

**Primordial Lunar Mantle Melts and Assimilated Magma Ocean Cumulates: Implications for the Depth of the Lunar Magma Ocean Based on Ultramafic Glass Compositions.** J. A. Barr<sup>1</sup> and T. L. Grove<sup>1</sup>, <sup>1</sup>Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA 02139, USA (jaybarr@mit.edu; tlgrove@mit.edu).

**Introduction** This work attempts to quantify the magmatic processes that led to the compositional variability observed in the enigmatic lunar ultramafic glasses. Our working model is that lunar ultramafic glass magmas are partial melts of primordial lunar mantle [1,2,3] that have assimilated/re-equilibrated with lunar magma ocean (LMO) cumulates. The two primary variables are: 1) the depth and extent of melting of the primordial lunar mantle and 2) the composition of the cumulates that were assimilated.

**Model Approach** We will test a range of models and see which can reconcile both the major and trace element compositional characteristics of the lunar low-Ti ultramafic magmas. We have recently refined a petrologic model that predicts the melt composition in equilibrium with garnet peridotite, which is the expected rock type of the primordial lunar mantle that would be present beneath the base of a magma ocean. We have used experimental data, incorporating experiments carried out on terrestrial mantle compositions, and found them [3] to be inadequate at predicting garnet peridotite saturated melts of lunar affinity (lower Mg# and alkalis than the Earth). In order to improve the garnet peridotite melt prediction model for lunar relevant compositions, we have performed a series of phase equilibrium studies on low-Ti green glasses of Group A, [4].

**Experimental Calibration** The experiments of [1] and [2] on end member compositions from the Group A suite show that olivine and orthopyroxene saturate on the liquidus at ~2.1 GPa, with clinopyroxene joining the crystallization sequence at lower temperatures. Results of [5,6] found garnet in the sub-liquidus phase relations of other Apollo 15 and Apollo 14 ultramafic compositions that were compositionally similar to the Group A glasses. However our results [2] demonstrated the absence of garnet as a saturating phase in the near liquidus phase relations of the Apollo 15 Group A green glasses. In addition to experiments on actual ultramafic glass compositions, [2] performed experiments on analog green glass compositions that had higher Al<sub>2</sub>O<sub>3</sub> wt% and CaO wt%. These compositions saturate with olivine + clinopyroxene + garnet at sub-liquidus conditions, however further crystallization causes the liquids to become critically undersaturated with respect to SiO<sub>2</sub>, moving them away from any possible saturation with orthopyroxene and far

away from the composition of the Group A green glasses.

Further work by [3] combined the experimental composition that saturates with olivine + clinopyroxene + garnet with the green glass compositions, which saturate with olivine + orthopyroxene + clinopyroxene, in order to produce a garnet peridotite assemblage (olivine + orthopyroxene + clinopyroxene + garnet). The combined experimental compositions failed to generate the desired 4-phase saturated liquid. However, the experimental results allowed us to gain an understanding of the phase equilibrium constraints that would generate experimental liquids saturated with a garnet peridotite residue. We found that the addition of 10% orthopyroxene and 10% garnet to the green glass composition yielded two experiments that successfully saturated with all 4 phases at 2.35 GPa. In this study we have produced another 4-phase saturated experiment at 2.6 GPa by adding 10% Fo<sub>81</sub> olivine (composition of the liquidus olivine) to the green glass melt composition.

These three experimental glass + 4-phase saturated experiments have been used to update our previous garnet-peridotite melting model [2]. The new model calibration more faithfully predicts the compositions of melts in equilibrium with garnet-peridotite of a primordial lunar mantle chemistry.

**Garnet in the lunar interior** Studies of Lu-Hf isotopes [7] and trace element compositions [8] of high-Ti mare basalts and ultramafic glasses suggest that garnet was involved in the melting regime for these samples. This suggests that evidence of deep melting in the presence of garnet is also evidence of the existence of primordial lunar mantle. If so, then the melts of this primordial material can be used in conjunction with proposed magma ocean cumulates to develop model depths for the primordial material, and thus the maximum depth of a lunar magma ocean.

**Mineral Phase Equilibrium Constraints on Lunar Magma ocean depth:** Previous work has suggested that the Apollo 15 green glasses have undergone assimilation of LMO cumulates over a pressure range of >2.4 to ~1.3 GPa [5]. Over this pressure range the green glasses have orthopyroxene and olivine as near-liquidus phases, implicating a harzburgite as the assimilated lithology. Lunar magma ocean crystallization models indicate that orthopyroxene begins

to crystallize with olivine at ~40% total solidification [9]. If the cumulate layers remain undisturbed for the full solidification history of a whole-Moon magma ocean, then the residual harzburgite assemblage predicted by the phase equilibria studies of [1,2,5] would be at a maximum depth of ~450 km within the Moon. This corresponds to a pressure of ~2.5 GPa [10], which is near the greatest pressure of olivine + orthopyroxene multiple saturation measured for the Apollo 15 green glasses [5]. When considering non-batch melting processes [e.g. 11], the depth of the olivine + orthopyroxene multiple saturation point would represent an average depth of melt generation, thus requiring harzburgite to exist above and below this level. This precludes the existence of a whole-Moon lunar magma ocean that retained the original stratification.

