THE ORIGIN OF THE APOLLO 14, 15 AND 17 YELLOW GLASSES

Stephanie M. Brown[1] and Timothy L. Grove[1], [1] Department of Earth, Atmospheric, and Planetary Science, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139 (brownsm@mit.edu, tlgrove@mit.edu)

The yellow glasses collected during Apollo 14, 15, and 17 are of intermediate composition between the low titanium green glasses and the high-titanium black, red and orange glasses (Figure 1). While intermediate, the Apollo 14 yellow glasses have the highest amount of iron ever found in lunar glasses (Figure 2). A previous study [1] used major and trace elements to model the origin of the Apollo 15 yellow-brown glasses. They proposed 3% and 10% partial melting of a hybridized lunar mantle composed of 88 - 95% early cumulates (olivine and orthopyroxene) and 5 - 12% late state cumulates (clinopyroxene, pigeonite, plagioclase, ilmenite, and residual liquid).

Compositional Variability: The yellow volcanic glasses have an extremely interesting suite of compositions, as they show a large degree of compositional heterogeneity which indicates magma mixing prior to eruption (Figures 1 - 3). The variability indicates that there must be at least two compositionally different source regions (and so at least two magmas) for these glasses, one of ultramafic composition (high FeO, high MgO) and one of a more evolved composition (high CaO, high Al_2O_3, high TiO_2).

The trend within the yellow glasses shows MgO enrichment at the expense of FeO, CaO, and Al_2O_3 (Figures 2 and 3), which is consistent with one of the partial melts comprising an ultramafic cumulate source. This is in stark contrast to the 15A green glasses, which show opposite MgO - FeO trends [2]. Additionally, the intermediate titanium composition indicates that another liquid from a late stage cumulate layer that includes plagioclase and ilmenite must be contributing to the yellow glasses.

Rare Earth Elements Europium anomalies (Eu/Eu*), calculated as the measured Europium concentration divided by the expected concentration according to typical REE systematics, are thought to reflect the flotation of plagioclase in the lunar magma ocean, as Europium partitions preferentially into plagioclase but no other mineral. The 14 suite has an Eu/Eu* = 0.47, the 15 suite has an Eu/Eu* = 0.48 and the 17 suite has an Eu/Eu* = 0.79 calculated from data in [4] and using CI chondrite concentrations from [5]. As plagioclase crystallization is

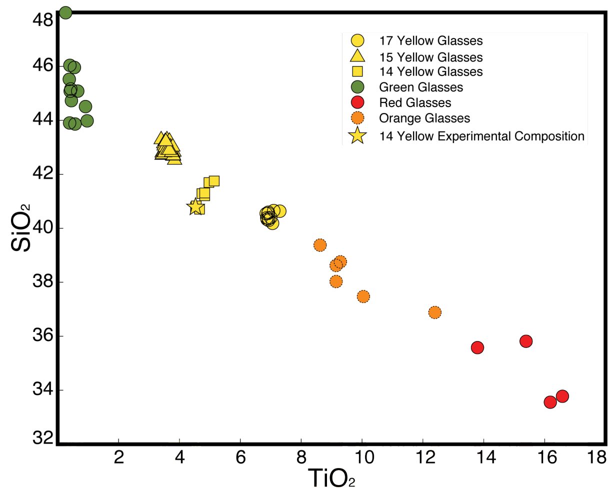

Figure 1: SiO_2 versus TiO_2 of lunar ultramafic volcanic glasses. The yellow glasses are intermediate between high-Ti red and orange glasses and low-Ti green glasses. Data is from [3].

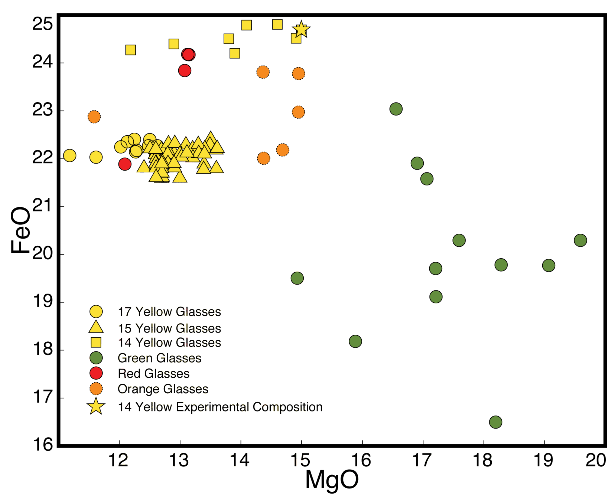

Figure 2: FeO versus MgO of lunar ultramafic volcanic glasses. The yellow glasses are likely nearer to cumulate remelt than the green glasses. The 14 yellow glasses have the most iron of all the glasses. Data is from [3].

suppressed until 78 - 80% of the magma ocean has already solidified [6], at least one cumulate source region of the yellow glasses must be a late cumulate layer that included plagioclase, producing a CaO - Al_2O_3 - TiO_2 rich melt.

