

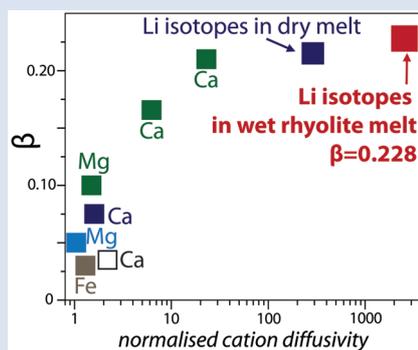
## Diffusive fractionation of Li isotopes in wet, highly silicic melts

M.E. Holycross<sup>1,2\*</sup>, E.B. Watson<sup>1</sup>, F.M. Richter<sup>3</sup>, J. Villeneuve<sup>4</sup>



doi: 10.7185/geochemlet.1807

### Abstract



time-temperature histories of natural rhyolite samples.

The discovery of large lithium isotopic gradients in geologic media has motivated recent work examining the kinetic fractionation of Li isotopes in silicate materials. Here, piston-cylinder experiments were used to determine Li diffusivities in rhyolitic melts containing ~6 wt. % H<sub>2</sub>O at 1 GPa pressure and 790–875 °C. Lithium transport in wet rhyolitic melt is almost an order of magnitude faster than diffusion in dry obsidian glass over the investigated temperature range. Li isotope profiles collected by ion microprobe show that the kinetic exponent  $\beta = 0.228$  for diffusive fractionation of Li isotopes in wet rhyolite. This value is very close to  $\beta = 0.215$  determined by Richter *et al.* (2003) for Li isotope diffusion in a dry basalt-rhyolite couple at 1350 °C. The similarity of the two values indicates little or no dependence of  $\beta_{Li}$  in silicate melts on either temperature or melt composition. The new data confirm a very high potential for diffusive fractionation of <sup>6</sup>Li from <sup>7</sup>Li and can be confidently used to model deviations in  $\delta^7Li$  to determine the

Received 16 November 2017 | Accepted 9 February 2018 | Published 5 March 2018

### Introduction and Experimental Approach

The detection of large lithium isotope variations in variety of terrestrial and planetary materials has driven significant advancements in Li isotope geochemistry over the past two decades (see recent reviews by Tomascak *et al.*, 2016 and Penniston-Dorland *et al.*, 2017 for details). The ~17 % mass difference between the two isotopes of lithium (<sup>6</sup>Li and <sup>7</sup>Li) can lead to considerable equilibrium and kinetic fractionation in Earth systems. Experimental demonstrations have shown that Li diffusion in melts and minerals is subject to a large mass effect (Richter *et al.*, 2003, 2014, 2017; Dohmen *et al.*, 2010). In natural samples, diffusive fractionation of Li isotopes has been recorded at the  $\mu\text{m}$  to m scale (*e.g.*, Barrat *et al.*, 2005; Lundstrom *et al.*, 2005; Teng *et al.*, 2006; Jeffcoate *et al.*, 2007; Gao *et al.*, 2011). The relative diffusivities of the two isotopes of Li are expressed by the empirical constant  $\beta$  in the equation

$$\frac{D_{7Li}}{D_{6Li}} = \left(\frac{6}{7}\right)^\beta \quad \text{Eq. 1}$$

where  $D$  is the diffusivity of the individual isotopes (Richter *et al.*, 1999); the larger the value of  $\beta$ , the more sensitive the diffusivity is to isotope mass.

Lithium's small ionic radius and +1 valence make it an exceptionally fast diffuser in silicate melts (Jambon and Semet, 1978; Lowry *et al.*, 1981; Cunningham *et al.*, 1983; Richter *et al.*, 2003). In recent years, lithium diffusion gradients in silicate rocks have been increasingly used as geospeedometers of short-lived heating events (*e.g.*, Coogan *et al.*, 2005; Parkinson *et al.*, 2007; Charlier *et al.*, 2012; Richter *et al.*, 2016). Quantitative application of Li-geospeedometry requires that the gradients used for this purpose are demonstrably due to diffusion along with knowledge of Li kinetic isotope behaviour (*i.e.*  $\beta$  factors). Richter *et al.* (2003) reported  $\beta = 0.215$  for the diffusive fractionation of Li isotopes in a dry basalt-rhyolite diffusion couple in a single experiment at 1350 °C. It was unclear if this  $\beta$  value applies to Li isotope fractionation in hydrous, silicic magmatic systems in which the behaviour of Li has drawn particular attention. In view of the widespread interest in the Li geochemistry of such systems, there is a compelling need for constraints on  $\beta$  in pertinent melt compositions and temperatures. Additionally, the work of Watkins *et al.* (2009, 2011, 2017) showed significant compositional dependence of  $\beta$  for isotope diffusion in simple silicate liquids, providing further motivation for determining the kinetic isotope fractionation of Li in a common but not previously studied molten silicate system.

