Beryllium silicate minerals in granite–pegmatite suites: Tracers of magmatic to hydrothermal and tectonic evolution (examples from Western Carpathians)

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Abstract: Beryllium silicate accessory minerals (beryl, gadolinite–hingganite, phenakite and bertrandite) represent useful mineral indicators of magmatic to hydrothermal processes and tectonic environment. It is well documented on examples from contrasting Carboniferous to Permian granite–pegmatite suites of the Western Carpathians (Slovakia). Primary magmatic beryl is characteristic accessory mineral in more evolved granitic pegmatites (Tatric Unit); Na–Fe–Mg enriched compositions occur in I-type granodiorite-affiliated pegmatites, whereas Al–(Cs–Li) enriched beryl is typical for S-type granite-related pegmatites. On the contrary, late-magmatic gadolinite-(Y) partly replaced by hingganite-(Y) occurs in rift-related A-type granite (Turčok, Gemeric Unit). Consequently, beryl and gadolinite as the most widespread magmatic accessory minerals of Be show antagonistic relationship in aluminous versus alkaline granite–pegmatite suites. Beryl is frequently replaced by post-magmatic assemblage: secondary Be silicate minerals (phenakite and bertrandite), late quartz, muscovite and K-feldspar. The beryl breakdown clearly documents post-magmatic tectonic event related with late- to post-Variscan uplift or Alpine (Mesozoic to Cenozoic) tectono-metamorphic overprint of the West-Carpathian crystalline basement.

Beryllium abundance

Beryllium belongs to the rare litophile elements (RLE) concentrating especially in felsic (Si-rich) peraluminous or alkaline magmatic rocks of the Earth continental crust. Average Be content of common granitic rocks usually attains 2 to 7 ppm (London & Evensen 2002). The highest Be concentrations exhibit some highly evolved F- and alkali-rich magmatic lithologies, such as A-type (topaz-bearing) rhyolites: ≤270 ppm, rare-element S-type leucogranites: 500 ppm, as well as beryl and complex Li–Cs–Ta granitic pegmatites: ~50 to 600 ppm (London & Evensen 2002). An unique combination of low valency and very small effective cation radius of Be^{2+} in tetrahedral coordination ($0.27 . 10^{-10}$ m; Shannon 1976) determine highly incompatible behaviour and very limited incorporation of Be into crystal structure of common granitic rock-forming minerals (quartz, feldspars, biotite, muscovite), probably by $Be^{2+} + Si^{4+} = 2Al^{3+}$ and $Ca^{2+} + Be^{2+} = (Na,K)^{+} + Al^{3+}$ substitutions. However, some silicate minerals could concentrate Be in notable concentrations: 10^2 to 10^4 ppm, such as cordierite with $Na^{+} + Be^{2+} = Al^{3+} + \square$ or Ca-micas of bityite–margarite series showing $Li^{+} + Be^{2+} = \square + Al^{3+}$ substitution (e.g., Černý 2002).

Carboniferous orogenic I-, S-type and Permian rift-related A-type granite to pegmatite suites of the pre-Alpine Paleozoic basement of the Western Carpathians represent a good example for Be behaviour study in contrasting geochemical and tectonic magmatic series.

Beryl versus gadolinite antagonism

Beryl [$(\square,Na,Cs,H_2O)(Al,Sc,Fe,Mg)_2(Be,Li)_3(Si_6O_{18})$] and gadolinite–hingganite-(Y) series [$(Y,REE)_2(Fe,\square)Be_2Si_2(O,OH)_2$] are generally the most widespread accessory Be minerals in magmatic rocks. However, both minerals precipitate only in highly fractionated, RLE-rich leucogranites and especially in granitic pegmatites due to strongly incompatible nature of Be. Beryl occurs in some evolved peraluminous pegmatites of parental Variscan granitic suites with I- and especially S-type affinity in the Tatric Unit of the Western Carpathians (Uher & Broska 1995; Uher et al. 2010). Beryl commonly associates with primary Nb–Ta oxide minerals (columbite, rarely tapiolite and wodginite groups, Nb–Ta rutile) almandine–spessartine, Hf-rich zircon and locally also gahnite; the pegmatites belong to the beryl–columbite subtype of LCT family. Beryl shows a sequence from Na–Fe–Mg enriched compositions in relatively less evolved pegmatites in I-type biotite granodiorites (Vysoké and Nízke Tatry Mountains) to Na–Fe–Mg poor and Al–(Cs–Li) enriched beryl in more evolved, S-type two-mica granites to granodiorites of the Bratislava and Bojná Massifs (Malé Karpaty and