Additionally, the 17 yellow glasses have a Europium anomaly that is much smaller than that of the 14 and 15 yellow glasses and may reflect either a slightly different source region that had crystallized plagioclase earlier or a greater influence of plagioclase free cumulates. Interestingly, the general abundances of the rare earth elements are similar in all yellow glasses, but 17 is closer to KREEP than both 14 and 15 as shown in Figure 4.

Some models for the origins of ultramafic glasses call upon melting of hybridized sources consisting of different solid magma ocean cumulate mixtures. The yellow glasses show remarkably different origins and are instead likely derived from magma mixing of at least two melts of cumulate sources.

Preliminary High Pressure Experiments To find the depth of the source region, we are conducting experiments using a 1/2" Boyd-England end-loaded piston cylinder on the most primitive Apollo 14 yellow glass composition [3]. The results are presently preliminary, but the pressure of multiple saturation of olivine, low-Ca pyroxene, spinel and ilmenite in graphite capsules is near 8 kbars, around 200 km deep. If the conditions during melting are more reducing to form these intermediate-Ti liquids, then the multiple saturation point will shift to greater pressures/depths by 80-100 km [7].

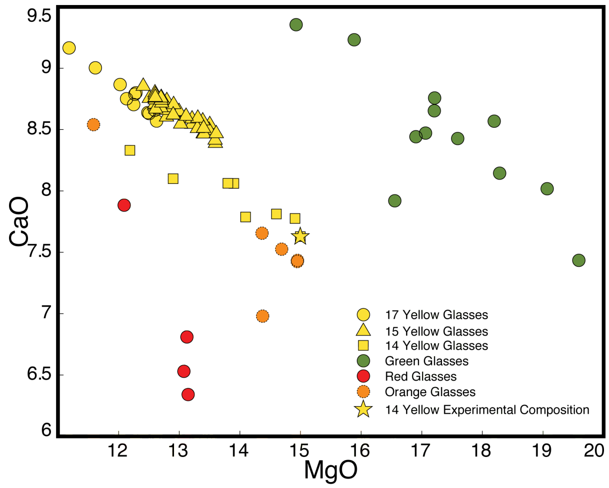

Figure 3: CaO versus MgO of lunar ultramafic volcanic glasses. The yellow glasses are intermediate between the high-Ti red and orange glasses and the low-Ti green glasses. Calcium and magnesium are inversely correlated. Data is from [3].

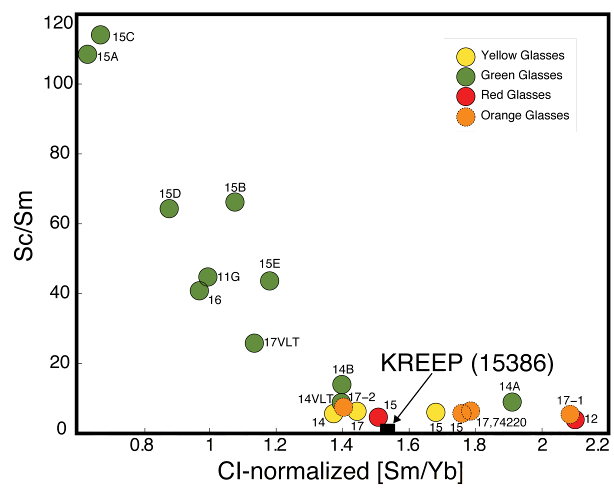

Figure 4: Sc/Sm versus CI - normalized [Sm/Yb] is a measure of KREEP addition to ultramafic glasses [8]. The yellow glasses are much closer to KREEP than most of the green glasses. Data is from [9].

References

[1] S. Hughes, et al. (1988) *Geochimica et Cosmochimica Acta* 52(10):2379 ISSN 00167037 doi.

[2] J. A. Barr, et al. (2013) *Geochimica et Cosmochimica Acta* 1–35 ISSN 00167037 doi.

[3] J. W. Delano (1986) *Journal of Geophysical Research* 91(B4):D201 ISSN 0148-0227 doi.

[4] C. Shearer, et al. (1993) *Geochimica et Cosmochimica Acta* 57(19):4785 ISSN 00167037 doi.

[5] E. Anders, et al. (1989) *Geochimica et Cosmochimica Acta* 53(1):197 ISSN 00167037 doi.

[6] L. T. Elkins-Tanton, et al. (2011) *Earth and Planetary Science Letters* 304(3-4):326 ISSN 0012821X doi.

[7] M. J. Krawczynski, et al. (2012) *Geochimica et Cosmochimica Acta* 79:1 ISSN 00167037 doi.

[8] C. R. Neal (2001) *Journal of Geophysical Research* 106(E11):27865 ISSN 0148-0227 doi.

[9] C. Shearer, et al. (1994) *Geochimica et Cosmochimica Acta* 58(23):5349 ISSN 00167037 doi.