Experimental calibration of aluminum partitioning between olivine and spinel as a geothermometer

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ABSTRACT

The temperature dependence of the partitioning of Al₂O₃ between forsterite-rich olivine and Cr-rich spinel has been experimentally calibrated at 100 kPa between 1250 and 1450 °C under reducing conditions. For spinel with values of Y_Cr between 0.07 and 0.69, and containing <0.1 Fe³⁺ atoms and <0.025 Ti atoms per 4 O atoms the experimental data can be fit to an equation:

\[ T (°C) = \frac{10000}{0.512 + 0.873Y_{Cr} - 0.91\ln(K_{sp})} - 273 \]

where \( Y_{Cr} = \frac{Cr}{(Cr + Al)} \) in spinel in atomic proportions and \( K_{sp} = \frac{Al_{2}O_{3}/Al_{2}O_{2}}{Al_{2}O_{3}} \) in wt%. This equation reproduces the temperature of the experiment for the calibration data set within ±22 °C. Empirical tests suggest that this geothermometer has little pressure dependence within the range of pressures encountered in the crust and upper mantle.

Keywords: Olivine, spinel, aluminum, thermometer, experiment

INTRODUCTION

Olivine and spinel coexist in selected types of igneous and metamorphic rocks such as peridotites, primitive basalts, and some type of meteorites. If we could readily determine the equilibrium temperatures of these rocks, it would provide insight into important geodynamic questions (e.g., how does the mantle geotherm vary?). The only existing geothermometer applicable to olivine-spinel assemblages is the Mg-Fe exchange geothermometer (Fabries 1979; Roeder et al. 1979; O’Neill and Wall 1987; Ballhaus et al. 1991; Sack and Ghiorso 1991). However, all existing calibrations of this geothermometer appear to be subject to large uncertainties as has been recently demonstrated by Kessel et al. (2007). Additionally this geothermometer is readily reset by short-lived changes in temperature due to rapid Mg-Fe interdiffusion in both of these phases (Liermann and Ganguly 2002; Dohmen and Chakraborty 2007). This problem motivated us to investigate the potential of using the temperature dependence of Al partitioning between olivine and spinel as a geothermometer. Here we present the results of the experimental calibration of the temperature dependence of the partition coefficient (\( K_{sp} \)) for Al₂O₃ between olivine and spinel at low pressure.

BACKGROUND

The majority of Cr-rich spinels found in the upper mantle and in primitive lavas has low Fe³⁺ and Ti⁴⁺ contents and are largely solid solutions within the system spinel-hercynite-chromite-magnesiochromite (e.g., Barnes and Roeder 2001). In this study, we focus on spinel with low Fe³⁺ and Ti⁴⁺, and in equilibrium with ~Fo₉₀ olivine. For spinel with low Fe³⁺ and Ti⁴⁺, and in equilibrium with olivine of fixed composition, the Mg/Fe²⁺ ratio in the spinel is a function only of temperature, pressure, and spinel Y_Cr_2 (Cr(Cr + Al) in atomic proportions; e.g., O’Neill and Wall 1987). Under these conditions, the activity coefficient for Al₂O₃ in spinel will be a function of temperature, pressure, and spinel Y_Cr_2.

Aluminum occurs in olivine at minor to trace levels (tens to hundreds of parts per million). The mechanism by which Al substitutes into olivine is unclear. Several charge-balancing mechanisms for this heterovalent substitution have been suggested, including:

\[
\begin{align*}
(MgFe)Si & \leftrightarrow viAlviAl \quad (A) \\
3(MgFe) & \leftrightarrow 2Al + 1(MgFe) \quad \text{vacancy} \quad (B) \\
(MgFe)Si & \leftrightarrow viCrviAl \quad (C) \\
2(MgFe) & \leftrightarrow viNaviAl \quad (D) \\
(MgFe)Si & \leftrightarrow viAlviFe²⁺ \quad (E)
\end{align*}
\]

(Colson et al. 1989; Agee and Walker 1990; Nielsen et al. 1992; Beattie 1994; Taura et al. 1998). Mechanisms A and B are difficult to evaluate with published data because the precision of Al and Si analyses of olivine are inadequate to resolve Si and Mg + Fe deficits relative to a perfect olivine stoichiometry. Mechanism C has been suggested for Sc³⁺ substitution into olivine based on the growth of olivine with Sc concentrations too high to be charge balanced by tetrahedral Al (Colson et al. 1989; Nielsen et al. 1992). The occurrence of significant amounts of Al in olivine grown in the CaO-MgO-Al₂O₃-SiO₂ system (e.g., Soulard et al. 1994) suggests that at least one of mechanisms A and B must be important. Mechanism C is difficult to evaluate because Cr