CONSTRAINTS ON THE GEOCHEMICAL VARIATIONS AND EVOLUTION OF THE LUNAR CRUST AND MANTLE AS REVEALED BY FE, MN, CR CONCENTRATIONS IN OLIVINE.

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Introduction: Basaltic volcanism is a fundamental process that has occurred on most terrestrial planets like Earth, Moon, and Mars. As partial melts of planetary interiors, basalts have compositions that reflect the planet's bulk composition, its oxidation state, and the size and composition of its core. Several previous studies have compared bulk-rock major-, minor-, and trace-element compositions of basalts to understand differences among the terrestrial planets [1,2]. Other studies have recognized that minor and major element compositions of silicate phases in basalts reflects the chemical and physical conditions of the melt from which they crystallized, and can be used to differentiate distinct origin and settings [e.g., 3-5]. In particular the Fe/Mn ratios of basalts and their minerals do not change much during basalt genesis and fractionation. Therefore, it is not surprising that this ratio is used to categorize the basaltic source compositions (i.e. mantles) and is used as a discriminant among particular planetary bodies, e.g. Moon vs. Earth vs. Mars [5-7].

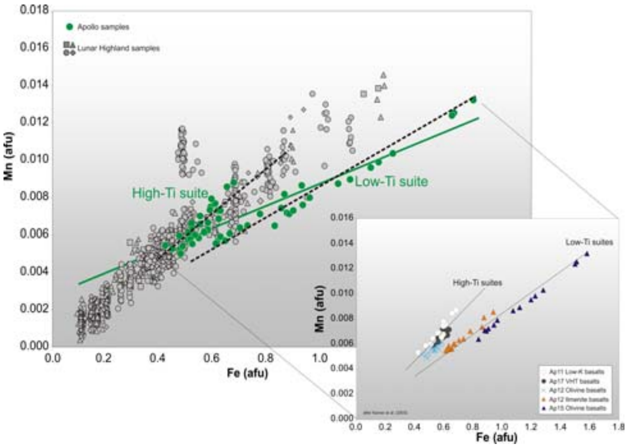

Figure 1: *Mn vs. Fe (afu) for olivine analyses of lunar highland material in ALHA81005 (gray symbols). The green solid line is the lunar trend line suggested by [9], the black dotted lines are from [5].*

However, lunar mafic minerals in fact have extensive variation in their Fe/Mn ratios and appear to fit several different trends, not a single one. Karner [5] noted that olivines in mare basalts fall on two distinct trends (Fig.1 inset), which were averaged by [6] to a single trend (Fig. 1 green solid line).

Here, we use the compositions of olivine in lunar meteorite ALHA81005 (specifically the Fe/Mn and Cr/Fo ratios) to constrain the chemical variation and evolution of the lunar crust and mantle in areas not visited by Apollo or Luna missions.

Sample and Method: Antarctic meteorite Allan Hills A81005 is a polymict, anorthositic regolith breccia from the lunar highlands [8,9] and is thought to come from the far side of the Moon [10,11]. Its clasts include granulites, FAN, mafic clasts, isolated mineral fragments, mare basalts, impact melts, and impact glasses. Clasts in this study were analyzed from the polished thin section ALHA81005,9.

Mineral analyses were performed using an electron microprobe at NASA JSC. Operating conditions: 15kV, 20nA, 1µm beam, and times of 20-40s per element.

Results: In lunar meteorite ALHA 81005, olivines in anorthosites, granulites, mafic clasts, basaltic clasts (low Ti and VLT) and isolated mineral fragments have a Fe/Mn ratios of ~76 to 96 (Fig. 1), similar to high-Ti mare basalts (Fe/Mn ~87; [5]) although they are not rich in Ti. Additionally the olivines seem to have several distinct Fe/Mn ratio trends, not just a random spread, see Figure. 2.

The Cr contents of the olivines seem to be correlated with the Fe/Mn ratio and the Fo-content. Olivine with a higher Fe/Mn ratio (~96) tends to have higher Cr contents then olivine that follow the ~84 trend line (Fig. 3). The basaltic clasts are different, their olivines have the highest Cr content and the lowest Fe/Mn ratio (~76) (Fig. 3).

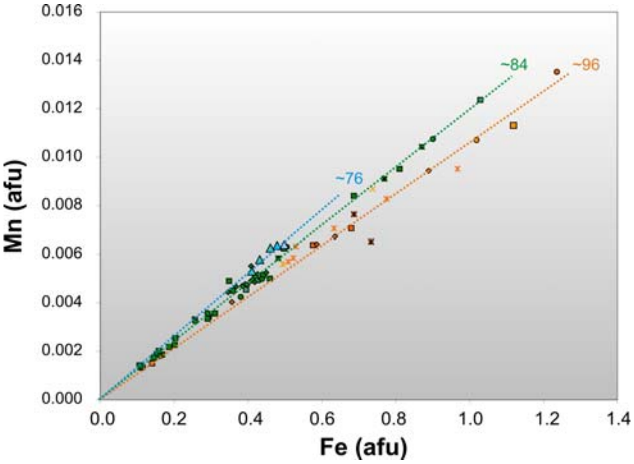

Figure 2: *Mn vs. Fe (afu) for averaged olivine anlayses in ALHA81005. Colors refer to clasts that follow the same trend line (orange ~96; green ~84; blue ~76). Different symbols refer to different clasts.*

Discussion and Implications: Fe^{2+} and Mn^{2+} share the same charge and have a similar ionic radii. During partial melting and crystallization, the fractionation of

Mn^{2+} follows that of Fe^{2+} thus the Fe/Mn ratio should remain approximately constant.

