PRIMARY AND SECONDARY MAGMATIC PROCESSES INVOLVED IN THE PRODUCTION OF LUNAR HIGH-TITANIUM ULTRAMAFIC GLASSES.

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Introduction: Formed during high-temperature, explosive fire fountain eruptions, the lunar mare glasses provide insight into the evolution of the lunar interior. They are highly ultramafic, with a combined FeO + MgO content of 35 to 40 wt.%, with highly variable TiO_2 contents that ranges from 0.2 to 16.4 wt. % [1]. The 25 suites of ultramafic glasses cluster in distinct groups of TiO_2 content. Within each of these suites, the glasses show compositional variability. (Fig. 1)
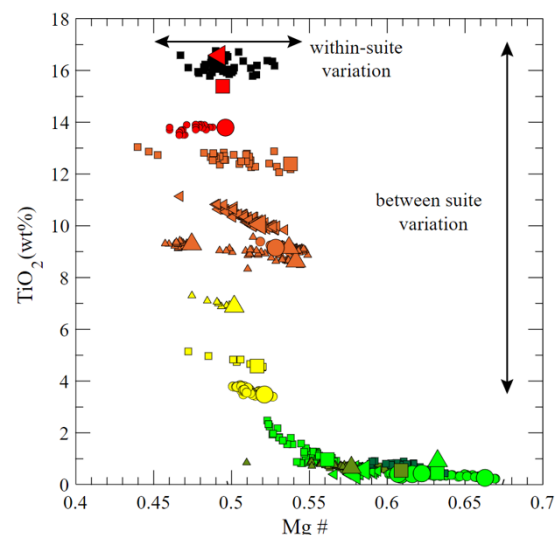

Fig. 1. Compositional variability demonstrated in the 25 ultramafic glass suites.

Several studies have attributed this between-suite and/or within-suite compositional variability to the secondary process of fractional crystallization, perhaps combined with mixing of magmas produced from two or more source regions [e.g., 2-7]. However, neither models of fractional crystallization nor the mixing of magmas from different pristine cumulate source regions can reproduce the variation seen in the high-titanium glass suites [8].

The suite with the highest TiO_2 contents and most complex compositional variability is the Apollo 14 Black glass (A14B, 16.4 wt. %). From the results of models and several experiments, [8] proposed that the high-titanium glass suites are produced by a primary magma formed through the melting of a hybridized cumulate at high pressures. This hybridization occurred through lunar mantle overturn, whereby material from various source regions were relocated to a giv-

en depth and combined. Secondary chemical trends can be explained by a small amount of fractional crystallization, mixing/assimilation with other ultramafic glasses, and a redox reaction between FeO in the melt and Na and K in the eruptive gasses (described in [9]).

To further support our understanding of the primary and secondary processes involved in producing the high-titanium glasses, as well as the pressure of melting for the primary magmas, we conduct experiments on potential hybridized cumulate source compositions and apply results from an inverse petrological model to account for secondary melt modification processes.

Methods: We are conducting high-temperature, high-pressure experiments in a 0.5" piston cylinder device [10] on synthetic compositions of lunar magma ocean cumulates.

To investigate the source of the high-titanium glasses, we use a hybridized cumulate composition, designed to produce a liquid similar to a primary magma component of A14B. To calculate a viable starting material, which we call HyTi1, we use the batch melting equation (Eq. 1) to solve for each element in the erupted A14B glass. We assume a 30% degree of melting (F) and use mineral/melt partition coefficients (D) from A14B multiple saturation experiments (60% opx, 40% ol). The calculated HyTi1 composition has an Mg# = 74.

$$C_{source} = D \cdot C_{melt} \cdot (1-F) + C_{melt} \cdot F \qquad (1)$$

We have performed melting experiments on the HyTi1 composition over a range of pressures (1-2.5 GPa). Experimental containers are graphite capsules, which impose an fO_2 ($\Delta IW=1.5$) expected for the source region of A14B [11].

To solve for the influence of secondary processes on chemical compositional variation, we utilize the models as described in [8].

