**Experimental petrology of Apollo 15 Group A ultramafic green glasses: In search of a primordial lunar interior.**
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**Introduction:** The extent of melting experienced by the moon during the lunar magma ocean (LMO) event has remained a topic of discussion since the existence of an LMO was first proposed [1,2]. Initial estimates of lunar magma ocean thickness were on the order of 300 km deep [3] and ranged up to 500 km [4]. Some investigators have suggested that the entire moon was molten and then differentiated [5]. The magma ocean had solidified by 4.2 Ga and mare basalts and lunar ultramafic glasses were produced ~ 0.4 to 1.1 billion years after magma ocean solidification. Since the prevailing view of mare basalts has always been that they are remelts of magma ocean cumulates, a source of heat for this remelting event is required. Depth estimates for the origin of lunar ultramafic glasses [6] are consistent with melt generation near the base of a 500 km deep magma ocean, and some investigators have proposed that the lunar ultramafic glasses are derived from primitive mantle that melted after the magma ocean had solidified [7]. These primitive magmas then assimilated varying amounts of magma ocean cumulates to form the mare basalts and ultramafic glasses.

The Apollo 15 green glasses are one group of ultramafic lunar glasses that may preserve evidence of a melt of undifferentiated lunar material that might have existed beneath the base of the magma ocean. Petrologic studies of the green glasses of Apollo 15 record a complicated history of melt generation and assimilation that extends over a pressure range from >2.4 down to ~1.3 GPa [7]. The depth estimates come from the pressure and temperature of liquidus multiple-saturation with residual mantle phases. This multiple-saturation point is used to infer the pressure and temperature at which the melt was extracted from its residue, and the phases remaining in the residue are assumed to represent the phases on the liquidus under these conditions. Elkins-Tanton et al. [7] concluded that some Apollo 15 green glasses left harzburgitic residues (olivine + low-Ca pyroxene) at shallow depths (The Apollo 15 Group C glasses). However, experiments performed on an Apollo 15A glass composition reported in [8] showed that the multiple saturation point at 2.2 GPa and 1520°C was near the phase boundary for the appearance of garnet (~2.4 GPa at 1520°C). Fig. 1 shows the results of the experiments on the Apollo 15 Group A glass [7]. This glass composition was one reported by Hlava et al. [8] that was published before Delano [6] recognized the compositional heterogeneity that existed in the Apollo 15 green glasses.

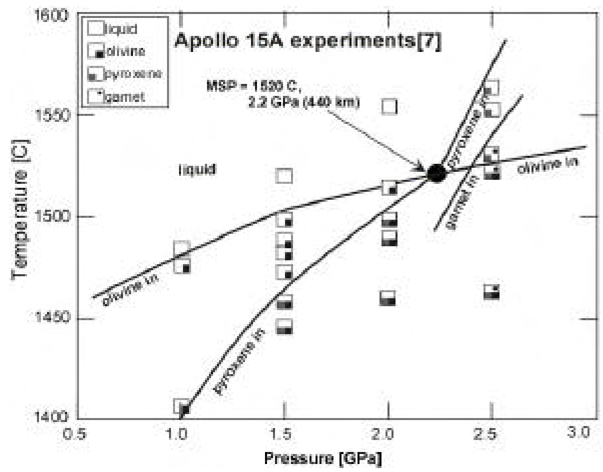

Fig. 1 Experiments on Apollo 15 A glass composition from Elkins-Tanton et al. [7].

**Experimental Petrologic studies of Apollo 15 Group A glasses:** We have reinvestigated the phase equilibria of selected members of this potentially important glass group. We chose a Group A glass from Elkins-Tanton et al. (15A # 57) that defined one extreme of the compositional trend exhibited by the Group A glasses. The glass compositions used in these two previous studies [7,8] are shown in Table 1 along with #57 and another liquid that will be discussed below. Elkins-Tanton et al. concluded that the 15C exhibited chemical characteristics consistent with the assimilation of Lunar Magma Ocean (LMO) cumulates at a pressure of 1.3 GPa. This Group C glass lies at the high MgO extension of the Group C trend and extends back to low $SiO_2$ and high FeO liquids that are likely closer to primordial melts of the lunar mantle that have not seen as much LMO cumulate assimilation. This prompted us to re-examine a 15A composition to determine the minerals present in the residue and depth of multiple saturation. The experiments on this new Group A composition (#57) are summarized in Fig. 2. We hoped that this composition would represent a liquid that had seen less cumulate assimilation than the other 15A glass that was examined by [7]. However, the multiple-saturation assemblage was found to be the same as the Group C glass (olivine + orthopyroxene), at a pressure of ~1.9 GPa. The change in liquid composition from 15A[7] to 15A (#57) served to move the multiple-saturation point further from the garnet stability field that was present in the 15A[7] composition. In hindsight, this change is not unexpected because the #57 liquid composition represents the lower $Al_2O_3$ and lower CaO end of the compositional variations spanned by the Group A glasses. The change in multiple-saturation pressure without a large change in the Mg# suggests that the 15A glasses have also experienced a cumulate assimilation process that involved a cumulate that is more FeO rich, lower in $SiO_2$ and present at greater depths than the cumulate assimilated to form the Group C glass trend.