To address the question of the general applicability of the earlier result of Richter *et al.* (2003), we performed piston-cylinder experiments to measure the relative diffusivities

1. Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
  2. National Museum of Natural History, Smithsonian Institution, Washington, DC 20560, USA
  3. Department of the Geophysical Sciences, University of Chicago, Chicago, IL 60637, USA
  4. CRPG, CNRS, Université de Lorraine, UMR 7358, Vandoeuvre-les-Nancy F-54501, France
- \* Corresponding author (email: holycrossm@si.edu)



of Li isotopes in a melt composition and temperature range directly relevant to highly silicic volcanism (790–875 °C). Lithium diffusion couples were fabricated in Ag containers from two polished and juxtaposed cylinders of pre-synthesised hydrous rhyolite glass with different amounts of Li (Table S-1). The couples were placed in ¼" NaCl-Pyrex®-MgO assemblies, cold pressurised to ~12 kb and allowed to settle for 1 hr in the piston-cylinder before heating to the desired run temperature. This necessitated only minimal adjustments to the sample pressure once the run had reached the final temperature. A two-part ramping routine was used to heat the experiments quickly without significantly overshooting the desired temperature (see Supplementary Information). Experiment conditions are recorded in Table 1.

**Table 1** Experiment conditions for diffusion couple runs and measured  $^7\text{Li}$  diffusion coefficients.

experiment	T (°C)	t (s)	$D^7\text{Li}$ ( $\text{m}^2/\text{s}$ )	$2\sigma$ SE
LiDiff2	875	492	7.40E-10	~7.4 E-11
LiDiff3	850	261	6.50E-10	~6.5 E-11
LiDiff4*	810	266	5.74E-10	7.53E-11
LiDiff5	790	205	5.25E-10	5.02E-11
LiDiff6*	830	133	6.28E-10	1.14E-10

\*SIMS analysis

## Lithium Diffusion Coefficients in Wet Rhyolitic Melt

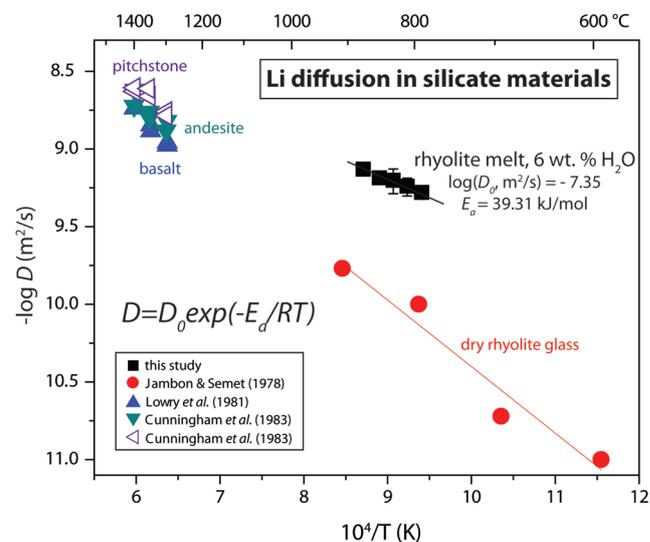
Experimental glasses were analysed for  $^7\text{Li}$  using the laser ablation ICP-MS at Rensselaer Polytechnic Institute.  $^7\text{Li}$  diffusivities were derived by fitting the concentration profiles obtained from LA-ICP-MS measurements (Fig. S-2) with the time-dependent solution for diffusion in an infinite diffusion couple

$$C_{(x,t)} = C_{+\infty} + \left( \frac{C_{-\infty} + C_{+\infty}}{2} \right) \left( 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right) \quad \text{Eq. 2}$$

Resulting  $^7\text{Li}$  diffusivities are listed in Table 1. All diffusion couples were ramped to the final temperature as quickly as possible to limit Li diffusion in the melt during run-up. However, it is inevitable that some Li diffusion occurred during the heating interval. The effects of diffusion during ramp up are accounted for in our data reduction scheme (see Supplementary Information). In two instances where the rapid diffusivity of Li resulted in an increase in Li concentrations at the end of the diffusion couple (experiments LiDiff2 and LiDiff3), an explicit finite-difference method was used to determine Li diffusion coefficients in a confined rhyolite melt system with zero-flux boundaries.