Results: Melting experiments were carried out around the temperature of spinel disappearance, because that is where the maximum TiO_2 content will occur at each pressure. Melts were also saturated with olivine and orthopyroxene. At 1 GPa, the maximum TiO_2 content at the temperature of spinel disappearance is 10.3 wt.%, which is lower than the TiO_2 content of the A14B glass. At 1.5 and 2 GPa TiO_2 contents reach maximum values of 18.8 wt.%, and at 2.5 GPa the TiO_2 content is 16.3 wt. %.

Our experimental results show that melts of the hybridized cumulate composition HyTi1 have TiO_2, MgO, and CaO contents that closely match the primary component in the A14B glass (Fig. 2, 3). We find that TiO_2 content is pressure dependent and that high pressures are essential for generating these high-Ti liquids. We find that our melting experiments at pressures of 1.5-2 GPa best match the A14B composition. This is in line with the pressures predicted from multiple saturation experiments on the A14B composition (~1.7 GPa).

Conclusions: The primary magma of the high-Ti glasses originated from a hybridized cumulate source. Experiments on pristine late-stage and very late-stage cumulates (Cumu-TiCum, Cumu-TR5, Cumu-TR6) [12, 13] suggest that they cannot be the source for the primary magma component of A14B. These melts have lower Mg#s, low MgO and high CaO compared to the high TiO_2 ultramafic glasses and therefore cannot produce these high-Ti liquids (Fig. 2, Fig. 3). In contrast, calculated hybridized cumulate compositions including HyTi1 as well as those in other studies [14] have very high Mg#s and produce liquids that are much better fits. Further work is being conducted to understand the secondary processes (e.g., fractional crystallization, mixing/assimilation with other ultramafic glasses, redox reaction) that may have further altered the primary magmas to produce the erupted compositions of the high-TiO_2 ultramafic glasses.
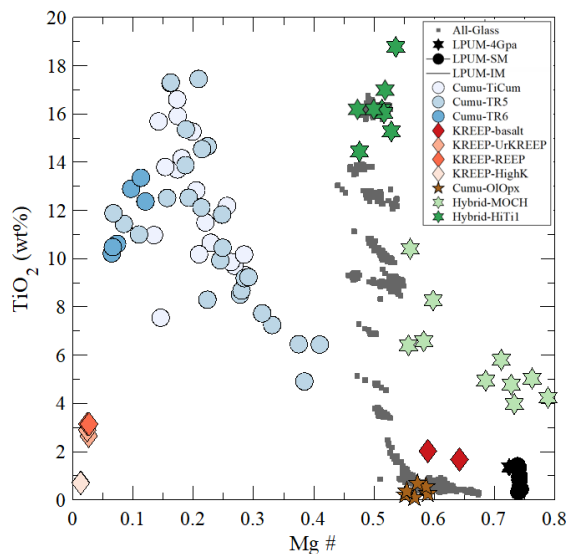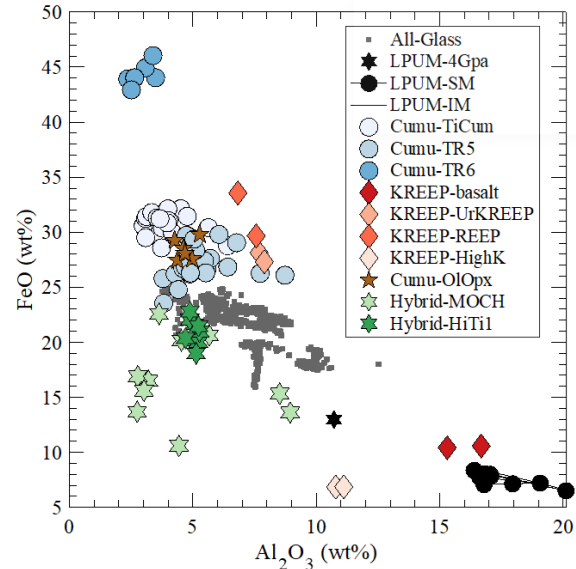

Fig. 3. FeO vs. Al_2O_3 content of liquid from melting experiments of various compositions overlain on all lunar ultramafic glass compositions.

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Fig. 2. TiO_2 content vs. Mg# of glass from melting experiments of various compositions overlain on all lunar ultramafic glass compositions.