Accuracy of timescales retrieved from diffusion modeling in olivine: A 3D perspective†

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ABSTRACT

Diffusion modeling in olivine is a useful tool to resolve the timescales of various magmatic processes. Practical olivine geospeedometry applications employ 1D chemical transects across sections that are randomly sampled from a given 3D crystal population, but the accuracy and precision with which timescales can be retrieved from this procedure are not well constrained. Here, we use numerical 3D diffusion models of Fe-Mg to evaluate and quantify the uncertainties associated with their 1D counterparts. The 3D diffusion models were built using both simple and realistic olivine morphologies, and incorporate diffusion anisotropy as well as different zoning styles. The 3D model crystals were sectioned along ideal or random planes, which were used to perform 1D models and timescale comparisons. Results show that the timescales retrieved from 1D profiles are highly inaccurate and can vary by factors of 0.1–25 if diffusion anisotropy is not taken into account. Even when anisotropy is corrected for, timescales can still vary between 0.2–10 times the true 3D diffusion time due to crystal shape and sectioning effects. Simple grain selection procedures are described to reduce the misfit between calculated and actual diffusion times, and achieve an accuracy and precision of ~5% and ~15–25% relative, respectively. Provided that the grains are carefully selected, about 20 concentration profiles and associated 1D models suffice to achieve this accuracy.

Keywords: Olivine, geospeedometry, diffusion modeling, numerical modeling, crystal morphology, random sectioning

INTRODUCTION

The diffusion of atoms during magmatic reactions (e.g., melting, crystallization, solid-state re-equilibration) can be broadly described as the random jumps or movements of particles relative to other particles in a region of many particles (Onsager 1945; Chakraborty 2008). Because these movements occur at different rates for different chemical components and thermodynamic conditions, modeling of element diffusion can be used for geospeedometry, i.e., to backtrack the durations of geological processes (cf. Watson 1994; Chakraborty 1995, 2008; Ganguly 2002; Watson and Baxter 2007; Costa et al. 2008; Zhang 2010 for reviews). Diffusion modeling is thus becoming an essential utensil of the Earth scientist’s toolbox.

This investigation focuses on modeling chemical diffusion in minerals, a technique now regularly used to decipher magma residence times beneath volcanoes (e.g., Zellmer et al. 1999; Costa et al. 2003, 2008; Kahl et al. 2011; Cooper and Kent 2014), magma mixing/recharge events (Morgan et al. 2006; Druitt et al. 2012; Ruprecht and Cooper 2012), ascent times from the mantle (Demouchy et al. 2006; Ruprecht and Plank 2013), and assimilation of crustal material (Bindeman et al. 2006). In particular, olivine is well suited for diffusion studies involving mafic to intermediate magmas, because the diffusion coefficients (D) for major (Mg, Fe) and minor/trace (Ca, Mn, Cr, Co, Ni) elements are well constrained with respect to temperature (T), forsterite component (X\textsubscript{Fo}), crystallographic orientation, and oxygen fugacity (f\textsubscript{O2}) (e.g., Chakraborty 1997, 2010; Petry et al. 2004; Coogan et al. 2005; Dohmen and Chakraborty 2007; Spandler and O’Neill 2010). As a result, several studies have used diffusion modeling within olivine to decipher the durations associated with various magmatic processes (Nakamura 1995; Coombs et al. 2000; Pan and Batiza 2002; Costa and Chakraborty 2004; Costa and Dungan 2005; Ito and Ganguly 2006; Kahl et al. 2011, 2013; Martí et al. 2013; Ruprecht and Plank 2013; Longpre et al. 2014), and user-friendly diffusion modeling algorithms are becoming available (e.g., DIPRA, Girona and Costa 2013). To date, however, diffusion modeling has been applied to natural magmatic crystals using almost exclusively one-dimensional chemical profiles. Analyses are typically performed along crystals exposed within two-dimensional thin sections, meaning that there are several potential sources of uncertainty: (1) diffusion occurs along the three spatial dimensions of a complex volume (e.g., Costa et al. 2003, 2008); (2) diffusion may occur anisotropically within the mineral, implying that a 1D profile may sample the crystal along a fast or slow direction, or anywhere in between (e.g., Chakraborty 1997); and (3) thin sections intersect crystals randomly, meaning that concentration gradient geometry may be dependent on section orientation and distance from the crystal core (Pearce 1984; Wallace and Bergantz 2004).

In their investigation of Mg in plagioclase, Costa et al. (2003) found that adding a second dimension resulted in shorter calculated