Považský Inovec Mts.). The Na–Fe–Mg beryl (Prašivá, N. Tatry Mts.) exhibits 1.9–2.5 wt. % Na_2O (0.35–0.48 Na *apfu*), 2.7–5.0 wt. % FeO (0.21–0.40 Fe *apfu*), 2.0–2.7 wt. % MgO (0.29–0.38 Mg *apfu*), whereas cesium concent attains up to 2.0 wt. % Cs_2O (0.08 Cs *apfu*) in the Jezuitské Lesy pegmatite near Bratislava (M. Karpaty Mts.).

On the other hand, gadolinite-(Y) to hingganite-(Y) are characteristic accessory minerals of the Turčok A-type granites and related aplitic rocks (Gemeric Unit, Western Carpathians). The gadolinite associates with zircon, allanite-(Ce), xenotime-(Y) and (Y,REE)–Nb–Ta–Ti oxide minerals [fergusonite-(Y) and aeschynite/polycrase-(Y)] (Uher et al. 2009). Gadolinite-(Y) precipitated at late-magmatic stage consolidation whereas hydroxyl-bearing hingganite-(Y) partly replaced it probably during subsolidus alteration of the Turčok granite.

Consequently, both beryl and gadolinite show antagonistic behaviour in late-magmatic conditions. Beryl is characteristic accessory mineral for evolved mainly peraluminous REE-poor suites (S-, I-, rarely mildly A-type tendency) in contrast to gadolinite-(Y) as typical Be accessory mineral in fractionated metaluminous, REE-Fe-rich A-type granites.

Phenakite and bertrandite: products of beryl alteration

Investigated beryl is frequently replaced by post-magmatic mineral assemblage including secondary Be silicate phases (phenakite and bertrandite), late quartz, muscovite and K-feldspar. This replacement assemblage forms fine-crystalline (<1 mm) irregular veinlets and cluster aggregates along rims and fractures of primary magmatic beryl crystals. Phenakite and bertrandite were identified by XRD, Raman spectroscopy and EBSD, phenakite shows distinctive cathodoluminescence signal. Based on the mineral assemblage and textural relationships, the following reactions of beryl breakdown could be assumed in investigated West-Carpathian granitic pegmatites:

$6Brl+4K^++4H_2O+O_2=9Ph+4Ms+15Qz$

$2Brl+4K^++10O_2=3Ph+4Kfs+6Qz$

$2Brl+2Kfs+2H_2O=3Ph+2Ms+9Qz+O_2$

$4Brl+8K^++H_2O+7O_2=3Bd+8Kfs$

$4Brl+4K^++5H_2O+O_2=3Bd+2Kfs+2Ms+6Qz$

$24Brl+16K^++16H_2O+13O_2=18Bd+16Ms+60Qz$

(Brl: beryl; Ph: phenakite; Ms: muscovite; Qz: quartz; Kfs: K-feldspar; Bd: bertrandite).

Partial breakdown of beryl to phenakite, bertrandite and associated minerals is connected with post-magmatic (hydrothermal) fluids at T ~250–400 °C; the process has been related with late- to post-Variscan uplift or Alpine (Mesozoic to Cenozoic) tectono-metamorphic overprint of the West-Carpathian crystalline basement.

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