Al diffusion in quartz

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ABSTRACT

Aluminum diffusion in synthetic and natural quartz was characterized under anhydrous conditions at 1 atm and temperatures from 700 to 950 °C. Experiments were carried out on polished quartz slabs immersed in fine-grained powder of spodumene or K-feldspar. Diffusion profiles were measured using Nuclear Reaction Analysis (NRA) and yield the following Arrhenius parameters: \( D_{\text{Al}} = 2.48 \times 10^{-11} \exp(-199 \pm 10 \text{ kJ/mol}/R\theta) \text{m}^2\text{s}^{-1} \), where \( \log D_{\text{Al}} = -10.6 \pm 0.55 \).

The diffusivity of Al through the quartz lattice is sufficiently slow (e.g., akin to Ti) that diffusive modification or loss of Al in magmatic or metamorphic quartz is unlikely in all but the most extreme temperature-time conditions seen in natural systems. In other words, core to rim Al zonation produced during crystal fractionation from a granitoid, or metamorphic overgrowths on quartz during metamorphism, are likely to be preserved at the crystal scale but may show some diffusive relaxation at sub-micrometers to tens of micrometers in scale. The similar diffusivities of Al and Ti also suggest that diffusive modification of Al/Ti is highly unlikely to occur at all but the smallest length scales (e.g., sub-micrometers to tens of micrometers). These observations indicate that the two most abundant impurities in quartz (Al and Ti) are likely to record primary information regarding the crystallization conditions in most geological environments.

Keywords: Quartz, diffusion, Al, Ti, trace element, granite, nuclear reaction analysis, Arrhenius parameters; Mechanisms, Rates, and Timescales of Geochemical Transport Processes in the Crust and Mantle

INTRODUCTION

Quartz is arguably the defining mineral of the continental crust and is found in a wide range of rock types, including the host metasediment of our planet’s oldest materials (e.g., Jack Hills; Compston and Pidgeon 1986). Recent studies have indicated that the concentration of some trace elements in quartz may be used as geochemical indicators (Ackerson et al. 2015). The Ti content of quartz, for example, has been linked to crystallization temperature and pressure (Wark and Watson 2006; Thomas et al. 2010), and analyses reported from natural quartz have also been used to suggest that Al/Ti is a measure of melt fractionation (Müller et al. 2002; Jacamon and Larsen 2009; Breiter et al. 2012, 2013). Trace element studies from several granitic bodies have also indicated that quartz Al content may be elevated in highly peraluminous melts (Jacamón and Larsen 2009). These observations and hypotheses, combined with the fact that Al is often reported as the most abundant trace element to substitute within the quartz lattice [generally ranging from tens to thousands of parts per million by weight (ppmw); Götzte 2009], make constraining Al diffusion in quartz particularly pertinent.

The only study of Al diffusion to date is that of Pankrath and Flörke (1994), who used electron paramagnetic resonance (EPR) to determine kinetics and diffusivity within heat-treated natural grains (displaying notable Al zonation). This study, by contrast, reports measurement of Al diffusion through direct profiling methods, and results from experiments carried out on synthetic, initially Al-free quartz. Additional experiments were carried out on polished natural quartz grains from Arkansas and Herkimer (New York) to ensure natural grains display similar Arrhenius parameters.

In this study we report results from Al diffusion experiments carried out at 700–950 °C to define the Arrhenius parameters in quartz. Li profiling on selected samples is also employed to explore the possibility of coupling of Al and Li diffusion and the potential role of other coupled substitution mechanisms is considered as well. We also investigate the effects of crystallographic orientation on Al diffusion. The Al diffusion parameters obtained in this study are subsequently used to model Al diffusion within systems of comparable composition to those seen in granitic systems, both with and without Ti, and determine how diffusive processes may redistribute trace elements during cooling or thermal perturbations.

METHODS

The majority of experiments were carried out on Al-free synthetic quartz (Westinghouse), though several experiments were also carried out on natural, gem-quality quartz from Herkimer (New York) and Arkansas. The quartz crystals were cut into \( \pm 2 \times 2 \text{ mm slabs} \) with a low-speed wafering blade in two orientations—parallel and perpendicular to the c-axis. Crystal orientation was