractionated granitic rocks such as the leucogranites in the Himalaya. Here, we report beryllium mineralization that was continuous from the earlier and less-evolved two-mica granite to the highly evolved albite granite and pegmatite in a typical leucogranite pluton at Pusila in the central of Himalaya. Textural and mineral chemical evidence support a magmatic origin for beryl, and the trends of beryl crystal chemistry indicate magma differentiation. Despite low to moderate fractionation of the biotite granite and two-mica granite in the Pusila leucogranite pluton, the Be contents (~7 µg/g, beryl-free and ~22 µg/g, beryl-bearing, respectively) of these granites are much higher than the average for biotite- and two-mica granites worldwide (~3–4 and 5–10 µg/g, respectively), indicating that the initial magma had a relatively high-Be concentration. The gneisses of Greater Himalayan System, considered the protolith, also show a higher Be abundance (~4–6 µg/g) than the mean value of pelitic rocks worldwide (~2–3 µg/g), which could be the source reservoir of Be. The source contributed the initial Be to the melt, and fractionation resulted in the onset of beryl crystallization from the interstitial residual melt in the two-mica granite. The ubiquity of beryl in two-mica granite to pegmatite stages of the Pusila pluton is explained by a continuous crystallization model, although there was a delay in the onset of beryl crystallization in the two-mica granite. Modeling based on Rayleigh fractionation indicates that Be becomes compatible once saturation is attained because of the beryl crystallization. Our findings indicate that the enrichment of critical elements (e.g., Be) is controlled not only by fractional crystallization but also by the buffering action of a saturating phase (e.g., beryl) on the concentration of the critical element in the melt.

**Keywords:** Himalayan leucogranite, beryllium, beryl, source, fractionation, delayed crystallization; Lithium, beryllium and boron: Quintessentially crustal

**INTRODUCTION**

Beryllium is a lithophile element that is considered a critical metal because of its high demand in technologically strategic materials in next-generation industries (e.g., new energies, new alloys) (Chakhmouradian et al. 2015; Trueman and Sabey 2014; Sovacool et al. 2020). The world’s largest beryllium deposit is the Spor Mountain in the U.S.A., a rhyolite-hosted deposit where the ore mineral is bertrandite. The remainder of global Be production is almost entirely from beryl, which is typically hosted by granitic pegmatites (Linnen et al. 2012), although phenakite may also be important at some deposits.

On average, granites contain only ~4–8 µg/g Be (Beus 1966; Norton and Redden 1990; London and Evensen 2002). Beryl saturation in granitic melts requires extreme fractionation and low temperatures (London 2008, 2015). Consequently, Be mineralization is generally linked to highly evolved granites, in particular to granitic pegmatites.

The Himalayan leucogranite belts are endowed with extensive beryl mineralization (Wang et al. 2017). Particularly, the Pusila pluton, west of Mount Everest, is an excellent site to study Be-Nb-Ta-Li mineralization (Liu et al. 2020). Beryl at this location is widely present as a magmatic phase not only in highly evolved intrusions (albite granite and pegmatite) but unexpectedly also in the earlier, less-evolved two-mica granite stage of the magmatic evolution. This striking first-order observation provides the opportunity to investigate the mechanisms involved in beryl mineralization, beginning with two-mica granite and continuing to pegmatite in the leucogranite pluton, which may be more complicated than simple fractionation in a granitic system.

In this study, we present the whole-rock chemical composition of beryl-bearing leucogranites in Pusila, together with the petrography and mineral chemistry of beryl, and characterize the initial Be mineralization in two-mica granite. The evolutionary mechanism(s) for continuous Be mineralization from moderately to highly evolved granites and pegmatites are then evaluated, which may offer new insights into the Be mineralization generally. Our results reveal that beryllium concentration is