VOLATILE DISTRIBUTION WITHIN GLASS-RICH FAYALITIC OLIVINE IN LUNAR SAMPLE 15555,246

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Introduction: Lunar volatiles have been extensively studied over the past decade, bringing about several hypotheses to their delivery and overall abundances [1-8]. Studies have shown hydrogen, fluorine and chlorine trapped within olivine-hosted melt inclusions [8] and apatite [2-7]. The timing and method in which these melt inclusions and apatite form can have a critical impact on their volatile abundances. Here we study late-stage fayalitic olivine grains ($Fo_{14}Fa_{86}$) that are peppered with K- and Si-rich glass inclusions and apatite (Fig. 1), that may be the result of late-stage igneous crystallization [12], silicate liquid immiscibility [10-12], or intrusion of granitic liquid [11]. By measuring the distribution of volatile-rich phases within these olivine grains, we may be able to determine through what process they could have formed.

Lunar sample 15555, an olivine-normative basalt, contains a diverse abundance of late-stage lunar igneous mineralogy [9], including abundant granitic melt inclusions which differ significantly from the bulk of the rock. In thin section 15555,246, we looked at one of these areas to observe the distribution of volatiles in glass and apatite trapped within fayalitic olivine (Fig.1). This could be the result of late stage crystallization or due to liquid immiscibility [10-12]. Utilizing new techniques in SCAPS (Stacked CMOS-type Active Pixel Sensor) mapping, we measured the distribution of volatiles throughout this area efficiently, which can allow us to describe their distribution in this late-stage crystallization area.
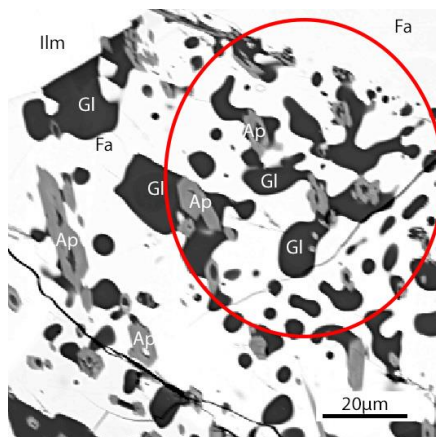
Methods: Ion microscope analysis with SCAPS mapping was conducted utilizing the Cameca ims 1270 with SCAPS detector for 2D ion mapping at Hokkaido University. Volatiles were mapped with SCAPS in a grid of 80 spots (Fig. 2) of 80 µm diameter area each throughout this part of the sample. We measured ion counts of ^1H, ^{19}F, and ^{35}Cl in each area with SCAPS in one overnight session (e.g. Fig. 3). Quantitative element analyses and Kα WDS mapping were conducted on a JEOL JXA-8530F (FEG) 'Hyperprobe' at Yale University.
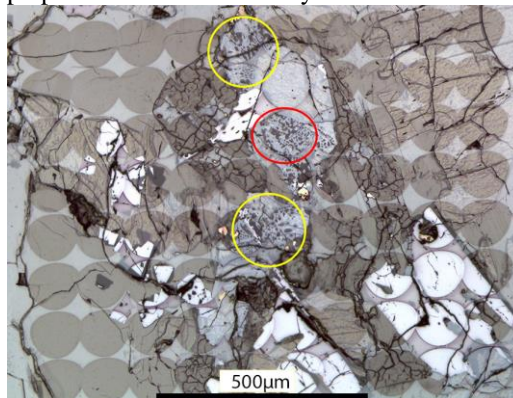

Fig. 2: Reflected light image of 15555,246 displaying the grid of SCAPS mapping. The SCAPS spot shown in Figs. 1 and 3 is encircled in red. Additional similar areas are in yellow.
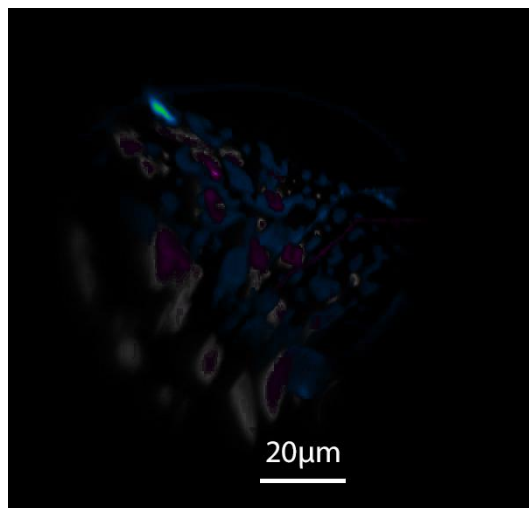

Fig. 1: BSE image of fayalitic grain within lunar sample 15555,246 Gl= Glass, Ap = Apatite, Fa = Fayalitic Olivine, Ilm = ilmenite, circled area is the SCAPS spot shown in Fig 3.

