Amphibole equilibria in mantle rocks: Determining values of mantle $a_{H_2O}$ and implications for mantle $H_2O$ contents

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ABSTRACT

$H_2O$ can affect the thermophysical properties of the mantle, and nominally anhydrous mantle minerals, such as olivine, pyroxenes, and garnet, may be an important reservoir of mantle $H_2O$. However, the $H_2O$ content of nominally anhydrous mantle minerals now at the Earth’s surface may not always reflect mantle values. It is, therefore, desirable to develop different techniques to estimate mantle $H_2O$ contents, or values of the activity of $H_2O$ ($a_{H_2O}$) at the conditions of equilibration in the mantle. To examine the potential of amphibole equilibria to determine values of mantle $a_{H_2O}$, the chemical compositions of co-existing amphibole, olivine, two-pyroxenes, and spinel from a mantle xenolith, sample DH101E of McGuire et al. (1991), were used to estimate values of pressure ($P$), temperature ($T$), and $a_{H_2O}$.

A value of $a_{H_2O}$ was estimated from pargasite dehydration equilibria using chemical compositions of minerals as the basis for estimating activities of end-members in the natural phases (e.g., the activity of forsterite in olivine). These calculations were performed with the THERMOCALC software package and, at an estimated maximum $T$ and $P$ of 900 °C and 20 kbar, they yield an estimated value of $a_{H_2O} \approx 0.02$ for sample DH101E. The application of oxy-amphibole equilibrium, as described by Popp et al. (2006a, 2006b), using the composition of the amphibole in DH101E yields a value of the log of the hydrogen fugacity ($f_{H_2O}$) of –1.37. This value of $f_{H_2O}$ together with the estimated log $f_{O_2}$ of –9.9 yields a value of $a_{H_2O} \approx 0.0005$ for sample DH101E. The lower estimated $a_{H_2O}$ compared to that estimated from dehydration equilibria may reflect a slight loss of H from amphibole in the post-formation environment, but both types of amphibole equilibria are consistent with a low value of $a_{H_2O}$.

Values of mantle $a_{H_2O}$ can be used to predict the $H_2O$ content of mantle olivines. At 900 °C and 20 kbar, the olivine in a sample that equilibrates at $a_{H_2O} < 0.04$, as estimated for sample DH101E, should contain <10 wt ppm $H_2O$. This value is consistent with the lower end of the range of measured $H_2O$ contents of mantle olivines (~4-400 wt ppm). Thus, estimates of values of $a_{H_2O}$ from amphibole equilibria can produce useful predictions of both the activity of $H_2O$ as well as the $H_2O$ content of nominally anhydrous mantle minerals.

Keywords: Amphibole, mantle $H_2O$ activity, $H_2O$ in mantle, amphibole equilibria, phase equilibria, mantle $a_{H_2O}$, thermobarometry, thermodynamics

INTRODUCTION

Trace amounts of $H_2O$ have a large effect on the physical properties of upper mantle rocks, including viscosity, conductivity, and possibly seismic properties (Karato and Jung 1998; Karato 1987; Ranalli 1995). Deformation experiments on olivine, for example, have shown that the creep rate is proportional to the fugacity of $H_2O$ ($f_{H_2O}$) in both the dislocation creep and diffusion creep regimes (Mei and Kohlstedt 2000a, 2000b). Consequently, a complete understanding of mantle rheology will require accurate estimates of the values of the activity of $H_2O$ ($a_{H_2O}$) for different regions of the mantle ($a_{H_2O} = f_{H_2O}/f_{H_2O}^0$; where $f_{H_2O}^0$ is the fugacity of pure $H_2O$ at the $P$-$T$ conditions of interest).

The availability of $H_2O$ also has a significant effect on the quantity and compositions of liquids derived from anatexis of the mantle (Gaetani and Grove 1998; Green and Falloon 1998). The presence of a melt phase may reduce the viscosity of the mantle. On the other hand, the melting process probably removes $H_2O$ from the solid phases, which would increase the viscosity of the residual mantle if the melt migrated upward (Hirth and Kohlstedt 1996). Thus, according to Hirth and Kohlstedt (1996), melting at mid-ocean ridges is responsible for the rheological difference between the lithospheric mantle and the asthenosphere.

Olivine, clinopyroxene, orthopyroxene, and garnet comprise the bulk of the Earth’s upper mantle. The presence of small amounts of hydrogen in these nominally anhydrous minerals (NAMs) is an important line of evidence indicating that the mantle contains small amounts of “water.” The “water” contained in mantle-derived NAMs is probably present in the form of hydrogen defects and may not be molecular $H_2O$ (e.g., Wright 2006). However, in the literature, the H content of NAMS has also been expressed in terms of the weight or mole equivalent of $H_2O$; both designations will be used in the discussion below.

The $H_2O$ content of mantle pyroxenes ranges from ~30 to 1100 wt ppm $H_2O$ (Skogby 2006). Olivines and garnets from the mantle typically contain less H than mantle pyroxenes; the