

SOURCE REGIONS OF THE LUNAR ULTRAMAFIC GLASSES CONSTRAINED BY EXPERIMENTS AND MODELS. S. Brown Krein, M.E. Guenther^{1b}, T. L. Grove^{1c}, ¹Massachusetts Institute of Technology, 77 Massachusetts Ave 54-1210, Cambridge MA 02139, ^abrownsm@mit.edu, ^btlgrove@mit.edu, ^cmegang@mit.edu

Introduction: The compositional variability in 20 suites of lunar ultramafic volcanic glasses is a unique record of the chemical and thermal evolution of the lunar interior [1]. Using these glasses to infer lunar interior evolution requires solving for the secondary magmatic processes that modify primary melt compositions. Previous studies have determined that the within-suite compositional variability of the glasses is secondary and occurs by fractional crystallization perhaps combined with magma mixing/assimilation [e.g., 1–6]. When a glass has experienced significant secondary modification such that it is no longer primary, multiple saturation experiments do not faithfully record the conditions (pressures, temperatures, compositions) of melting [7].

To separate secondary processes from primary processes, we combine results of new melting experiments on potential source regions of these glasses with an inverse petrologic model of their melt modification. This technique solves for secondary magmatic processes to obtain primary composition(s) of all of the ultramafic glasses, which can then be used to infer their true melting conditions.

Conclusion: There are three distinct groups of lunar primary magmas that likely derived from different sources, potentially at different pressures. At least one of these sources (the high TiO₂ source) was a hybridized cumulate. The secondary processes in the ultramafic magmas reflect a small amount of fractional crystallization, redox between FeO in the melt and Na and K in the eruptive gasses (described in [8]), and mixing/assimilation with other ultramafic glasses. Future work will further constrain the melting pressures of these primary magmas, directly by experiments or estimation by thermobarometry [9], as well as link their petrogenesis with the mare and pre-mare basalts.

Experimental Methods: We are conducting high temperature, high pressure piston cylinder experiments on three different synthetic lunar magma ocean cumulates, TR5, TR6, and HyTi1. TR5 and TR6 are pristine ilmenite-bearing cumulates (IBCs) (results presented in [10–11]). TR5 is late stage with an Mg#=36 and TR6 is very-late stage with Mg#=10. HyTi1 is a hybridized cumulate (with Mg#=74) designed to produce a liquid similar to a primary magma component of the highest TiO₂ Apollo 14 black glass. Hybridized cumulates are mixtures of pristine, or melts of pristine, ICBs and early-stage MgO-rich magma ocean cumulates.

Petrologic Model Methods: We set up and solve an inverse problem that models the influence of secondary processes on chemical compositional variability by mass balance. The model is comprised of multiple sub-models that increase in complexity. For each of the 20 glass suites with more than one glass analysis, we find the least complex sub-model that best explains the compositional variability in that suite, which then identifies the primary magma(s) of that suite. The models that we have found to be most relevant, with increasing complexity, include:

1. Low-pressure fractional crystallization of olivine (one primary magma). [1]
2. Model 1 and another liquidus phase, e.g., Cr-spinel (one primary magma). [1,12]
3. Model 2 and a FeO-Na-K redox reaction [8] (one primary magma).
4. Model 3 combined with 2-component mixing (2 primary magmas) that assumes at least one within-suite glass is primary. Components are a within-suite glass and either a glass from another suite (preferably from the same landing site) or an experimentally determined cumulate remelt or KREEP composition. [3–6]
5. Model 3 combined with 2 or 3-component mixing (2 or 3 primary magmas) that assumes no within-suite glass is primary. Components include any glass from another suite (preferably from the same landing site) or any experimentally determined cumulate remelt or KREEP composition. [2,9]

Mixing in our model refers to either simple mixing of magmas or assimilation. The variables in each sub-model are the phases involved and the masses required by each glass bead within the suite. Given the data (a single suite of one or more glass bead compositions) and a single set of end-member phases (as defined by the sub-model), we solve for the masses of each phase by multiple linear regression. We then find the single set of phases for each suite that minimizes the mean compositional distance between the data and the model.

Experimental Results: Our experimental study of melts of relatively pristine late-stage and very late-stage ilmenite-bearing cumulates (IBCs) suggests that they cannot be the source of the high-titanium primary component of the high-titanium Apollo 14 black glasses (~17 wt% TiO₂), even when mixing with other melt compositions is considered. The problem is that melts of pristine late and very late-stage ilmenite-bearing cumulates are too high in CaO and too low in MgO to

match any viable high-TiO₂ end member given by the six models. By contrast, melts of HyTi1 and other hybridized cumulates have appropriate MgO and CaO contents that match the primary component in the highest-titanium black glasses.

