Zircon saturation and Zr diffusion in rhyolitic melts, and zircon growth geospeedometer

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ABSTRACT

Zircon is a ubiquitous accessory mineral in silicic igneous rocks. We have carried out new zircon dissolution experiments to refine our understanding of Zr diffusion and zircon solubility in several rhyolitic melts. Zr diffusivity depends strongly on temperature and H2O content, and weakly on pressure and anhydrous melt composition. The diffusion data for each individual melt follows the Arrhenius relation. The dependence of Zr diffusivity on temperature, pressure, and melt composition (including H2O content) is modeled for different rhyolitic melts in this study and for the combined literature and our data. Our data on Zr concentration at zircon saturation in silicic melts show strong dependence on temperature and weak dependence on pressure and melt composition, and are somewhat off the trend based on existing zircon solubility models. The dissolution or growth rate of a freely falling zircon crystal in a specific hydrous rhyolitic melt is modeled. The controlling factors are mostly the temperature and Zr concentration in the melt. Typical zircon growth rate in wet rhyolitic melt is 0.01 to 1.0 µm/yr. The size of zircon crystals can be used to place limit on the cooling rate of its hosting magma. The presence of large indigenous zircon crystals in Bishop Tuff requires slow cooling of the Bishop Tuff magma chamber.

Keywords: Zirconium diffusion, Zr diffusivity, zircon solubility, zircon growth, zircon geospeedometer, cooling rate, Bishop Tuff, Invited Centennial article

INTRODUCTION

Zircon is a ubiquitous accessory mineral in silicic igneous rocks. Even though its abundance is low, it is one of the most often used minerals (e.g., Hanchar and Hoskin 2003) in dating and in inferring paleo-formation conditions (Valley et al. 2005). Survival of pre-eruptive zircon crystals has often been reported, and these crystals can be used to obtain eruption history and magma chamber residence time (Simon et al. 2008). The formation and survival of zircon depends on the saturation condition (or solubility) of zircon and diffusivity of Zr in silicate melts, which have been investigated extensively (e.g., Watson 1979; Watson and Harrison 1983; Harrison and Watson 1983; Ellison and Hess 1986; Baker and Watson 1988; Keppler 1993; LaTourrette et al. 1996; Mungall et al. 1999; Koepke and Behrens 2001; Baker et al. 2002; Hanchar and Watson 2003; Rubatto and Hermann 2007; Behrens and Hahn 2009; Bohneke et al. 2013).

Still there are unresolved issues. One is the dependence of Zr diffusivity on melt composition, especially the H2O content. In the earlier years, it was not easy to directly measure H2O concentrations in experiments, but now with FTIR it is straightforward to determine H2O concentrations in experimental charges. Natural silicate melts span a large compositional range. We limit our experimental study to different rhyolitic melts because zircon forms and survives more easily in rhyolitic melts (Boehnke et al. 2013). However, in modeling, we try to combine with previous data so as to cover a large range of melts from basalts to rhyolites. The second is the dependence of Zr diffusion and zircon solubility on pressure. Although crustal pressure variation is not large, nonetheless it is of interest to understand the pressure effect for accurate prediction of these properties. We aim at obtaining the dependence of Zr diffusivity as a function of temperature, pressure, melt composition and water content. We also compare our zircon solubility data with the recent model by Boehnke et al. (2013). Furthermore, we will use the data to evaluate zircon dissolution kinetics as part of our systematic studies of mineral dissolution kinetics in silicate melts (Zhang and Xu 2003; Chen and Zhang 2008, 2009). Finally, we explore the use of newly grown zircon crystal size to constrain host magma cooling rates.

EXPERIMENTAL AND ANALYTICAL METHODS

Zircon dissolution experiments are conducted in piston-cylinder apparatus to investigate Zr diffusion and zircon solubility in dry and hydrous rhyolitic melts at 0.5 to 1.5 GPa and 1270–1890 K. ZrO2 concentration profiles are measured by electron microprobe. Experimental and analytical methods mostly follow those of Harrison and Watson (1983) and Zhang et al. (1989), and details can be found below.

Starting materials

The starting materials include a large zircon crystal and five rhyolitic glasses. The large transparent gem-quality zircon crystal was purchased online and measures 13 × 8 × 7 mm. The composition of this zircon crystal is roughly Hf0.01Zr0.984Si0.02 (Table 1). After cutting, the best zircon wafers without visible cracks and inclusions under microscope are chosen for experiments. Starting rhyolitic glasses include three natural glasses in our collection: Newberry Crater obsidian with about 0.1 wt% total H2O (Newman et al. 1986), CIT-1 with 0.2 wt% total H2O (Newman et al. 2002; Hanchar and Hess 1983; Harrison and Watson 1983; Ellison and Hess 1986; Baker and Watson 1988; Keppler 1993; LaTourrette et al. 1996; Mungall et al. 1999; Koepke and Behrens 2001; Baker et al. 2002; Hanchar and Watson 2003; Rubatto and Hermann 2007; Behrens and Hahn 2009; Bohneke et al. 2013).

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