The effect of elemental diffusion on the application of olivine-composition-based magmatic thermometry, oxybarometry, and hygrometry: A case study of olivine phenocrysts from the Jiagedaqi basalts, northeast China

Le Zhang1,*, Lu-Bing Hong2, Sheng-Ping Qian3, Peng-Li He1, Miao-Hong He1,†, Ya-Nan Yang4, Jin-Tuan Wang1,‡, Yan-Qiang Zhang4, and Zhong-Yuan Ren1,*,†

1State Key Laboratory of Isotope Geochemistry and CAS Center for Excellence in Deep Earth Science, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
2College of Earth Science, Guilin University of Technology, Guilin 541004, China
3State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China
4College of Earth Science, Guilin University of Technology, Guilin 541004, China
5Chinese Academy of Sciences, Guangzhou 510640, China

ABSTRACT

Olivine compositions are widely used to constrain magmatic thermodynamic conditions such as magmatic temperature, oxygen fugacity, and H2O content. However, elemental diffusion may change the initial compositions and lead to large uncertainty on the estimation of these thermodynamic conditions. In this study, we conducted LA-ICP-MS elemental mapping and EPMA analysis of olivine phenocrysts and olivine-hosted spinel from the Jiagedaqi (JGD) alkaline basalts in northeast China to evaluate the influence of elemental diffusion on olivine-composition-based geothermometry, oxybarometry, and hygrometry. The JGD olivines show normal Fo [Mg/(Mg + Fe) × 100 in moles] zoning, with cores having Fo of 77–87 and rims having Fo of 67–73. The constant P contents from core to rim indicate that these compositional zonings were caused mainly by diffusion. Because Al is a slow-diffusing element and its content is relatively constant from core to rim, the temperature calculated by the Al-in-olivine thermometer is not influenced by elemental diffusion and preserves the JGD olivine crystallization temperature up to 1150 °C. The temperatures calculated using the Sc/Y-in-olivine thermometer, the oxygen fugacity calculated using the olivine–spinel oxybarometer, and the H2O content calculated on the basis of Ca partitioning between olivine and melt are strongly influenced by the diffusion of Fo, Sc/Y, and Ca. However, the compositional plateaus in olivine cores, which were not influenced by elemental diffusion, preserve the magmatic temperature (1150 °C), oxygen fugacity (QFM+1.4), and H2O content (4 wt%) that applied during the formation of the JGD olivines. Together, these findings suggest that the mantle source of the JGD basalts was metasomatized by fluids released from the subducted slab. This study highlights that elemental diffusion in olivine phenocrysts can strongly affect the application of olivine-composition-based geothermometers, oxybarometers, and hygrometers. However, primitive olivine cores that have not been influenced by diffusion preserve the initial magmatic thermodynamic conditions.

Keywords: Olivine, diffusion, magma storage, compositional zoning, NE China, Jiagedaqi basalts

INTRODUCTION

Basalt, originating from the Earth mantle, is considered as a probe to detect the composition of the deep Earth and the material recycling between Earth surface and deep spheres (Abraham et al. 2001; Fisk and Kelley 2002; Herd 2008; Herzberg 2011a; Hofmann 2003). The formation and evolution of basaltic magmas depends on various factors, such as source lithology, water content, temperature, and redox state. As olivine is an early crystallized silicate mineral from primitive basaltic magma, several recent studies have suggested that olivine chemistry may be used to evaluate these factors. For example, Ni and Mn contents and Mn/Zn ratios of primitive olivine are suggested to be controlled by source lithology and can thus be used as discriminators between pyroxenite and peridotite sources (Hersberg 2011b; Howarth and Harris 2017; Liu et al. 2021; Sobolev et al. 2005).

The partitioning of Ca between olivines and their host magmas is affected by magmatic H2O and can thus act as a proxy for magma H2O content (Gavrilenko et al. 2016; Hong et al. 2017). As the partitioning of V, a multivalent element, is sensitive to oxygen fugacity (Canil 1997; Mallmann and O’Neill 2009; Shearer et al. 2006; Shishkina et al. 2018; Wang et al. 2019), it has been suggested that the partitioning of a ratio of V to a homovalent element (e.g., V/Sc) between olivine and silicate melt is a proxy for oxygen fugacity (Mallmann and O’Neill 2013; Wang et al. 2019). Mallmann and O’Neill (2013) proposed an empirical thermometer based on the partitioning of Sc/Y between olivine and silicate melt. The partitioning behavior of Al between coexisting olivine and spinel can be used to reconstruct magmatic temperature (Coogan et al. 2014; Wan et al. 2008).

To use olivine compositions as thermodynamic proxies, an assumption is that these element contents or ratios remain unchanged after the formation of olivine. However, chemical zoning in olivine is a common phenomenon, and the presence of this chemical zoning means that elemental diffusion is certain to