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Fast diffusion path for water in silica glass

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Abstract

Diffusion experiments of ^2H_2O at 900–750 °C and water vapor pressure of 50 bar found diffusion of water in SiO_2 glass more than one order of magnitude faster than that reported previously. The fast diffusion profile of water was observed as an extended tail of the normal water diffusion profile by a line scan analysis with SIMS, and it can be fitted with a diffusion model with a constant diffusivity. The obtained fast diffusion coefficient suggests that the diffusion species responsible for the fast diffusion is not molecular hydrogen but molecular water. The diffusivity and activation energy for the fast water diffusion can be explained by the correlation between diffusivities of noble gases in silica glass and their sizes. Because noble gases diffuse through free volume in the glass structure, we conclude that molecular water can also diffuse through the free volume. The abundance of free volume in the silica glass structure estimated previously is higher than that of ^2H observed in the fast diffusion in this study, suggesting that the free volume was not fully occupied by ^2H_2O under the present experimental condition. This implies that the contribution of the fast water diffusion to the total water transport in volcanic glass becomes larger under higher water vapor pressure conditions.

Keywords: Water, silica glass, SIMS, diffusion pathway, free volume

Introduction

Water inside the Earth changes physical and chemical properties of rocks, minerals, and magma. Water circulates into the mantle through subduction zones and back to the surface through arc volcanism. The arc volcanism is affected by water in magma because water changes the physical and chemical properties of magma. For instance, water influences eruption styles through changing magma ascent rates via its influence on bubble nucleation, bubble growth, and degassing (e.g., Sparks 1978; Rutherford 2008). Bubble growth in magma is controlled by viscous relaxation and water diffusion, the relative influence of which depends on magma properties such as temperature, pressure, and chemical compositions.

Water diffusion in magma is, therefore, one of the important basic parameters to control water degassing from magmas. Water diffusion in various silicate glasses, as an analog of silicate melts, has been intensively studied (e.g., Zhang et al. 2007 and references therein). Although the dependences of water diffusion on temperature, water concentration, and pressure have been obtained and formulated, water diffusion in silicate glasses is not yet fully understood as an atomistic-scale process. Kuroda et al. (2018) performed water diffusion experiments in silica glass and proposed a water diffusion model, where water molecules diffuse through pathways formed by hydroxyls. They also showed that the model is applicable to the water diffusion in various silicate glasses to explain the concentration dependence of water diffusion in rhyolite and basalt glasses.

Here we report a new diffusion pathway of water molecules in silica glass through which water can be transported at a rate of one order of magnitude faster than that previously reported values in similar conditions as Kuroda et al. (2018). We discuss the mechanism of water molecule diffusion through the fast pathway and its potential contribution to the water transport in silicate glasses.

Experimental and analytical methods

Diffusion experiments were performed using the same protocol as in Kuroda et al. (2018). An optical silica glass plate (5 × 3 × 2 mm; Sigma Koki Co.) was flame-sealed in a silica glass tube (3.5 and 4.7 mm in inner and outer diameters, and 80 mm in length) with deuterated water (^2H_2O) (7.10–8.17 μL) under atmospheric pressure. The sealed glass tubes were heated in a box furnace at temperatures of 900, 850, 800, and 750 °C for different durations (Table 1). The ^2H_2O vapor pressure inside the glass tube was controlled to be 50 bar by complete evaporation of deuterated water.

Polished cross sections of the run products were prepared for measurements of concentration profiles of ^1H, ^2H, and ^{30}Si along the diffusion direction from the glass surface with a secondary ion mass spectrometer (SIMS; Cameca ims-6f) at Hokkaido University. A 15–20 nA Cs^+ primary beam was focused to form a 20–25 μm spot on the sample, and negatively charged secondary ions of ^1H, ^2H, and ^{30}Si were counted by an electron multiplier for 2, 10, and 1 s, respectively, with a 5 μm step. A normal electron flood gun was used for charge compensation. A field aperture was used to permit transmission of ions from the central area of 10 μm in diameter of the sputtered region to minimize the hydrogen signals from absorbed water on the sample surface. A few profiles (mostly three) were obtained for each sample to assess the analytical reproducibility. A starting material glass sample was also measured as a reference with the same analytical condition. The position of the glass surface was determined as being the point from which ^{30}Si counts became constant.

