# TIMESCALES OF MAGMA TRANSFER IN APOLLO 15 MARE BASALTS OBTAINED THROUGH FE-MG DIFFUSION MODELLING IN OLIVINE CRYSTALS.

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**Introduction:** The chemical characteristics of crystals in igneous rocks provide a record of the magmatic environments and processes they experienced [1]. Here we use compositional zoning within crystals (Fig.1) to extract information about the timescales of lunar magmatic processes.

Chemical zonation in crystals is produced in response to changing magmatic variables, such as the surrounding melt composition, as the crystal grows [1]. Atoms may diffuse across initially sharp compositional boundaries within a crystal as the mineral re-equilibrates with its surrounding magmatic environment. Diffusion is a time-dependent process with known diffusion rates for certain elements within different minerals [1]. Therefore, we can fit diffusion models to chemical profiles in zoned crystals to determine how long the crystal resided in a particular magmatic environment.

Diffusion modelling has been successfully used on samples with a terrestrial magmatic origin, allowing for a better understanding of magmatic plumbing systems and processes prior to eruption [2,3,4]. Here we present diffusion timescales for Apollo 15 mare basalts to gain insight into lunar magmatic processes.

Erupted ~3.35 to 3.25 billion years ago, the Apollo 15 mare basalts have been chemical classified as either quartz-normative or olivine-normative based on differences in bulk rock $SiO_2$, FeO and $TiO_2$ wt% [5,6]. The petrogenetic relationship between the two suites has proven to be controversial. The most recent hypothesis, based on trace element abundances, is that the quartz-normative suite underwent a multi-stage crystallization history whilst the olivine-normative suite predominantly crystallized in lava flows on the lunar surface [7]. We aim to use quantitative petrological techniques to understand how differences in magmatic histories, recorded in crystal zoning patterns, may have resulted in the chemical differences between the two Apollo 15 mare basalt suites.

**Methods:** Backscattered electron (BSE) maps, of each of the thin sections used in this study, were collected using an FEI QUANTA 650 field emission gun (FEG) scanning electron micro-scope (SEM) at the University of Manchester. Crystal zoning patterns were examined in BSE maps of greyscale intensity profile using ImageJ, since greyscale intensity is a direct proxy for the Fe-Mg ratio in olivine [1]. Zoned crystals either displayed kinked greyscale profiles or curved greyscale profiles. Kinked profiles are indicative of crystal growth whereas curved profiles suggest diffusional smoothing of an initially sharp compositional boundary. A total of 48 olivine crystals from nine thin sections were identified as suitable candidates for Fe-Mg diffusion modelling based on their zonation patterns.

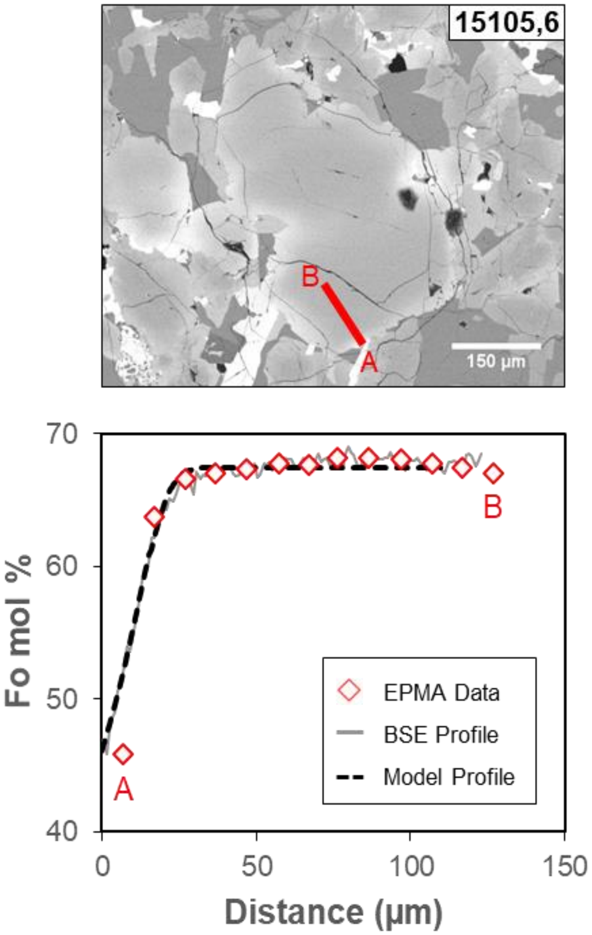

**Figure 1:** A BSE image of an olivine crystal in thin section sample 15105,6. The crystal shows diffusion zoning from a Mg-rich core to an Fe-rich rim. The orientation of the EPMA profile is shown in red. Points A and B in the BSE image correspond to points A and B on the graph showing chemical variation within the crystal as a function of distance from the crystal edge. Diamond symbols represent the EPMA data used to calibrate the greyscale BSE profile (shown in grey). The black dashed line denotes the best-fit diffusion model, corresponding to a diffusion timescale of 1.78 years.

