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Trace element zoning in hornblende: Tracking and modeling the crystallization of a calc-alkaline arc pluton

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Abstract

Recent studies of arc volcanic systems have shown that major and trace element zoning in calcic amphibole yields information about magmatic processes such as fractional crystallization and mixing. Similar studies of plutonic amphibole are scant, yet hold the potential to yield comparable information. To that end, calcic amphibole from late-stage rocks of the English Peak plutonic complex (EPC; Klamath Mountains, northern California) was analyzed in situ, in textural context. The pluton's late stage consists of three nested intrusive units inwardly zoned from tonalite to granite. Bulk-rock compositions and U-Pb (zircon) ages are consistent either with internal fractional crystallization of a single magma batch or with episodic emplacement of successively evolved magmas, ± magma mixing. Major and trace element abundances and zoning patterns in hornblende (s.l.) are used to test these two interpretations, identify specific magmatic units, determine the temperature range of hornblende stability, and model magma crystallization. In each mapped unit, euhedral to subhedral hornblende displays prominent olive-brown core zones that crystallized at 880–775 °C. Cores are embayed and rimmed by green hornblende crystallized from 775–690 °C. These distinctions are preserved even in samples with moderate deuteric alteration. Some trace elements (Zr, Hf, Sr, Ti, V) decrease monotonically from core to rim, suggesting co-precipitation of hornblende with plagioclase, ilmenite, and zircon. Others (Ba, Rb) are approximately constant in highest-T core zones, then decrease, consistent with onset of biotite crystallization. In contrast, initial rim-ward decreases in Sc, Y, and REE change to near-constant values within olive-brown cores, a change modeled by a decrease in bulk partition coefficients (D) due to onset of biotite crystallization. These elements then increase in abundance in green rims, with as much as a fourfold enrichment. Such enrichments can result from resorption/re-precipitation attending changing P and T during final emplacement, whereby trace elements in core zones were redistributed to the rims. Although hornblende compositions from the three zones are similar, outer-zone hornblende has higher Ti, Ba, Sc, and REE, whereas interior-zone hornblende has higher Mn. These differences are consistent with episodic ascent of compositionally similar but not identical magmas from a mid-crustal reservoir. Evidence for in situ magma mixing is lacking in hornblende. Core-to-rim decrease in Zr indicates hornblende and zircon crystallized together, at T as high as 880 °C. Because zircon saturation thermometry yields T estimates <720 °C for all EPC samples, many of the analyzed rocks are inferred to be cumulates. This study illustrates the utility of detailed major and trace element analysis of hornblende as a means to identify magmatic units and model petrogenetic processes in calc-alkaline granitic rocks.

Keywords: Hornblende, trace element zoning, granite petrogenesis, calc-alkaline