Results

Diffusion profiles of ^2H in samples heated at 900 °C for 1, 3, and 20 h are compared in Figure 1. The ^2H intensity decreases rapidly from rim to core of the sample with diffusion distances of about 50, 100, and 250 μm for the samples heated for 1, 3, and

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Table 1. Experimental conditions and diffusion coefficients of fast water diffusion in silica glass

Run no.	T (°C)	t (h)	D (m^2/s)
900-1	900	3	1.61 (±0.42) ×10^{-12}
900-2	900	3	1.87 (±0.60) ×10^{-12}
900-3	900	20	–
900-4	900	1	–
850-1	850	3	0.92 (±0.25) ×10^{-12}
850-2	850	3	1.58 (±0.41) ×10^{-12}
800-1	800	3	0.42 (±0.14) ×10^{-12}
800-2	800	3	0.66 (±0.11) ×10^{-12}
800-3	800	3	0.57 (±0.37) ×10^{-12}
750-1	750	3	0.67 (±0.17) ×10^{-12}
750-2	750	3	0.55 (±0.08) ×10^{-12}
750-3	750	20	–

Notes: Errors are 2σ standard deviations of the diffusion coefficients evaluated from multiple diffusion profiles. The samples heated for 1 and 20 h were not used to determine the diffusion coefficients because of their short diffusion profiles and homogeneous ^{2}H distributions, respectively.

20 h, respectively. This is consistent with the diffusion experiments with ^1H_2O (Kuroda et al. 2018), and the profile shape can be explained by water concentration-dependent diffusion in silica glass (Kuroda et al. 2018) of which detail is discussed below.

It is found that the tail of deuterium profile extends further into the deep region of the sample, where the ^{2}H ion intensity is higher than the original value in the starting material (^{2}H/^{30}Si < 2×10^{-7}) (Fig. 1). Comparison between the concentration profiles heated at 900 °C for 1 and 3 h clearly shows that ^{2}H migrated into the deeper region of the glass with time (Fig. 1). The ^{2}H finally seems to have an almost homogeneous distribution inside the glass after 20 h heating (Fig. 1). This observation clearly shows that a small fraction of deuterium-bearing species migrate at a faster diffusion rate than the dominant fraction that diffuses as the concentration-dependent profile. This newly observed fast diffusion profile was also confirmed in samples heated at 850, 800, and 750 °C (Fig. 2).

Discussion

Profile fitting

The profiles of ^{2}H/^{30}Si in the run products are used to discuss the ^2H_2O diffusion because it has a linear relation to the water concentration (Kuroda et al. 2018). The ^{2}H/^{30}Si profiles, normalized to the ratio at the glass surface, are shown in Figure 2. The concentration-dependent diffusion profiles can be explained by the water diffusion model in silica glass (Kuroda et al. 2018), where molecular water is proposed to diffuse through the pathway formed by hydroxyls (-OH). The model attributes the

