Barometric constraints based on apatite inclusions in garnet

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ABSTRACT

Compiled volumetric data for fluor-, chlor-, and hydroxyl-apatite has been fitted to a pressure-volume-temperature ($P-V-T$) equation of state for volume calculation at elevated $P$ and $T$. The regressions were used to assess the potential of apatite inclusions in garnet for thermobarometric applications, according to the pressurization of inclusions resulting from elastic differences between the inclusion and host minerals. Isomeke contours (lines in pressure temperature space, representing permissible entrapment conditions that yield a given inclusion pressure) were calculated and show that apatite inclusions in garnet are a particularly useful barometer, owing to the large differences in the bulk moduli and similar thermal expansivities between apatite and garnet. Heating experiments were conducted on fluorapatite inclusions in andraditic garnets from the Casting Copper skarn, Nevada, to assess the variation in measured inclusion pressure with heating relative to that predicted with isotropic elastic theory. Negligible departures between theoretical and measured pressurization suggests no significant correction is needed for applying room-$T$ inclusion pressure measurements for barometry constraints.

Keywords: Apatite, garnet, pressure, heating, Raman spectroscopy

INTRODUCTION

Apatite is the most abundant phosphate mineral on Earth and commonly occurs as an accessory phase in igneous and metamorphic rocks, and as detritus in sedimentary rocks. The chemistry of Ca-apatite is $\text{Ca}_5(\text{PO}_4)_3X$, where $X$ is occupied by a halogen element or volatile compound, with the major end-members being fluorapatite (FAP), chlorapatite (CAP), and hydroxyapatite (HAP), in which $X = \text{F}, \text{Cl}$, and $\text{OH}$, respectively. Pure FAP and HAP have been experimentally shown to be stable at pressures up to 11–13 GPa at 1300–1800 K before decomposing to a $\text{Ca}_5(\text{PO}_4)_3$ pseudomorph (Murayama et al. 1986), and apatite is stable to at least 7.5 GPa at 950 $^\circ\text{C}$ when a component in mid-ocean ridge basalts (Konzett and Frost 2009). Thus, apatite is stable at conditions from Earth’s surface through the upper mantle. The ubiquitous occurrence of apatite as an accessory phase in a wide variety of rock types and across large ranges of pressure ($P$) and temperature ($T$) makes apatite an attractive mineral for petrologic applications such as interpreting pressure-temperature-time paths. Here, we describe application of apatite in thermobarometry, according to the physical properties of apatite inclusions in garnet.

The growth of minerals in rocks may result in the encapsulation of crystallites (either preexisting mineral grains, or mineral grains produced via metamorphic reactions) within larger mineral grains. At the time of entrapment, the molar volumes of the host and inclusion minerals correspond exactly to the same $P-T$ conditions of encapsulation. However, upon exhumation, any elastic difference between the host and inclusion may lead to the pressurization of the inclusion mineral, such that at Earth’s surface inclusion pressure ($P_{\text{in}}$) differs from the externally applied pressure (1 bar). Garnet commonly occurs as poikiloblasts in metamorphic rocks, in which inclusions of quartz, calcite, micas, feldspars, and accessory phases are commonly reported. Analysis of inclusions in garnet has been used for numerous purposes, including: bracketing the timing of garnet growth (Catlos et al. 2001), correlating garnet growth to deformation and fabric development (e.g., Passchier and Trouw 2005, and references therein), reconstructing conditions of early-prograde deformation (Ashley et al. 2017), constraining fluid flux and composition (e.g., Vry and Brown 1991), and barometry from pressurized quartz inclusions (e.g., Rosenfeld and Chase 1961; Enami et al. 2007; Ashley et al. 2014).

Garnet is a suitable host mineral for thermobarometry of mineral inclusions because it is an isotropic host with a high bulk modulus. The high bulk modulus of garnet allows for stress retention within the inclusions, leading to the development and preservation of inclusion pressure upon exhumation. Previous studies of mineral inclusions have focused mainly on thermobarometry based on inclusions of silica polymorphs within garnet (namely quartz and coesite). However, similar to quartz, apatite is a relatively soft, compressible mineral that would be expected to develop pressurization if entrapped at elevated pressures and exhumed to Earth’s surface. As noted above, apatite is a common accessory phase and is a typical inclusion phase within garnet in some environments. Moreover, apatite is characterized by a sharp, easily resolvable Raman band at ca. 964 cm$^{-1}$, and experimental data for the pressure-dependent shift of this Raman band are available (e.g., Comodi et al. 2001; Schouwink et al. 2010). In this paper, we present new modeling of the physical and spectroscopic characteristics of apatite for...