Calculated diffusion coefficients are fit to the Arrhenius equation to demonstrate the temperature dependence of Li transport in silicate melt (Fig. 1). A linear regression fit to  $D_{\text{Li}}$  vs.  $T^{-1}$  yields the Arrhenius parameters  $\log(D_0, \text{m}^2/\text{s}) = -7.35 \pm 0.14$  and  $E_a = 39.31 \pm 2.91$  kJ/mol for Li diffusion in hydrous rhyolitic liquid. Figure 1 shows the Arrhenius relationship for Li diffusion in hydrous rhyolite melt compared to Li diffusivities in rhyolite glass and various silicate melt compositions. Lithium diffusion is very fast even in dry rhyolite glass and the significant decrease in viscosity that occurs across the glass transition and from the addition of 6 wt. %  $\text{H}_2\text{O}$  to the melt network increases Li diffusivities by ~10x over the investigated  $T^{-1}$  range (cf. Jambon and Semet, 1978). As water is added to silicate liquid,  $\text{OH}^-$  molecules break bridging oxygen bonds, decreasing melt viscosity and increasing cation diffusivities

(e.g., Watson, 1979, 1981; Zhang *et al.*, 2003 and many others). The rapid diffusion of Li in hydrous, highly silicic melts implies that any gradients in total Li in rhyolite magma systems will be quickly homogenised while other trace element concentration gradients may persist (Hollycross and Watson, 2016a).



**Figure 1** Arrhenius plot showing temperature dependence of Li diffusion in silicate materials. Lithium diffusion in wet rhyolite melt is significantly faster than in dry obsidian glass due to the decrease in viscosity from glass to liquid and from the addition of 6 wt. % dissolved  $\text{H}_2\text{O}$  to the melt.

## Lithium Isotope Fractionation in Wet Rhyolitic Melt

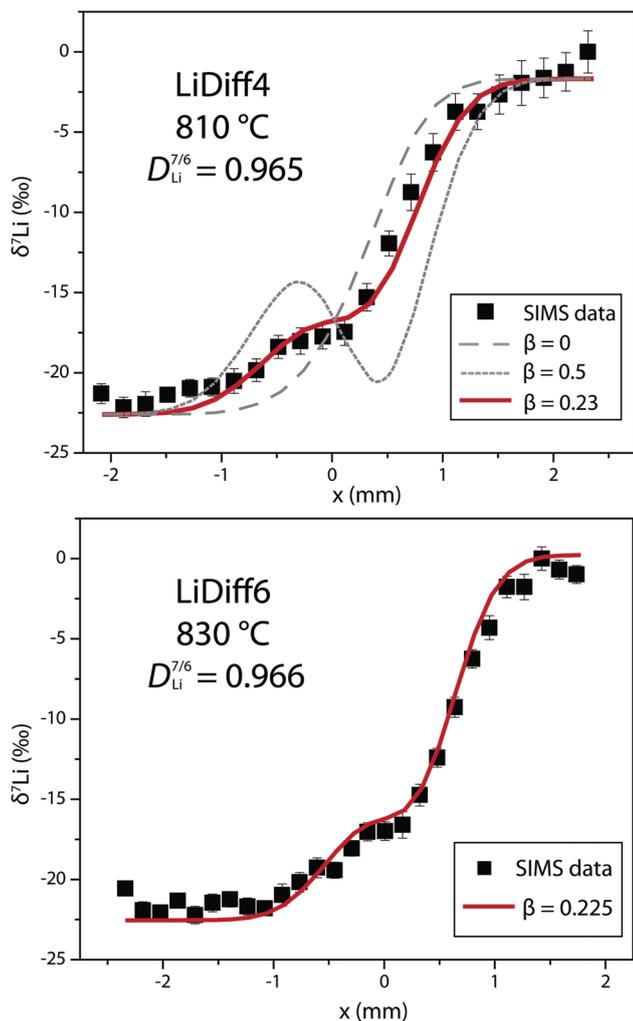
To assess possible effects of melt composition on  $\beta_{\text{Li}}$ , we determined the relative diffusivities of the two Li isotopes in our hydrous rhyolite melts for comparison with the results of Richter *et al.* (2003). Lithium isotopic analyses were carried out on a Cameca IMS 1270-E7 ion probe at the Centre de Recherches Pétrographiques et Géochimiques (CRPG) in Nancy, France. Information about the data collection routine is listed in the Supplementary Information. Lithium isotope fractionation profiles for two experiments are presented in Figure 2. Ion probe analyses revealed the two glasses used to form the diffusion couples had different  $^7\text{Li}/^6\text{Li}$  compositions. Diffusion between the two glasses with different  $^7\text{Li}/^6\text{Li}$  produced a somewhat unconventional  $\delta^7\text{Li}$  profile characterised by a pronounced shoulder in the diffusion couple.