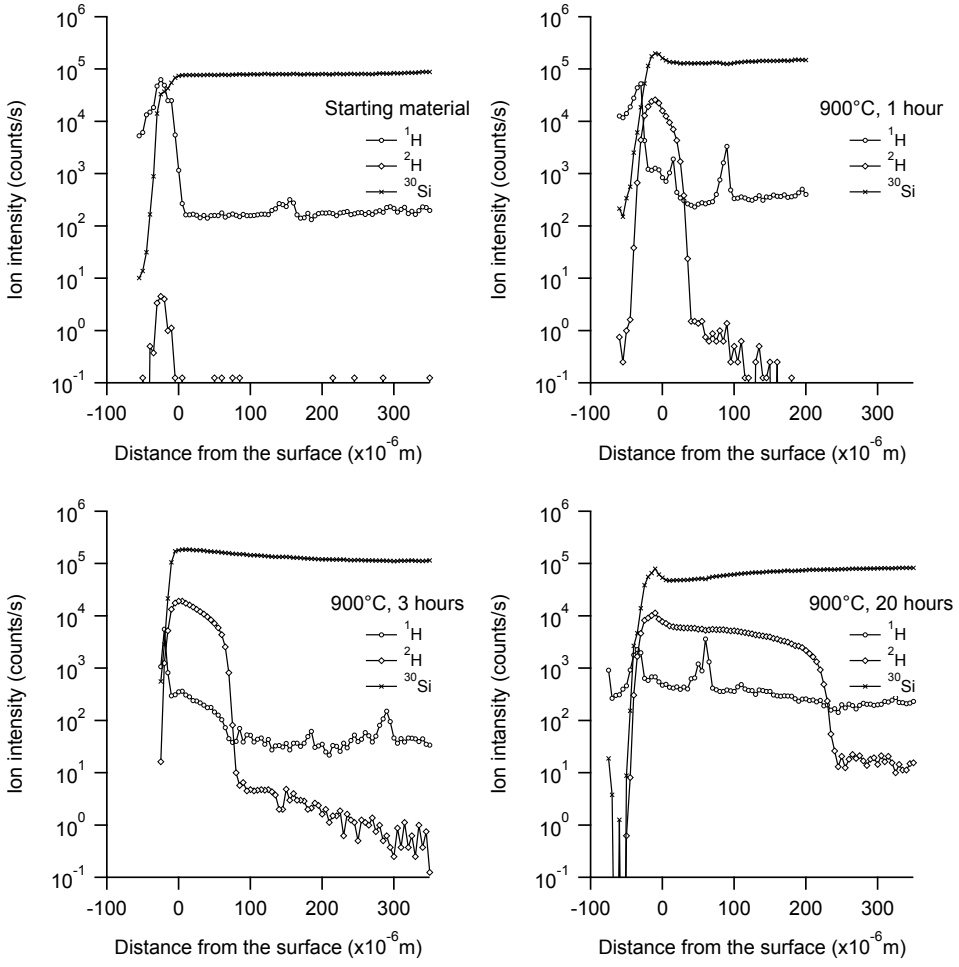


Figure 1. Typical ion intensity profiles of ^{1}H, ^{2}H, and ^{30}Si (900 °C for 1, 3, and 20 h). ^{1}H signals inside the glass are from backgrounds.

