



The role of magma mixing in the evolution of high-K calc-alkaline granitoid suites: in situ trace element and Sr–Nd–Hf isotope constraints

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The so-called "I-type", high-K calc-alkaline granitoids are often considered as "hybrid" in origin, i.e. involving both mantle and crustal components in their petrogenesis. The interactions between both components either take place (1) at mantle levels (i.e. enriched mantle source); (2) at emplacement levels (i.e. crustal contamination and/or magma mixing with crustal melts) or (3) both. Magma mixing is, in particular, frequently invoked to explain the compositional range of high-K calc-alkaline granitoid suites, especially phases of intermediate composition ($\text{SiO}_2 = 60\text{--}65$ wt.%) such as quartz-diorites or granodiorites. We investigated the role of magma mixing in the origin of such rocks using elemental and isotope (Sr–Nd–Hf) chemistry of magmatic minerals (plagioclase, zircon, apatite, titanite, epidote), measured in situ by LA-(MC-)ICPMS, allowing a much greater spatial resolution than classical whole-rock geochemistry. We focused on a suite of late-Archaean (2.69 Ga-old) high-K, calc-alkaline granitoids from the Pietersburg block, northern Kaapvaal Craton (South Africa): the Mashashane, Matlala, Matok and Moletsi plutons. Those plutons range from diorites to monzogranites, emplaced at different crustal levels but all within a relatively short time span and showing evidence for interactions (mingling), both at the outcrop and mineral scale.

Hf isotope data on zircon confirm that all rocks are cogenetic (identical $\varepsilon_{\text{Hf}}(t)$), but trace element and Sr isotopes in plagioclase point to the involvement of several components in their petrogenesis, at different stages of the magma evolution. The most mafic rocks (diorites) derive from the interaction, at mantle levels, between depleted peridotite and a sedimentary component of quartzofeldspathic nature. The mineral chemistry of more felsic rocks can be explained by (1) differentiation from the diorite magmas through Amp + Plag fractionation; (2) interactions with magmas derived from melting of local crust (tonalites, metasediments); or (3) a combination thereof.

We paid particular interest on a sample of intermediate granodiorite sampled in an outcrop showing compelling macroscopic evidence for mingling between different magmatic phases. In this sample, apatite show complex chemical zoning (especially regarding REE, Y, Th and U) and heterogeneous Sr–Nd isotope compositions. On the other hand, single titanite grains are homogeneous in both chemistry and Sr–Nd isotopes, but are characterized by striking inter-grain variations that mimic the compositional variability of coexisting apatites. We interpret these relationships as reflecting crystallization of apatite during a dynamic, chaotic mixing process, while titanite formed later on during relatively steady conditions, but from a magma that preserved small-scale chemical heterogeneities. Consistently, thermometry and textural relationships indicate that apatite crystallized early in the magmatic sequence at $T > 900^\circ\text{C}$, while titanite formed closer to the solidus ($\sim 650\text{--}750^\circ\text{C}$). This implies that magma mixing necessarily took place early in the magma evolution, probably deep in the crust, and did not result in chemical homogenization of the hybrid magma at the hand-sample scale. This conclusion shows that the efficiency of magma mixing is essentially a matter of scale, and questions its ability to produce large volumes of "true" hybrids in high-K calc-alkaline granitoid suites.