The  $\beta$  value for Li isotope diffusion in rhyolite was determined by generating individual model concentration profiles of  $^7\text{Li}$  and  $^6\text{Li}$  and then comparing the model  $^7\text{Li}/^6\text{Li}$  values to the SIMS data. Model Li isotope profiles for experiments LiDiff4 and LiDiff6 were calculated using the solutions given by Equations 1 and 2.  $^7\text{Li}$  diffusion coefficients obtained from least-squares fits to measured LA-ICP-MS profiles were kept constant while the diffusivity of  $^6\text{Li}$  was varied so that the output of the  $^7\text{Li}/^6\text{Li}$  model profile best matched the  $^7\text{Li}/^6\text{Li}$  SIMS profile, as evaluated by obtaining the smallest  $\chi^2$  parameter for each ratio profile (Hollycross and Watson, 2016b).

In Figure 2, the Li fractionation data from experiment LiDiff4 is compared to profiles calculated with various  $\beta$  factors showing that  $\beta = 0.23$  is the best fit. When  $\beta \neq 0$ , the different diffusivities of  $^7\text{Li}$  and  $^6\text{Li}$  create a shoulder or reversal in the  $\delta^7\text{Li}$  profile near the couple interface. In the present experiments a  $\delta^7\text{Li}$  sigmoidal profile is superimposed on the gradient due to the two end members having different  $\delta^7\text{Li}$ . The overall good



fit of the calculated Li fractionation profiles to the measured data confirms that  $^7\text{Li}$  and  $^6\text{Li}$  diffuse at different rates. Kinetic fractionation profiles from LiDiff4 and LiDiff6 are best fit when  $^6\text{Li}$  diffuses  $\sim 3.5\%$  faster than  $^7\text{Li}$  in the melt (*i.e.*  $D_{\text{Li}}^{7/6} = 0.965$ ), corresponding to an average  $\beta$  of 0.228.

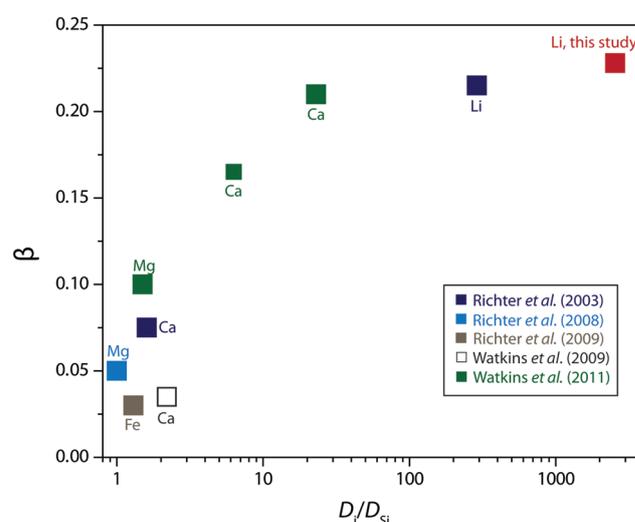


**Figure 2**  $\delta^7\text{Li}$  profiles produced from SIMS analyses.  $^6\text{Li}$  diffuses into the “low” Li glass ( $x > 0$ ) faster than  $^7\text{Li}$ , fractionating the isotopes in the melt. If the Li isotopes were diffusing at the same speed in rhyolitic melt ( $\beta = 0$ ), a smoothly varying isotope gradient would be present near  $x = 0$ . When  $\beta \neq 0$ , calculated profiles show a shallow or reversed slope near the diffusion couple interface at  $x = 0$ , as is seen in the data in both panels. The kinetic fractionation of Li isotopes in hydrous rhyolitic melt is best fit by an average  $\beta = 0.228$ .