Fig. 3: SCAPS spot showing the distributions of H, Cl and F across the olivine grain in 15555,246, White = F, Purple =Cl, Blue = H
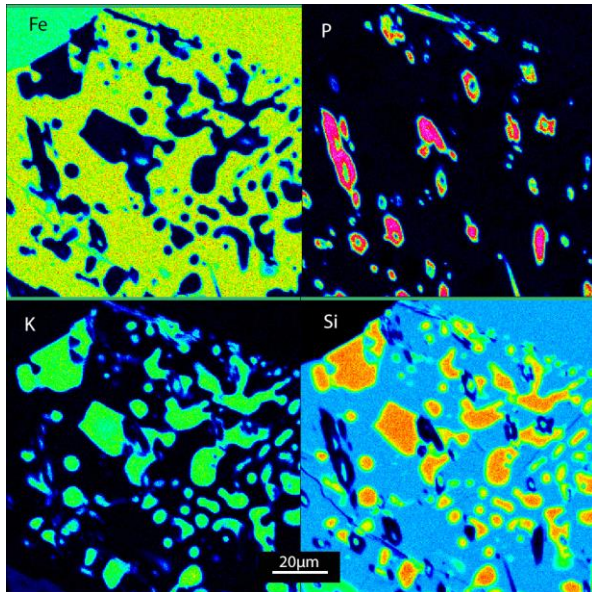
Fig. 4: WDS Kα maps of Fe, P, K and Si of the region in Figs. 1 and 3.

Results: Our analysis of lunar sample 15555,246 yielded a suite of information about the distribution of incompatible and volatile elements. We found that the apatite and glass were fairly homogenous across this studied region. The data from the distribution of volatiles in the region noted in Fig. 1 utilizing SCAPS mapping (Fig. 3), paired with the Kα WDS maps for Fe, P, K, and Si (Fig. 4), allow us to observe that the K-rich glass contains the only detectable H in this region, and apatite the majority of F and Cl. Previous measurements of the OH content of apatite in 15555 have been found to be several thousand ppm [6, 7], suggesting that these glass areas could be very rich in OH. Electron microprobe data was acquired from 14 apatite grains in the 3 circled areas in figure 2 and they contained an average $2.3 \pm 0.4\%$ F and $0.19 \pm 0.06\%$ Cl. This suggests significant missing OH in this apatite from consideration of halogen site occupancy. The larger 4 glass inclusions measured in Fig. 1 had $72.6 \pm 0.8\%$ SiO_2, $11.5 \pm 0.4\%$ Al_2O_3 and $6.7 \pm 0.1\%$ K_2O and $2.1 \pm 0.1\%$ FeO (n=4). These melt inclusions and apatite are trapped within this optically continuous fayalite grain and do not extend beyond its boundaries.

Discussion: Experimental models utilizing varied compositions of lunar samples have suggested the following possibilities to explain this enrichment of volatiles within the apatite and melt inclusions in comparison to the bulk composition of the whole rock: [10-12] 1) This is the result of crystallization of the immiscible liquid at the final stages of crystallization [10-12], 2) The result of late stage crystallization [10-12], or 3) the result of granitic melt insertion to the system [11].

In liquid immiscibility experiments [10,11] the produced high-Si immiscible liquids had similar SiO_2 concentrations, but a much higher FeO and Al_2O_3 concentration than what was observed in the glass areas analyzed here. The K-rich aluminosilicate glasses are surrounded by abundant smaller secondary inclusions and have previously been studied in 15555 [12], and suggests this could be the result of immiscible liquids in the final stages of crystallization. In Roedder's analysis, the onset of immiscibility is marked by inclusion rich areas on otherwise inclusion free pyroxene without SiO_2 variation in melt inclusions. This bears a similarity to what was observed in the olivine in this sample. Neither of the experimental studies on liquid immiscibility included H, F, or Cl in their starting compositions [10, 11]. Our study of this late stage fayalitic olivine grain and its inclusions of apatite and glass show that volatiles played an important role. If this texture is due to liquid immiscibility [10-12], then volatiles need to be considered in future experiments on liquid immiscibility in late-stage lunar melts. Alternatively, this texture is due to late-stage crystallization, and this would predict that other late-stage glasses trapped in minerals could be high in hydrogen.

References: [1] Saal A. E. et al.(2008), Nature, v. 454 ;10 [2] Greenwood, J. P. et al. (2011) Nature Geosci., 4, 79-82, [3] Boyce J. W. et al. (2014), Science, 344:400 [4] Boyce J. W. et al. 2010, Nature 466, 466 [5] McCubbin F. M. et al.(2011) GCA 75; 5073-5093 [6] Greenwood J. P. et al. (2014) LPSC abstract #2707 [7] Tartese R. et al. GCA vol 122, p. 58-74. [8] Hauri E. et al. (2011) Science. doi:10.1126/science.1235142 [9] Chappell B.W. et al. (1972) Science 175, 415-416 [10] Hess P. C. et al (1975) LPSC VI p. 895-909 [11] Rutherford M. J. et al. 1974 LPC V vol 1 569-583 [12] Roedder E. & Weiblen P.W. (1972) LPSC v.3 p. 251