The work of [12] suggests that the density stratification of the lunar magma ocean cumulates would lead to overturn, a disruption of the layers whereby dense late stage cumulates are taken to depth and early stage cumulates are displaced upward. If this process was active during the mare volcanism period, high pressure multiple saturation with a harzburgite assemblage provides a minimum depth estimate for the lunar magma ocean, if one assumes that the magma ocean cumulates will not flounder beyond the depth of the magma ocean. If the whole moon was not involved in the lunar magma ocean, then primordial lunar mantle would lie beneath the bottom of the magma ocean cumulates. We have used this assumption in our model approach. [12] suggests that the Ti-rich cumulates may have been able to settle out of the lunar magma ocean and sink to form a small lunar core, and if there was primordial lunar mantle still existing in the depths of the Moon then this could have been displaced, causing it to melt. These melts of a primordial mantle could then assimilate small amounts of the downward flowing Ti-rich cumulates, as well as undergo melting in regimes isolated from the cumulates. This is a conceivable method by which mare melts could have been produced, and it also requires the lunar magma ocean to be less than whole moon.

**Primordial Melt + Assimilant Models:** The newly developed melt prediction algorithm allows for the calculation of a melt composition, with a prescribed Mg#, Na<sub>2</sub>O and K<sub>2</sub>O content, that is in chemical equilibrium with a garnet-peridotite mineral assemblage at a chosen pressure. By making assumptions about the bulk composition of the bulk moon, one can model possible primordial lunar mantle melts. These are shown here in the projection scheme of Olivine-Plagioclase-Quartz-Clinopyroxene (Fig 1).

Shown are two preliminary models in which melts of a primordial lunar mantle remelt and assimilate LMO cumulates. Different proportions of primordial melt, assimilant melt, and different compositions of assimilant will determine the final compositions of the melts and thus which of the ultramafic glasses they will most closely resemble. These model may be able to provide insight into the generation of low-Ti and high-Ti volcanics. The possible range of cumulate compositions and proportions will be explored and model depths for the lunar magma ocean will be estimated based on best model fits to the ultramafic glass compositions.

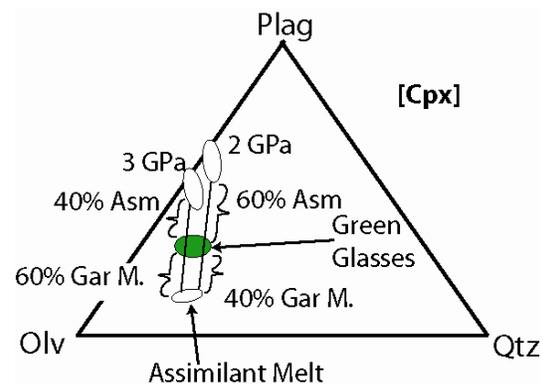


Figure 1. The projection is shown as projected through the Cpx component. The 2 GPa and 3 GPa fields represent the range of primordial melts based on a range in lunar bulk compositions (see [9]). The Assimilant Melt is based on a model of a late stage magma ocean cumulate mixed with early stage cumulate. Proportions of the primordial melt and the assimilant melt are approximated by the lever rule. The field for the Green Glasses is for compositions from [4].

#### References:

- [1] J. A. Barr and T. L. Grove (2007) *Proc. Lunar Sci. Conf 38th*, 1194b.
- [2] J. A. Barr and T. L. Grove (2008) *Proc. Lunar Sci. Conf 39th*, 1213.
- [3] J. A. Barr and T. L. Grove (2009) *Proc. Lunar Sci. Conf 40th*, 2161.
- [4] J. W. Delano (1986) *Proc. Lunar Sci. Conf. 16th*, D201-D213.
- [5] L. T. Elkins-Tanton et al. (2003) *Meteoritics & Planet. Sci.*, 38, 515-527.
- [6] H. K. Chen et al. (1982) *Proc. Lunar Sci. Conf 13th*, A171-A181.
- [7] B. L. Beard et al., (1998) *Geochem. Cosmochem. Acta*, 62, 525-544.
- [8] C. R. Neal (2001) *J. Geophys. Res.*, 106, 27865-27885.
- [9] G. A. Snyder et al., (1992) *Geochem. Cosmochem. Acta*, 56, 3809-3823.
- [10] M. N. Toksoz (1974) *An. Rev. Earth Planet. Sci.*, 2, 151-177.
- [11] J. Longhi (1992) *Proc. Lunar Planet. Sci.* 22, 343-353.
- [12] P. C. Hess and E. M. Parmentier (1995) *Earth Planet. Sci. Lett.*, 134, 501-514.