Multiple-reaction geobarometry for olivine-bearing igneous rocks

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Abstract

Efforts to map the vertical distribution of mafic and ultramafic igneous rocks in the Earth’s crust and uppermost mantle have long been hampered by the lack of precise geobarometers for the appropriate mineral assemblages. The average \( P_{avP} \) method (Powell and Holland 1994) is a multiple-reaction approach that uses a least-squares minimization to average the pressures derived from individual mineral equilibria, taking into account both their uncertainties and correlations. We applied average \( P \) to a carefully selected database of published phase-equilibrium experiments in dry to \( \text{H}_2\text{O} \)-saturated, andesitic to basaltic and peridotitic systems at \( P = 0.6-9.3 \text{ kbar} \), \( T = 940-1240 \text{ °C} \), with log \( f_\text{O}_2 \) from NNO-2.6 to NNO+3.6 log units (where NNO is nickel-nickel oxide buffer). We made minor modifications to the thermodynamic models of clinopyroxene, spinel, and olivine to improve the accuracy and precision of the results given by the \( avP \) method. Tests on the experimental database, using the modified thermodynamic models and spinel + clinopyroxene + olivine + plagioclase equilibria, showed that average \( P \) can reproduce the experimental \( P \), within the calculated 1σ uncertainties (0.9–2.6 kbar; 1.6 kbar on average), for 67% of the database. No systematic deviations of the calculated pressure \( P \) with temperature \( (T) \) or mineral compositions are observed. Given the large compositional range of the experimental database, these results suggest that the method can be applied to any gabbroic, pyroxenitic, or peridotitic rocks that contain the appropriate phase assemblage clinopyroxene + olivine + plagioclase ± spinel. For assemblages equilibrated at \( P < 5 \text{ kbar} \), the calculated \( P \) shows a slight dependence on \( T \), which therefore needs to be well constrained to keep the overall \( P \) uncertainties as low as possible. \( T \) can be estimated using either available independently calibrated geothermometers or a simple calculation routine suggested in this work. Application of average \( P \) to gabbroic xenoliths from Dominica, Lesser Antilles, and to gabbroic and peridotitic xenoliths from Wikieup, Arizona, demonstrates the ability of the method to produce precise \( P \) estimates for natural assemblages equilibrated at both mid- and lower crustal conditions, respectively. Depending on the errors on mineral composition, appropriateness of the \( T \) estimate, and attainment of equilibrium of the assemblage, \( P \) uncertainty for natural rocks is \( \pm 1.0 \text{ kbar} \). Such a level of precision can help to discriminate between rival petrogenetic processes in subduction zone, intra-plate, and mid-oceanic ridge settings.

Keywords: Geobarometry, phase equilibria, mafic crust, gabbros, peridotites; Rates and Depths of Magma Ascent on Earth

Introduction

Estimating the pressure \( (P) \) and temperature \( (T) \) of formation of mafic and ultramafic igneous rocks is a fundamental step in studying the evolution of magmatic systems and the thermal and lithological structure of the crust and crust-mantle transition zone. Developing accurate and precise thermobarometric methods for such rocks is therefore critically important. Conventional methods use phase compositions combined in either empirical or theoretical formulations to derive expressions for \( P \) and \( T \), with the fundamental assumption that the assemblage of interest attained equilibrium. Commonly used geothermometers and geobarometers for gabbroic and peridotitic rocks are based on single reactions between mineral end-members, often derived by simple regressions of experimental data. Examples include two-pyroxene thermometers (e.g., Wells 1977; Putirka 2008) and barometers (Putirka 2008), olivine-pyroxenes-plagioclase barometers (e.g., Fumagalli et al. 2017), hornblende-plagioclase thermobarometers (e.g., Holland and Blundy 1994; Molina et al. 2015), and magnetite-ilmenite thermometers (e.g., Ghiorso and Evans 2008). Empirical methods based on the composition of a single mineral phase, such as clinopyroxene barometers (e.g., Nimis 1995; Putirka 2008) and amphibole thermobarometers (e.g., Ridolfi and Renzulli 2012), are also available for gabbroic as well as basaltic and andesitic rocks. Mineral-melt thermobarometers potentially produce precise pressure and temperature estimates (Falloon et al. 2007; Putirka 2008, 2016a; Neave and Putirka 2017), but their application to gabbroic or peridotitic rocks is limited to assemblages containing melt in equilibrium with the solid phases (interstitial melt or trapped melt inclusions).

For any given plutonic suite, a barometer or thermometer should meet the following conditions: (1) sufficient precision to discriminate between rival petrogenetic processes;