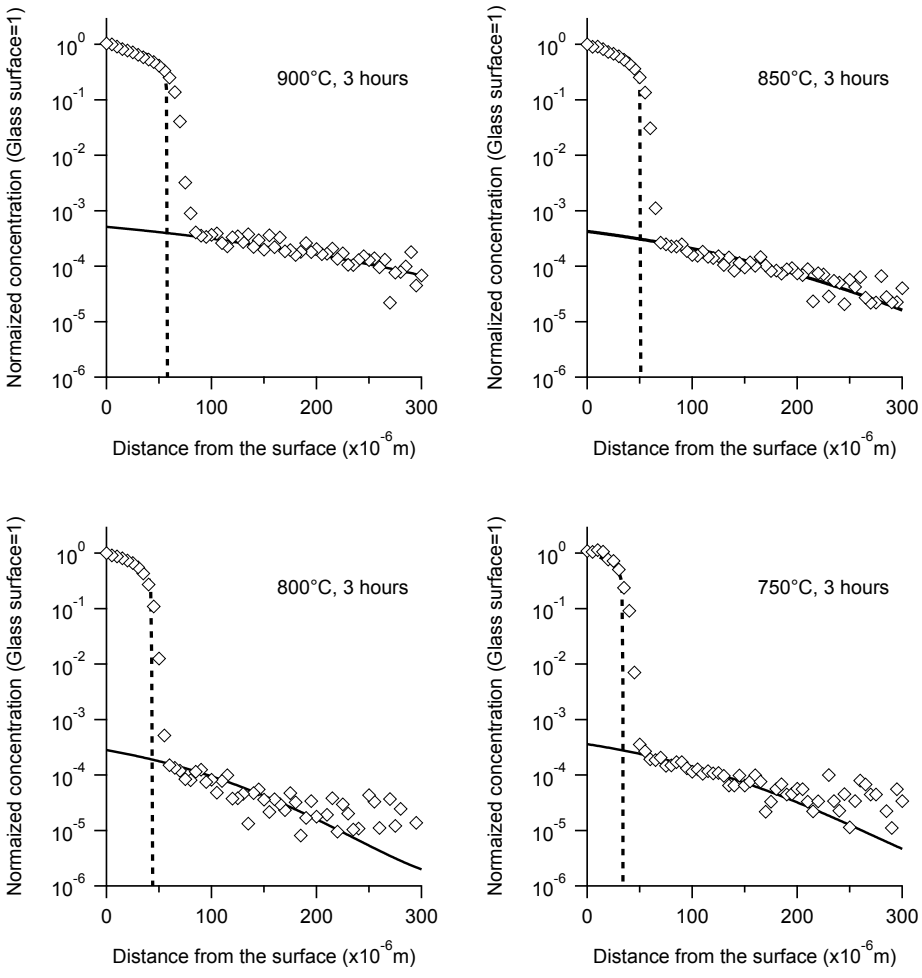


FIGURE 2. Typical diffusion profiles of ^{2}H, shown as $^{2}H/^{30}Si$ normalized to that at the surface, in silica glass at 900, 850, 800, and 750 °C and a water pressure of 50 bar. The "normal water diffusion" profiles are fitted with the concentration-dependent water diffusion model (dashed curves) (Kuroda et al. 2018), and the "fast water diffusion" profiles are fitted with the constant-independent water diffusion model (solid curves). All $^{2}H/^{30}Si$ ratios are normalized to the $^{2}H/^{30}Si$ at the glass surface. For fitting of the "normal water diffusion" profiles, D^*, K, and the surface water concentration were taken from Kuroda et al. (2018), where diffusion experiments were performed under the same condition as in the present study (850–650 °C). K and D^* for 900 °C were obtained by the extrapolation of those in Kuroda et al. (2018), and the surface concentration was assumed to be the same as at 850 °C. The surface water concentration of all run products in this study is estimated to be about ~0.3 mol% based on the experiments by Kuroda et al. (2018).

strong water concentration dependence for water diffusion in silica glass to the limited number of diffusion pathways. If water molecules (H_2O_m) favor a pathway formed by cutting Si-O-Si bonds to diffuse in the polymerized silica glass network, water molecules themselves should form the pathways through the hydroxyl formation reaction ($H_2O_m + O \leftrightarrow 2OH$). On the other hand, such pathways preexist in silicate glasses due to the presence of network modifier cations such as Na^+ and K^+ that cut the glass network. This difference results in the stronger water concentration dependence for water diffusion in silica glass than in silicate glasses because the number of diffusion pathways in silica glass depends on water concentration (Kuroda et al. 2018).

The total water diffusivity ($D_{H_2O_t}$) in silica glass through the pathways formed by hydroxyls ("normal diffusion" hereafter) is given by

$$D_{H_2O} = \frac{D^*K}{8}\left[\left(1+\frac{16X_{H_2O_t}}{K}\right)^{\frac{1}{2}}-1\right]\left[1-\left(1+\frac{16X_{H_2O_t}}{K}\right)^{-\frac{1}{2}}\right] \quad (1)$$

where X_i is the molar fraction of species i, D^* is a concentration independent term, and K is an equilibrium constant of the hydroxyl formation reaction (Kuroda et al. 2018). The water diffusion profiles fitted with the diffusion coefficient of Equation 1 are shown as dotted curved in Figure 2. The diffusivities for normal diffusion at the glass surface are about (5–0.8) $\times 10^{-13}$ m^2/s in the present experimental conditions, and decreases with decreasing $X_{H_2O_t}$ in rough proportion to $X^2_{H_2O_t}$ (Kuroda et al. 2018).