A Cameca SX100 electron microprobe (EPMA) at the University of Bristol was used to measure major elements in line profiles across the zoned olivines. Analyses were performed using a 20 keV accelerating voltage, 20 nA beam current and a spot size of 1µm. Measurements were made perpendicular to the crystal boundary at intervals of between 10 and 20 µm depending on the size of the crystal. Greyscale profiles from BSE maps were than calibrated with the EPMA data to provide a high-resolution proxy for chemical composition [8] (Fig.1).

Iron diffusivity in olivine is strongly anisotropic [9], so we used electron backscatter diffraction (EBSD) at the University of Manchester to determine the crystallographic orientation. Fe-Mg diffusivity is also dependent on temperature and oxygen fugacity. Appropriate values for these variables in the Apollo 15 magmatic system were established using existing literature and software (e.g. MELTS [10,11] and SPICES [12]), and used to calculate appropriate diffusion coefficients. The compositional data collected using BSE/EPMA were then modelled against simulated diffusion profiles [13] to produce diffusion timescale estimates (Fig.1).

**Results:** Of the 48 crystals identified, EPMA and EBSD data were successfully collected for 39 crystals. All olivine crystals displayed normal zoning between the core and rim of the crystal (Fig.1), with no evidence of complex zoning patterns. Olivine core compositions range from $Fo_{71}$ to $Fo_{69}$ in quartz-normative samples and from $Fo_{71}$ to $Fo_{49}$ in olivine-normative samples. Olivine rim compositions range from $Fo_{45}$ to $Fo_{27}$ in quartz-normative samples and from $Fo_{48}$ to $Fo_{15}$ in olivine-normative samples.

Preliminary results suggest diffusion timescales of 0.23-5.98 years for quartz-normative samples and 0.01-4.6 years for olivine-normative samples (Fig.2). For seven out of the nine samples, the average diffusion timescale for olivines within the same sample falls within the range 1.19-2.88 years. The remaining two samples, both from the olivine-normative group, return shorter average timescales of 0.37 and 0.48 years.

**Summary:** Preliminary results suggest diffusion timescales for olivine crystals in quartz-normative samples fall within a similar range as those in olivine-normative samples. This study will provide a greater understanding of the processes during magma storage and eruption of the Apollo 15 mare basalts. Our results may have implications for our understanding of the architecture of lunar magmatic systems, and the rates of magma transfer lunar magmatic processes across the Moon as a whole.

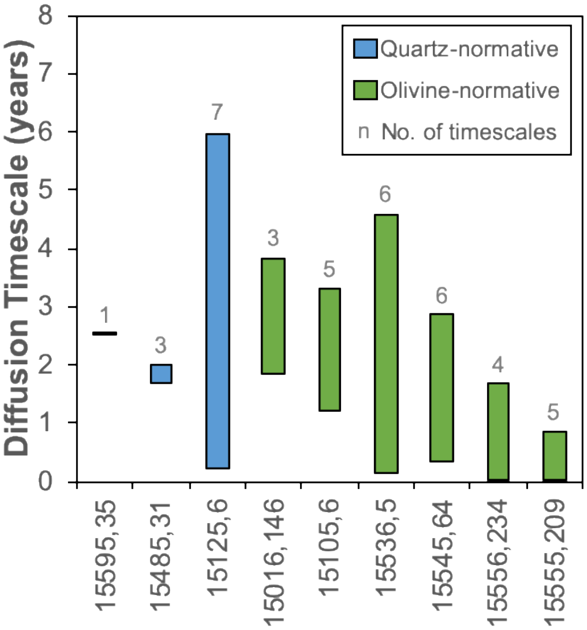

**Figure 2:** A plot showing calculated diffusion timescales for the samples analyzed in this study. Timescales for quartz-normative samples are shown in blue and olivine-normative samples in green. Minimum diffusion timescales for 15556,234 and 15555,209 are 0.02 and 0.01, respectively.

**References:** [1] Costa F. and Morgan D.J. (2010) *Wiley*, 125-159. [2] Costa F. et al. (2010) *Contributions to Mineralogy and Petrology, 159(3)*, 371-387. [3] Neave D.A. et al. (2014) *Journal of Petrology, 55(12)*, 2311-2346. [4] Hartley M.E. et al. (2016) *EPSL, 439*, 58-70. [5] Chappell B. W. and Green D.H. (1973) *EPSL, 18*, 237–246. [6] Rhodes J.M. and Hubbard N.J. (1976) *LSC VII, 2*, 1467-1489. [7] Schnare D.W. et al. (2008) *GCA, 72*, 2556–2572. [8] Martin V.M. et al. (2008) *Science, 321*, 1178. [9] Dohmen R. and Chakraborty S. (2007) *Phys. Chem. Miner., 34*, 409–430. [10] Gualda G.A.R et al. (2012) *Journal of Petrology, 53*, 875-890. [11] Ghiorso M.S. and Gualda G.A.R. (2015) *Contributions to Mineralogy and Petrology, 169*, 53. [12] Davenport J.D. et al (2014) LPSC XLV, Abstract #1111. [13] Allan, A.S.R. et al. (2013) *Contributions to Mineralogy and Petrology, 166*, 143–164.