The global dataset of experimentally-determined  $\beta$  values ( $\beta > 0$ ) for fractionation in silicate liquids spans  $\beta_{\text{Ca}} = 0.035$  to our new value of  $\beta_{\text{Li}} = 0.228$  (compiled by Watkins *et al.*, 2017). The  $\beta_{\text{Li}}$  determined here for diffusion in hydrous obsidian melt at 790–875 °C is close to the value of Richter *et al.* (2003), who found  $\beta = 0.215$  for Li isotopes in dry silicate melt in a single experiment at 1350 °C. It is unclear if our new value and that of Richter *et al.* (2003) are statistically different by a small amount given the difficulty of assigning realistic uncertainties for such a small number of experiments. Regardless, the key point is that the  $\beta_{\text{Li}}$  values are remarkably similar despite very different system compositions and temperatures.

The similarity of  $\beta_{\text{Li}}$  for both systems may be a consequence of Li decoupling from the silicate melt network during diffusion. Watkins *et al.* (2009, 2011, 2017) proposed that the  $\beta$  factor for isotopic fractionation of an element  $i$  in simple silicate melt may be a function of its Si-normalised diffusivity,

$D_i/D_{\text{Si}}$  (Fig. 3). Faster diffusing elements may be moving as single atoms in the melt network and thus show a greater isotope mass discrimination because their diffusion is not correlated with the mobilities of other network elements. At very large values of  $D_i/D_{\text{Si}}$ , changes in  $\beta_i$  in different melt compositions are minimal. This is observed comparing our new data to that of Richter *et al.* (2003). At 810 °C in a rhyolite melt with 6 wt. %  $\text{H}_2\text{O}$ ,  $D_{\text{Li}}/D_{\text{Si}} \approx 2560$  (Si value from Baker and Bossányi, 1994), roughly an order of magnitude greater than  $D_{\text{Li}}/D_{\text{Si}}$  in the experiment of Richter *et al.* (2003) and yet they have very similar values of  $\beta_{\text{Li}}$ . The high diffusivity of Li in wet rhyolite and the insensitivity of  $\beta_{\text{Li}}$  to liquid composition indicates Li isotope diffusion is independent of melt structure. This suggests that Li may jump primarily between coordinated sites in the melt network, perhaps not unlike the fast diffusion of Li *via* an interstitial mechanism in crystalline mineral phases (*e.g.*, Mullen, 1961; Dohmen *et al.*, 2010; Richter *et al.* 2014, 2017).



**Figure 3** The reported  $\beta$  factors for isotopes of an element  $i$  vary with its Si-normalised diffusivity,  $D_i/D_{\text{Si}}$ . Data point in red is for rhyolitic melt containing 6 wt. %  $\text{H}_2\text{O}$  at 810 °C. Silicon is an extremely slow diffuser in rhyolite while Li is extremely fast. This suggests diffusion of Li may be decoupled from the melt network and exhibit a greater mass discrimination. Figure after Watkins *et al.* (2017).

The vital aspect of our measurements is that they can be confidently applied to Li isotope diffusion profiles in rhyolitic rock specimens to determine the timescales of rapid heating events in highly silicic volcanic systems. Diffusive fractionation of Li isotopes in our experiments demonstrate the potential for creating considerable variations in the  $\delta^7\text{Li}$  of natural magmas during kinetically controlled growth of bubbles or crystalline mineral phases (Koga *et al.*, 2011; Watson, 2017). This raises the possibility that the isotopic composition of Li in rhyolitic rock systems may record significant kinetic fractionation, which can be modelled using  $\beta_{\text{Li}}$  derived from the experiments reported here.

## Acknowledgements

This study was supported in part by NSF grant no. EAR-0948204 to EBW. We thank Jared Singer for assistance with the LA-ICPMS. Comments by Ming Tang and an anonymous reviewer improved an earlier version of this manuscript.

Editor: Helen Williams



## Additional Information

**Supplementary Information** accompanies this letter at <http://www.geochemicalperspectivesletters.org/article1807>.



This work is distributed under the Creative Commons Attribution Non-Commercial No-Derivatives 4.0 License, which permits unre-

stricted distribution provided the original author and source are credited. The material may not be adapted (remixed, transformed or built upon) or used for commercial purposes without written permission from the author. Additional information is available at <http://www.geochemicalperspectivesletters.org/copyright-and-permissions>.