The extended tails of the diffusion profiles ("fast diffusion" hereafter) cannot be explained by the normal diffusion, while

they can be fitted by a one-dimensional, semi-infinite diffusion model with a fixed surface concentration and a constant diffusion coefficient (Crank 1975) assuming that the fast diffusion is independent of the normal diffusion (Fig. 2):

$$R(x) = (R_s - R_0)\left[1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right] + R_0 \quad (2)$$

where x is the distance from the glass surface, R is the $^2H/^{30}Si$ at a distance normalized to the total $^2H/^{30}Si$ at the glass surface ($x = 0$), R_s is the normalized $^2H/^{30}Si$ at the glass surface for fast diffusion, R_0 is the normalized background of $^2H/^{30}Si$, respectively. The fitting curves were obtained for the first ~100 μm of the tails (Fig. 2) because the ^2H intensities in the deeper region became comparable to the detection limit. The obtained diffusion coefficients of fast diffusion (Table 1) are about one order of magnitude larger than those of normal water diffusion at the glass surface at all temperatures. They are more than one order of magnitude larger than the normal diffusion coefficients inside the glass [(5–0.8) $\times 10^{-13}$ m^2/s at the glass surface under the present experimental conditions], where the total water concentration is lower than at the surface.

The diffusion model with a constant diffusion coefficient gives R_s of (2–6) $\times 10^{-4}$ at all the temperatures. Although the estimated R_s has a large uncertainty, it is comparable to the homogeneous $R(x)$ within the samples heated for 20 h [(4–12) $\times 10^{-4}$]. This suggests that the assumption of the fixed surface concentration in Equation 2 is valid.

Species and path for fast diffusion of water in silica glass

Mean values of the fast diffusion coefficients at different temperatures, obtained from multiple-line profiles of a single sample, are summarized in Table 1. The Arrhenius plot of the fast diffusion coefficient gives an activation energy of 80.5 ± 40.5 kJ/mol and a pre-exponential factor of 6.1 × 10^{-9} m^2/s (Fig. 3).

The obtained diffusion coefficient at 900–750 °C (Table 1) is two orders of magnitude smaller than that of H_2 in the same temperature range (Lou et al. 2003), and its activation energy is twice as large as that of H_2 diffusion in silica glass (Lou et al. 2003). Therefore H_2 is unlikely to be a diffusing species for the fast diffusion observed in this study.

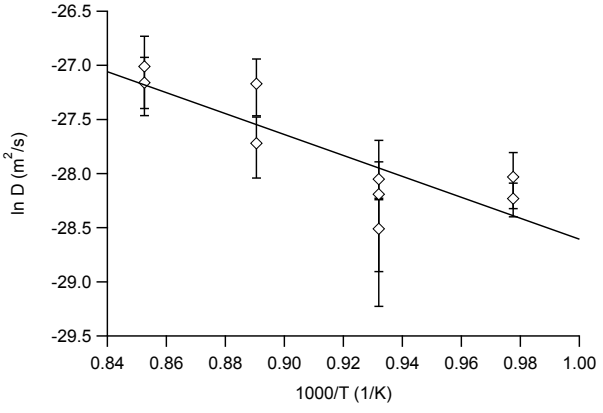


Figure 3. The Arrhenius plot of the diffusion coefficient of fast water diffusion (Eq. 2). The line is a fit to the data. Error bars represent 2σ of the diffusion coefficients evaluated from multiple diffusion profiles.

The activation energy of ~80.5 kJ/mol is similar to that of the normal diffusion of water in silica glass (e.g., Wakabayashi and Tomozawa 1989; Kuroda et al. 2018). This indicates that the main diffusion species for fast diffusion is molecular water and that water molecules jump within the glass structure with a similar energetic barrier (Kuroda et al. 2108).