Table 1. Compositions of Apollo 15 green glasses.

| | 15A[7] | 15C[7] | 15A#57 | 15A* |
|---|---|---|---|---|
| $SiO_2$ | 46.0 | 48.3 | 45.7 | 45.4 |
| $TiO_2$ | 0.43 | 0.23 | 0.39 | 0.35 |
| $Al_2O_3$ | 7.93 | 7.77 | 7.22 | 7.75 |
| $Cr_2O_3$ | 0.46 | 0.55 | 0.54 | 0.51 |
| FeO | 18.9 | 16.1 | 20.0 | 19.9 |
| MgO | 17.6 | 18.3 | 17.4 | 17.2 |
| CaO | 8.49 | 8.53 | 8.38 | 8.55 |

An Apollo 15A liquid with higher CaO and $Al_2O_3$ wt% along with the high FeO wt% of 15A#57 would have been a more appropriate choice for these experiments. We would predict that this composition (15A* in Table 1) is closest to one that represents a primordial melt of undifferentiated lunar mantle. We also predict that this 15A green glass composition will saturate with olivine + orthopyroxene + garnet on its liquidus at a pressure of about 2.5 GPa and a temperature of 1520 $^{o}$C. In other words at a set of conditions similar to those shown for garnet appearance in Figure 1.

So, perhaps we have finally found a lunar ultramafic melt that has experienced only minimal LMO cumulate assimilation. This glass composition may be the closest that we have yet come to finding the garnet signature in lunar ultramafic magmas predicted by Neal [9].

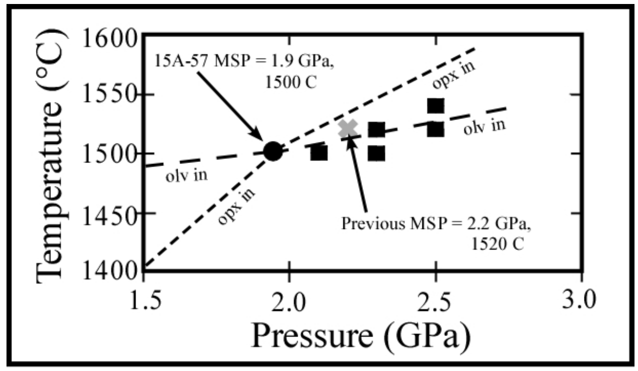


Fig. 2 Results of piston cylinder experiments on Apollo 15 Group A glass #57 are shown as black squares, with the inferred multiple-saturation point shown as the black circle. Also shown is the multiple-saturation points from [7].

**References:**

[1] J.V. Smith et al. (1970) *Proc Apollo 11 Lunar Sci. Conf.*, 897-915. [2] J. A. Wood et al. (1970) *Proc Apollo 11 Lunar Sci. Conf.*, 965-988. [3] S. R. Taylor and P. Jakes (1974) *Proc. Lunar Sci. Conf. 5$^{th}$*, 1287-1305. [4] P. H.Warren (1985) *Annu. Rev. Earth & Planet. Sci.*,13, 201-240. [5] P. C. Hess and E. M. Parmentier (1995) *Earth Planet. Sci. Lett.*, 134, 501-514. [6] J. W. Delano (1986) *Proc. Lunar Sci. Conf. 16th*, D201-D213. [7] L. T. Elkins-Tanton et al. (2003) *Meteoritics & Planet.Sci.*, 38, 515-527. [8] P. Hlava et al. (1973) *Inst. Meteoritics Spec. Publ. 11, Univ. New Mexico*. [9] C. R. Neal (2001) *J. Geophys. Res.*, 106, 27865-27885.