A comparison of olivine-melt thermometers based on $D_{\text{Mg}}$ and $D_{\text{Ni}}$: The effects of melt composition, temperature, and pressure with applications to MORBs and hydrous arc basalts

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ABSTRACT

A new olivine-melt thermometer based on the partitioning of Ni ($D_{\text{Ni}}^{\text{Oli/lq}}$), with a form similar to the Beattie (1993) $D_{\text{Ni}}^{\text{Oli/lq}}$ thermometer, is presented in this study. It is calibrated on a data set of 123 olivine-melt equilibrium experiments from 16 studies in the literature that pass the following five filters: (1) 1 bar only, (2) analyzed totals between 99.0–101.0 wt% for olivine and 98.5–101.0 wt% for quenched glasses, (3) olivine is the only silicate phase in equilibrium with the melt, (4) the NiO concentration is ≥0.1 wt% in olivine and ≥0.01 wt% in quenched glass, and (5) no metallic phase is present other than the capsule. The final data set spans a wide range of temperatures (1170–1650 °C), liquid compositions (37–66 wt% SiO$_2$; 4–40 wt% MgO; 107–11087 ppm Ni), and olivine compositions (Fo$_{99}$–Fo$_{10}$; 0.10–15.7 wt% NiO). The Ni-thermometer recovers the 123 experimental temperatures within ±29 °C (1σ), with an average residual of 0 °C. A re-fitted version of the Mg-thermometer of Beattie (1993), calibrated on the same 123 experiments as for the Ni-thermometer, results in an average residual of ±26 °C (1σ). When both thermometers are applied to the same 123 experiments, the average $\Delta T$ ($T_{\text{Mg}} – T_{\text{Ni}}$) is 1 ± 29 °C (1σ), which confirms that the Mg- and Ni-thermometers perform equally well over a wide range of anhydrous melt composition and temperature at 1 bar. The pressure dependence of the Ni-thermometer under crustal conditions (≤1 GPa) is expected to lead to negative $\Delta T$ ($T_{\text{Mg}} – T_{\text{Ni}}$) values (≤–52 °C). Application of the two thermometers to nine mid-ocean ridge basalts results in an average $\Delta T$ of −3°, consistent with shallow crystallization of olivine under nearly anhydrous conditions. In contrast, application of the two thermometers to 18 subduction-zone basalts leads to an average $\Delta T$ of +112°; this large positive $\Delta T$ value cannot be explained by the effect of pressure, temperature or anhydrous melt composition. It is well documented in the literature that $D_{\text{Ni}}^{\text{Oli/lq}}$ is affected by dissolved water in the melt and that Mg-thermometers overestimate the temperature of hydrous basalts if an H$_2$O correction is not applied (e.g., Putirka et al. 2007). Therefore, the reason why hydrous arc basalts have higher $\Delta T$ ($T_{\text{Mg}} – T_{\text{Ni}}$) values than MORBs may be because $D_{\text{Ni}}^{\text{Oli/lq}}$ is less sensitive to water in the melt, which is supported by new Ni-partitioning results on three olivine-melt equilibrium experiments on a basaltic andesite with up to 5 wt% H$_2$O. More hydrous experiments are needed to confirm that the Ni-thermometer can be applied to hydrous melts without a correction for H$_2$O in the melt.

Keywords: Ni partitioning, thermometry, olivine, subduction zone magma, H$_2$O

INTRODUCTION

The importance of obtaining the magmatic temperatures of basalts has long been recognized and pursued by Earth scientists. Numerous researchers have mapped global variations in mantle temperature by applying olivine-melt thermometers based on Mg-partitioning ($D_{\text{Mg}}^{\text{Oli/lq}}$) to basalts from mid-ocean spreading ridges (e.g., Falloon et al. 2007; Genske et al. 2012) and the Iceland and Hawaiian plumes (e.g., Neave et al. 2015; Xu et al. 2014). These efforts not only constrain conditions for mantle melting at different tectonic settings, including depth of melting (e.g., Lee et al. 2009) and thermal anomalies associated with mantle plumes (e.g., Herzberg et al. 2007; Falloon et al. 2007; Putirka et al. 2007), but also have contributed substantively to our understanding of how the Earth’s mantle has cooled through time (e.g., Herzberg and Gazel 2009).

The reliability of these results largely depends on the accuracy of applied olivine-melt thermometers. There is general agreement (e.g., Herzberg et al. 2007; Falloon et al. 2007; Putirka et al. 2008; Herzberg and Asimow 2015) that the Beattie (1993) form of the thermometer recovers experimental temperatures the best under anhydrous conditions (e.g., standard error estimate of ±44 °C; Putirka 2008) and produces temperatures similar to the model of Ford et al. (1983) and those obtained by the MELTS program (Ghiorso and Sack 1995; Asimow...