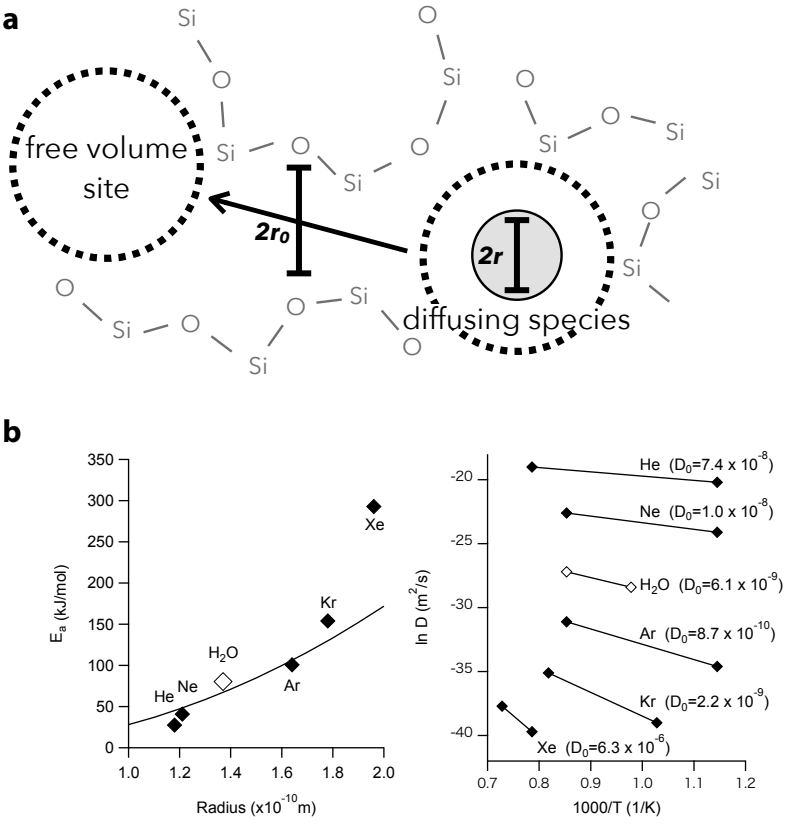
The similar energetic barrier for normal and fast diffusion suggests that the difference in diffusivity should be attributed to factors related to the pre-exponential term for diffusions such as a frequency factor and a diffusion pathway. Here we propose that a small fraction of water molecules diffuse through the pathways connecting free volume (Fig. 4) without reacting with the silica glass structure to form hydroxyls. The free volume is the intrinsic gap formed within the polymerized network (e.g., Cohen and Turnbull 1959; Vrentas and Duda 1977), and it has been proposed that noble gases diffuse through the free volume in the network structure of silica and silicate glasses (e.g., Behrens 2010; Amalberti et al. 2016) (Fig. 4a). In the free-volume diffusion model, the free volumes are connected by "doorways" of an average radius r_0. The activation energy for the diffusion may be given as the energy required to deform the glass network large enough to allow an atom to pass from one side to another. For instance, the following expression has been proposed for the relationship between the activation energy for diffusion and the atomic radius (r) for noble gases;

$$E_a = 8\pi G r_0 (r - r_0)^2 \quad (3)$$

where G represents a shear modulus of the glass. G and r_0 for silica glass are estimated to be 305 kbar and 1.1 Å, respectively (Anderson and Stuart 1954).

The obtained diffusivity and the activation energy for the fast diffusion of water molecules are compared with those of noble gas diffusion in silica glass (Swets et al. 1961 for He; Wortman and Shackelford 1990 for Ne; Carroll and Stolper 1991 for Ar; Roselieb et al. 1995 for Kr and Xe) (Fig. 4b). The radii of noble gasses and molecular water are taken from Zhang and Xu (1995), where molecule radii were obtained by treating the noble gas atoms as ions of zero oxidation states. The free volume diffusion of noble gases in silicate glasses shows the non-Arrhenius relation at temperatures close to the glass transition temperature (e.g., Amalberti et al. 2016) most likely because of the structural change of the glass network. However, the effect of the structural change on the free volume diffusion is negligibly small in this study because the temperature range discussed here is much below the glass transition temperature of silica glass (~1163 °C; calculated with Deubener et al. 2003), where the free volume diffusion of noble gases show a simple Arrhenius relation.