However, terrestrial basalts show a range of Fe/Mn ratios [12], reflecting their complex petrogenetic histories (i.e., fO_2, volatile content, crystallization history). Oddly, minerals in lunar basalts and highland rocks also show a range of Fe/Mn ratios [5,13].

The Fe/Mn ratio can be affected by several factors like the degree of partial melting, the residual mantle mineralogy, and the extent of olivine fractionation or accumulation experienced by the lavas. Given that olivine has a higher Fe/Mn ratio than its equilibrium melt, olivine fractionation from the lunar magma ocean should decrease the Fe/Mn ratio of later magmas, while olivine assimilation should increase the Fe/Mn ratio [14]. Enrichment in Mg-Al spinel in the source region of the samples should also increase the Fe/Mn as would co-crystallization of spinel and olivine from a melt [15]. Recently Mg-Al spinel-rich rocks were reported from the Moon [16,17] and are thought to represent an important new rock type of the lunar crust [16]. Sobolev et al. [18,19] have proposed a terrestrial interpretation involving a 2-stage melting of terrestrial eclogite (garnet pyroxenite) that is expected to yield melts with high Fe/Mn ratio.

Another significant factor that affects the Fe/Mn ratios of silicate phases during crystallization is oxygen fugacity, via it controls on the Fe^{2+}/Fe^{0} ratio. In highly reduced environments (below the IW oxygen fugacity buffer) the low fO_2 leads to low Fe^{2+} concentrations and thus low Fe/Mn in olivine.

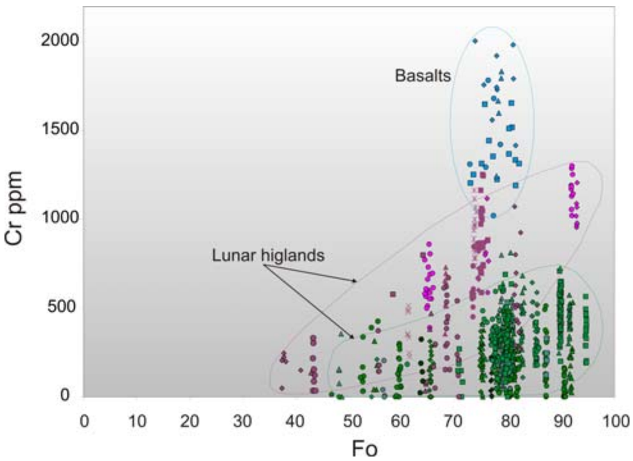

Figure 3: *Cr vs Forsterite (Fo) in olivine from highland materials. The colors refer to different Fe/Mn ratios based on Fig.2. Blue: olivine in basaltic clasts with the lowest Fe/Mn ratio; pink: olivine with the highest Fe/Mn ratio; green: olivine with a intermediate Fe/Mn ratio.*

It may be possible to distinguishing these two causes, crystallization history from changing fO_2 history, by considering fractionation trends of other elements. For example, a lower fO_2 will increase a magma's Cr^{2+}/Cr^{3+} ratio, and that Cr^{2+} can partition in to olivine. Thus (in the absence of chromite fractionation), a lower fO_2 could produce magmatic olivines with reduced Fe/Mn ratios, elevated Cr/Mn ratios, and moderate Cr/Fo ratios ([5], Figs. 2,3).

Changes in the melt composition (due to assimilation or fractionation of olivine) should not drastically affect the Cr-content of olivine. In olivine with a higher Fe/Mn ratio due to melt composition changes, it should therefore remain relatively constant. Co-crystallization and enrichment of Mg-Al spinel in the melt on the other hand should increases the Fe/Mn ratio in olivine but decrease the Cr-content.

Based on these hypotheses it is more likely that the Fe/Mn and Cr/Fo ratio variations within the olivine in ALHA 81005 are due to changes of the oxygen fugacity during crystallization as the Cr-contents in olivine increases with increasing Fe/Mn ratios.

Implications: In spite of the variation of the Fe/Mn and Cr/Fo ratios within ALHA 81005 olivines, one can still make a clear distinction between them and the Apollo low-Ti basalt samples. While the Apollo high-Ti basalts have Fe/Mn ~85, the low Ti basalts have a much higher Fe/Mn of ~ 115 [5]. One possible explanation is that the low-Ti basalts melted from a source mantle that was highly enriched in olivine. Nor can one, at this point, rule out a source region with a slightly higher fO_2. In either case, the source regions of the Apollo 12 and 15 low-Ti basalts must have formed from a source that was geochemically distinct from those behind the rest of the lunar samples [5].

This study emphasizes the complexity of lunar geology and formation history. It is clear that there are significant and subtle differences in a simple geochemical paramater, Fe/Mn, among lunar mare and highland rock types. These variations will provide another tool to help decode the Moon's geochemical history.

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