**Cite this letter as:** Holycross, M.E., Watson, E.B., Richter, F.M., Villeneuve, J. (2018) Diffusive fractionation of Li isotopes in wet, highly silicic melts. *Geochem. Persp. Let.* 6, 39–42.

## References

- BAKER, D.R., BOSSÁNYI, H. (1994) The combined effect of F and H<sub>2</sub>O on inter-diffusion between peralkaline dacitic and rhyolitic melts. *Contributions to Mineralogy and Petrology* 117, 203–214.
- BARRAT, J.A., CHAUSSIDON, M., BOHN, M., GILLET, P., GOPEL, C., LESOURD, M. (2005) Lithium behavior during cooling of a dry basalt: An ion-microprobe study of the lunar meteorite Northwest Africa 479 (NWA 479). *Geochimica et Cosmochimica Acta* 69, 5597–5609.
- CHARLIER, B.L.A., MORGAN, D.J., WILSON, C.J.N., WOODEN, J.L., ALLAN, A.S.R., BAKER, J.A. (2012) Lithium concentration gradients in feldspar and quartz record the final minutes of magma ascent in an explosive supereruption. *Earth and Planetary Science Letters* 319, 218–227.
- COOGAN, L.A., KASEMANN, S.A., CHAKRABORTY, S. (2005) Rates of hydro-thermal cooling of new oceanic crust derived from lithium-geospeedometry. *Earth and Planetary Science Letters* 240, 415–424.
- CUNNINGHAM, G.J., HENDERSON, P., LOWRY, R.K., NOLAN, J., REED, S.J.B., LONG, J.V.P. (1983) Lithium diffusion in silicate melts. *Earth and Planetary Science Letters* 65, 203–205.
- DOHMEN, R., KASEMANN, S.A., COOGAN, L.A., CHAKRABORTY, S. (2010) Diffusion of Li in olivine. Part I: Experimental observations and a multi species diffusion model. *Geochimica et Cosmochimica Acta* 74, 274–292.
- GAO, Y.J., SNOW, J.E., CASEY, J.F., YU, J.B. (2011) Cooling-induced fractionation of mantle Li isotopes from the ultra-slow spreading Gakkel Ridge. *Earth and Planetary Science Letters* 301, 231–240.
- HOLYCROSS, M.E., WATSON, E.B. (2016a) Diffusive fractionation of 25 trace elements in basaltic and rhyolitic melts (abstract). 2016 AGU Fall Meeting, San Francisco, CA, <http://adsabs.harvard.edu/abs/2016AGUFMMR51A2689H>.
- HOLYCROSS, M.E., WATSON, E.B. (2016b) Diffusive fractionation of trace elements in basaltic melt. *Contributions to Mineralogy and Petrology* 171, 1–15.
- JAMBON, A., SEMET, M.P. (1978) Lithium diffusion in silicate glasses of albite, orthoclase and obsidian composition: an ion-microprobe determination. *Earth and Planetary Science Letters* 37, 445–450.
- JEFFCOATE, A.B., ELLIOTT, T., KASEMANN, S.A., IONOV, D., COOPER, K., BROOKER, R. (2007) Li isotope fractionation in peridotites and mafic melts. *Geochimica et Cosmochimica Acta* 71, 202–218.
- KOGA, K.T., ROSE, E.F., LAPORTE, D., CLUZEL, N., SHIMIZU, N. (2011) Lithium-boron isotope fractionation during degassing of rhyolitic magma. *Mineralogical Magazine* 75, 1211.
- LOWRY, R.K., REED, S.J.B., NOLAN, J., HENDERSON, P., LONG, J.V.P. (1981) Lithium tracer-diffusion in an alkali-basaltic melt—an ion-microprobe determination. *Earth and Planetary Science Letters* 53, 36–40.
- LUNDSTROM, C.C., CHAUSSIDON, M., HSUI, A.T., KELEMEN, P., ZIMMERMAN, M. (2005) Observations of Li isotopic variations in the Trinity Ophiolite: Evidence for isotopic fractionation by diffusion during mantle melting. *Geochimica et Cosmochimica Acta* 69, 735–751.
- MULLEN, J.G. (1961) Isotope effect in intermetallic diffusion. *Physical Review* 121, 1649.
