

MAGNESIUM ISOTOPIC ZONING OF AN OLIVINE GRAIN FROM LUNAR MICROGABBRO 15555: CONSTRAINTS ON CRYSTALLIZATION AND COOLING. F. M. Richter¹, M. Chaussidon², and R.A. Mendybaev¹, and L.A. Taylor³.¹The University of Chicago, 5734 S. Ellis, Chicago, IL 60637, ²Institut Physique du Globe de Paris, Paris, France, ³University of Tennessee, Knoxville, TN 37996. (richter@geosci.uchicago.edu.)

Introduction: Apollo 15 brought back a large olivine-normative sample of mare basalt - sample 15555. A review of the petrology of this sample along with extensive references is given in <<http://curator.jsc.nasa.gov/lunar/lsc/15555r.pdf>>. Several papers presented at the 8th and 9th Lunar Science Conference are especially relevant to our present study of sample 15555 having reported experimental data on the crystallization of a plausible parental melt [1] and used Fe-Mg zoning of olivine to estimate cooling rates of the order of a few °C/day [2,3]. We expand on these earlier works using magnesium isotopic data to document the extent of Fe-Mg exchange by diffusion and how this modified the crystallization zoning of the olivine grain from sample 15555 shown below.

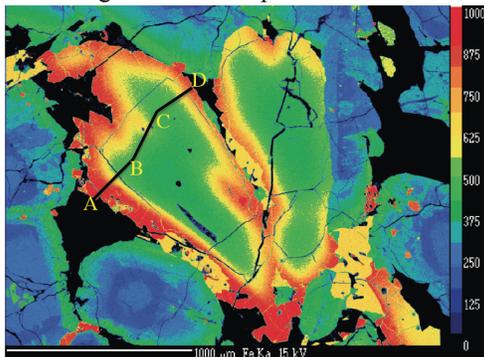


Figure 1. *FeK α image of a zoned olivine grain from lunar sample 15555 and surrounding minerals.*

Elemental and Mg Isotopic Analyses: The major element composition along the traverse A-B-C-D shown in Fig. 1 was measured using a JEOL JSM-5800LV scanning electron microscope equipped with an Oxford Link ISIS-300 energy dispersive X-ray microanalysis system giving a precision of better than 1% relative. The Mg isotopic composition at selected points across olivine grain and of matrix correction standards was measured with the CAMECA ims 1270 multicollector ion microprobe at the Centre de Recherches Pétrographiques et Géochimiques in Nancy France. The matrix correction was +2‰ at 30wt% MgO decreasing linearly to 0‰ at 5wt% MgO. The Mg isotopic fractionation is reported in per mil as

$$\delta^{26}\text{Mg}(\text{‰}) = 1000 \times \left(\frac{(^{26}\text{Mg} / ^{24}\text{Mg})_{\text{sample}}}{(^{26}\text{Mg} / ^{24}\text{Mg})_{\text{reference}}} - 1 \right)$$

Results: Figure 2 shows the olivine composition along traverse A-B-C-D in Fig. 1. Both Figs. 1 and 2 suggest that the olivine grain is actually two separate grains that became joined at an early stage of crystallization. For this reason we will focus our modeling on the segment A-B of the traverse across the olivine

grain in Fig. 1. Figure 3 shows the Mg isotopic fractionation between 0 and 300 μm from the left edge of the grain.

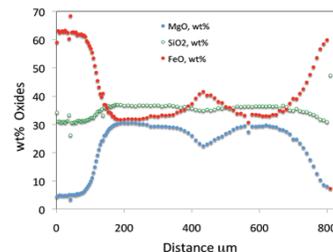


Figure 2. *Wt % of the major oxides measured along the traverse A-B-C-D shown in Fig. 1.*

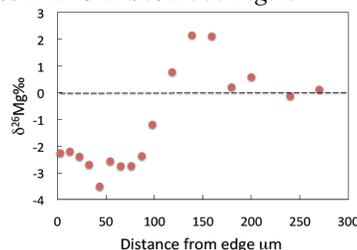


Figure 3. *Mg isotopic fractionation relative to the interior composition along segment A-B shown in Fig. 1. The 2 σ errors are smaller than the symbols.*

Diffusion Model Specifications: The diffusion model used to fit the data shown in Figs. 2 and 3 is based on the one-dimensional mass conservation equation for total magnesium or any of the isotopes written as

$$\frac{\partial C_i}{\partial t} = \frac{\partial}{\partial x} \left(D_i \frac{\partial C_i}{\partial x} \right), \quad (1)$$

with the diffusion coefficient D_i in the case of isotopes depending on their mass. For the relative diffusivity of magnesium isotopes ^{24}Mg and ^{26}Mg , we use

$$\frac{D_{^{24}\text{Mg}}}{D_{^{26}\text{Mg}}} = \left(\frac{26}{24} \right)^\beta \quad (2)$$

with $\beta \sim 0.2$ [4] for olivine. We also need to take into account that the diffusion coefficient of magnesium in olivine is a strong function of temperature, fayalite content, crystallographic orientation, and weakly, but not negligibly, of the $f\text{O}_2$. For $D_{24\text{Mg}}$ in the c-axis direction we use the parameterization from [5]

$$\text{Log}D = -9.21 - 201\text{kJ}/(2.303\text{RT}) + 3(X_{\text{Fa}} - 0.1) + 0.42 \quad (3)$$