The activation energies of noble gas diffusion in silica glass show a clear relation with the atomic radius, and they increase with increasing the atomic size (Fig. 4b). Although the reported activation energies of noble gases are not well fit by the relation with Equation 3, the activation energy for the fast diffusion of molecular water lies on the same trend of noble gas diffusion in silica glass. Moreover, the pre-exponential factor for the fast water diffusion (6.1 × 10^{-9} m^2/s) fits within the range of those for noble gas diffusion in silica glass (7 × 10^{-8} and 2 × 10^{-9} m^2/s for



►**Figure 4.** (**a**) Schematic illustration of the diffusion mechanism through connected free volume. (**b**) Comparisons of activation energy for fast water diffusion and noble gas diffusion in silica glass (left) and of the temperature dependence of diffusion coefficients (right). Activation energies and diffusion coefficients of noble gases in silica glass are taken from Swets et al. (1961) for He, Wortman and Shackelford (1990) for Ne, Carroll and Stolper (1991) for Ar, and Roselieb et al. (1995) for Kr and Xe. Radii of noble gases and water molecule are taken from Zhang and Xu (1995). The relation between the activation energy and the radius of the diffusing species, obtained with Equation 3 with G = 305 kbar and r_0 = 1.1 Å (Anderson and Stuart 1954), is also shown.

He and Kr, respectively) (Fig. 4b). These similarities of activation energy and pre-exponential factors suggest that fast diffusion of molecular water is also governed by molecular jumps between connecting free volume in the silica glass structure.

Implications

We found that there are, at least, two different pathways for water diffusion in silica glass (normal diffusion through pathways created by the hydroxyl formation reaction and fast diffusion through connected free volume). We discuss the possible contribution of fast water diffusion to water transport in silica glass.

The amount of water transported by fast diffusion can be estimated by integrating the fast diffusion profiles, and it is ~0.5% of the amount of water transported by normal diffusion at 900 °C. The surface concentration of water for the fast diffusion path is 3–4 orders of magnitude smaller than the total water concentration at the surface (Fig. 2). Because the surface concentration of dissolved water under the present experimental conditions is ~0.3 mol% (Kuroda et al. 2018), the surface concentration of fast diffusion is estimated to range from a few parts per million to several hundred parts per billion. The estimated surface concentration of fast diffusion is likely to represent the water concentration in connected free volume at the surface and is much smaller than the concentration of free volume in silica glass that was estimated from the solubility of Ar (~0.2 mol%; Shackelford 1999). This implies that the free volumes were not fully occupied by water molecules at the water vapor pressure of 50 bar in the present experiments. We note that water concentration in the starting silica glass is 10 ppm, well below the free volume concentration, such that it should not affect the fast diffusion of ^2H_2O even if the initial water was present in the glass's free volumes.

The solubility of molecular water in the fast diffusion path is expected to increase with increasing the water vapor pressure until free volume saturation. The concentration of molecular water occupying the free volume is likely to increase linearly with the water vapor pressure following Henry's law as noble gases, while the solubility of water in the bulk glass depends on the square root of water vapor pressure (<~200 MPa) (e.g., Zhang et al. 2007).

We emphasize that more experimental work is clearly needed to determine the pressure dependence of water solubility in free volume, but the finding in this study may imply that the contribution of fast water diffusion to water transport in silica glass may become larger under higher water vapor pressures. Especially, its contribution could be significant for water diffusion occurring within a timescale shorter than a few hours as seen in this study, which the timescale of magma ascent for explosive eruption (e.g., Lloyd et al. 2014). The fast water diffusion might affect the nucleation and growth of bubbles in ascending magma.

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