- PARKINSON, I.J., HAMMOND, S.J., JAMES, R.H., ROGERS, N.W. (2007) High-temperature lithium isotope fractionation: Insights from lithium isotope diffusion in magmatic systems. *Earth and Planetary Science Letters* 257, 609–621.
- PENNISTON-DORLAND, S., LIU, X.M., RUDNICK, R.L. (2017) Lithium Isotope Geochemistry. *Reviews in Mineralogy and Geochemistry* 82, 165–217.
- RICHTER, F.M., LIANG, Y., DAVIS, A.M. (1999) Isotope fractionation by diffusion in molten oxides. *Geochimica et Cosmochimica Acta* 63, 2853–2861.
- RICHTER, F.M., DAVIS, A.M., DEPAOLO, D.J., WATSON, E.B. (2003) Isotope fractionation by chemical diffusion between molten basalt and rhyolite. *Geochimica et Cosmochimica Acta* 67, 3905–3923.
- RICHTER, F.M., WATSON, E.B., MENDYBAEV, R.A., TENG, F.Z., JANNEY, P.E. (2008) Magnesium isotope fractionation in silicate melts by chemical and thermal diffusion. *Geochimica et Cosmochimica Acta* 72, 206–220.
- RICHTER, F.M., WATSON, E.B., MENDYBAEV, R., DAUPHAS, N., GEORG, B., WATKINS, J., VALLEY, J. (2009) Isotopic fractionation of the major elements of molten basalt by chemical and thermal diffusion. *Geochimica et Cosmochimica Acta* 73, 4250–4263.
- RICHTER, F., WATSON, E.B., CHAUSSIDON, M., MENDYBAEV, R., RUSCITTO, D. (2014) Lithium isotope fractionation by diffusion in minerals. Part 1: Pyroxenes. *Geochimica et Cosmochimica Acta* 126, 352–370.
- RICHTER, F., CHAUSSIDON, M., MENDYBAEV, R., KITE, E. (2016) Reassessing the cooling rate and geologic setting of Martian meteorites MIL 03346 and NWA 817. *Geochimica et Cosmochimica Acta* 182, 1–23.
- RICHTER, F., CHAUSSIDON, M., WATSON, E.B., MENDYBAEV, R., HOMOLOVA, V. (2017) Lithium isotope fractionation by diffusion in minerals. Part 2: Olivine. *Geochimica et Cosmochimica Acta* 219, 124–142.
- TENG, F.Z., McDONOUGH, W.F., RUDNICK, R.L., WALKER, R.J. (2006) Diffusion-driven extreme lithium isotopic fractionation in country rocks of the Tin Mountain pegmatite. *Earth and Planetary Science Letters* 243, 701–710.
- TOMASCAK, P.B., MAGNA, T., DOHMEN, R. (2016) *Advances in Lithium Isotopes Geochemistry*. Springer-Verlag, Berlin.
- WATKINS, J.M., DEPAOLO, D.J., HUBER, C., RYERSON, F.J. (2009) Liquid composition-dependence of calcium isotope fractionation during diffusion in molten silicates. *Geochimica et Cosmochimica Acta* 73, 7341–7359.
- WATKINS, J.M., DEPAOLO, D.J., RYERSON, F.J., PETERSON, B.T. (2011) Influence of liquid structure on diffusive isotope separation in molten silicates and aqueous solutions. *Geochimica et Cosmochimica Acta* 75, 3103–3118.
- WATKINS, J.M., DEPAOLO, D.J., WATSON, E.B. (2017) Kinetic fractionation of non-traditional stable isotopes by diffusion and crystal growth reactions. *Reviews in Mineralogy and Geochemistry* 82, 85–125.
- WATSON, E.B. (1979) Diffusion of cesium ions in H<sub>2</sub>O-saturated granitic melt. *Science* 205, 1259–1260.
- WATSON, E.B. (1981) Diffusion in magmas at depth in the Earth: The effects of pressure and dissolved H<sub>2</sub>O. *Earth and Planetary Science Letters* 52, 291–301.
- WATSON, E.B. (2017) Diffusive fractionation of volatiles and their isotopes during bubble growth in magmas. *Contributions to Mineralogy and Petrology* 172, 61.
- ZHANG, Y., XU, Z., LIU, Y. (2003) Viscosity of hydrous rhyolitic melts inferred from kinetic experiments, and a new viscosity model. *American Mineralogist* 88, 1741–1752.