Regardless of whether some source regions of the ultramafic glasses are pristine or hybridized, we have found that pressure is important for generating high TiO₂ liquids. The maximum TiO₂ content correlates with ilmenite-out. With increasing pressure in the same bulk composition, ilmenite-out occurs at lower degrees of melting and higher TiO₂ contents.

Model Results: So far, no experimental melt of pristine lunar magma ocean cumulates nor any KREEP component better reproduces the ultramafic glasses than mixing between and within suites. Sixteen of the 20 investigated glass suites are best-explained by Model 4, which identifies 16 unique lunar primary magmas. The four remaining suites (Apollo 14 orange, Apollo 15 green C, Apollo 16 green, and Apollo 17 yellow) are better explained by Model 5. The 16 primary magmas can be grouped into three dominant magmatic classes: Group 1 High-Ti (a high TiO₂ low CaO+Al₂O₃ ultramafic magma), Group 2 green glass (a low TiO₂ low CaO+Al₂O₃ ultramafic magma), and Group 3 Very Low Titanium or VLT (a high CaO+Al₂O₃, low TiO₂ ultramafic magma). Future experiments may revise the absolute number of unique primary magmas; however, these three groups are robust.

These three groups of primary magma are related to the three cumulate sources that have previously been invoked by different studies as required for the ultramafic glasses and include, respectively, (1) a high-Ti source, (2) an ultramafic (olivine + pyroxene) source, and (3) a KREEP component. In previous models, the KREEP component was poorly constrained but was needed to explain the low TiO₂ and higher CaO features of the ultramafic glasses. Our model results have clarified that this required KREEP component is compositionally similar to the VLT glasses. In addition, these two low-Ti components are akin to the two compositional arrays discussed in [1] that project to higher and lower Al₂O₃ contents at given TiO₂, MgO and FeO contents. In addition, here we find that at least one of these groups (Group 1 High-Ti) must be derived from a hybridized source.

FeO-Na-K Redox Reaction. As in [8], we find that there is a critical redox reaction during eruption between Fe²⁺ in the ultramafic melt and the Na and K in a highly reduced gas phase ($2\text{FeO}_{\text{melt}} + 2\text{Na}_{\text{gas}} + 2\text{K}_{\text{gas}} \rightarrow 2\text{Fe}_{\text{metal}} + \text{Na}_2\text{O}_{\text{melt}} + \text{K}_2\text{O}_{\text{melt}}$). This redox reaction is needed to explain the high Na₂O and K₂O contents in some lunar glasses that reach concentrations greater than 3–4 wt%

with a correlated reduction of FeO in the melt and an accumulation of Fe metal in the glass beads [8].

Group 1 Hi-Ti primary magmas: This group is best illustrated by the Apollo 14 black glass, which contains the highest TiO₂ contents and some of the most complicated compositional variability of the glass suites. Our models and experiments suggest that the High-Ti primary magma of the suite formed at high pressures by melting of a hybridized source. The secondary chemical trends suggest mixing from 0–45% by mass with an Apollo 14 orange-like glass as well as a strong influence (up to 6% by mass) of the FeO-Na-K redox reaction during eruption. The orange glass component is needed to explain an increase in Al₂O₃ at slightly lower TiO₂ contents in some of the black glasses. The Apollo 14 orange glasses are themselves best explained by mixing between Apollo 14 VLT glass and (different) Apollo 14 black glass. Thus, ultimately the Apollo 14 black glass is really a multi-stage mixture of Group 1 HiTi primary melt and Group 3 VLT primary melt, with little or no direct contribution from the Group 2 Green Glass primary melts. However, it is still unclear if the hybridization process that generated the source region of Group 1 also involved a Group 3 VLT melt or a Group 2 Green Glass melt. Multiple saturation experiments independently suggest melting pressures from 2.2–4 GPa [12–13]; the pressure depends on *f*O₂ of the glass during melting [e.g., 13].

Group 2 Green Glass Primary Magma: Multiple saturation experiments on this group of primary magmas suggests an olivine + orthopyroxene residue that melted at ~2.5 GPa [5].

Group 3 VLT Primary Magma: This primary magma class actually has more TiO₂ than Group 2 and is distinct from Group 2 by having higher CaO and Al₂O₃. Multiple saturation experiments on Apollo 14 and 17 VLT glasses suggests an olivine + pigeonite residue that melted at ~2.0 GPa [14].

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