where D is in m^2/s , R is the gas constant, T is absolute temperature, X_{Fa} is the mole fraction fayalite, and $f\text{O}_2$ 1.5 log units below IW was assumed. The simplest version of the diffusion problem requires specifying an initial condition and boundary conditions at the two ends of the profile being modeled. Posed in this fash-

ion, the calculation represents the limit when the crystal growth time scale is significantly shorter than the diffusion time scale and one can neglect any significant diffusion during the growth stage of the crystal. The results below show that this is not an unreasonable limit in that diffusion only had a relatively minor effect at modifying the zoning of the olivine grain. A more complete model will require calculating diffusion as the crystal grows, but this requires many quantities (i.e., grain radius as a function of time, temperature and composition) that we are not yet able to specify.

Model #1: Initial Zoning as a Step Function: In an earlier modeling effort of the elemental zoning of the same olivine grain we presently studying, [2] assumed a step function for the initial condition that was subsequently modified by diffusion. This model is interesting because, as shown in Fig. 4, it does produce a good fit to the wt% MgO data, but only if the compositional dependence of the magnesium diffusion is minimal. Figure 4 also serves to illustrate the effect of diffusion being a strong function of olivine composition as given by Eqn. (3) and that once this is taken into account, the calculated profile is very different from that of the constant diffusion case and no longer fits the measured data.

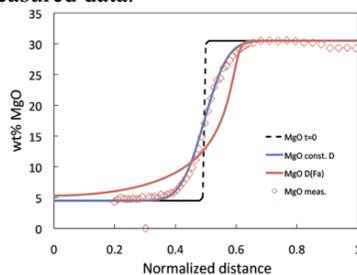


Figure 4. Model diffusion profiles as a function of normalized distance ($X_{A-B}/300\mu\text{m}$) calculated assuming a constant diffusion coefficient (black line) and when diffusion depends on composition (red line) as given by Eqn. (3). A no-flux boundary condition was used at both ends. The red diamonds show the measured data.

An important point to note in Fig. 4 is that in the constant diffusion coefficient case the calculated profile has the same curvature on both sides of the original step, but when the diffusion depends on composition the curvature at the higher magnesium side is much sharper than at the low magnesium side. This is due to the fact that the diffusion coefficient at 30.5 wt% MgO (Fa#~35) is about two orders of magnitude smaller than at 4.5 wt% MgO (Fa#~65). This implies that the observed zoning at the higher magnesium end must be primarily due to crystallization because it could not have been significantly affected by subsequent diffusive transport.

Model #2: Initial Zoning Required to Fit the Measured data: Figures 5a and 5b show the results of

a calculation in which the initial zoning was prescribed so that the diffusion-modified zoning results in a good fit to both the wt% MgO and the Mg isotopic data.

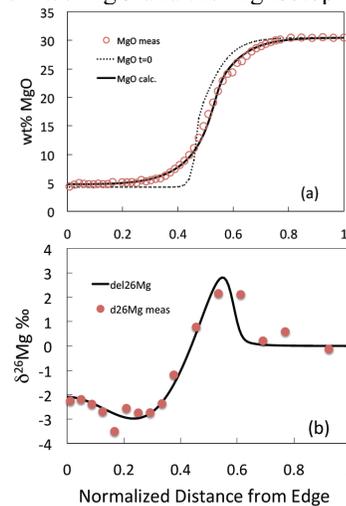


Figure 5. Measured data (red circles) compared to calculated wt% MgO (a) and Mg isotopic fractionation (b) calculated using the starting composition shown by the dotted line in (a), with the diffusion coefficient specified by Eqn. (3), the isotope fractionation exponent $\beta = 0.18$, and no flux at normalized distance 0,1. A uniform initial isotopic composition was assumed

Discussion: The magnesium isotopic data are crucial for demonstrating that diffusion did take place, but that it had a rather limited impact on the final zoning of the olivine grain, especially at the higher magnesium portion of the grain. At the lower magnesium concentrations diffusion becomes increasingly important with portions of the sample losing magnesium becoming isotopically heavy and those gaining magnesium becoming isotopically light. This is the result of ^{24}Mg diffusing slightly faster than ^{26}Mg as given by Eqn. (2). The extent of diffusion as documented by the isotopic fractionation can be used to constrain the cooling history, which using the diffusion coefficient given by Eqn. (3), results in an estimated linear cooling rate of about $10^\circ\text{C}/\text{day}$, broadly consistent with previous estimates [2,3]. A cooling rate of the order $10^\circ\text{C}/\text{day}$ and the associated crystallization of microgabbro 1555 would have been realized at a depth of less than ten meters below the surface of a lava flow cooled by thermal diffusion.

References: [1] Walker D. et al. (1977) *Proc. 8th Lunar Sci. Conf.* 1521-1547. [2] Taylor L.A. et al. (1977) *Proc. 8th Lunar Sci. Conf.* 1581-1592. [3] Onorato P.I.K. et al. (1978) *Proc. 8th Lunar Sci. Conf.* 613-628. [4] Sio C.K.I. et al. (2013) *Geochim. Cosmochim. Acta.* 123, 302-321. [5] Dohmen R. and Chakraborty S. (2007) *Phys. Chem. Minerals.* 34, 597-598.