

**ORIGIN OF THE HIGH-TITANIUM LUNAR GLASSES: CONSTRAINTS FROM CUMULATE REMELTING EXPERIMENTS.** H.F. Brodsky<sup>1</sup>, S.M. Brown<sup>2</sup>, T.L. Grove<sup>2</sup>, <sup>1</sup>Northeastern University, 360 Huntington Ave., Boston, MA., (Brodsky.H@husky.neu.edu), <sup>2</sup>Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA.

**Introduction:** The lunar ultramafic glasses returned by the Apollo missions vary in TiO<sub>2</sub> from 0.2 – 16.4 wt.% and are categorized into 25 suites of glass that display both between- and within-suite compositional variability [1]. The extreme compositions of these glasses require a cumulate mantle source; however, the melting of any single cumulate layer expected from the crystallization of the lunar magma ocean [e.g., 2] has consistently failed to reproduce their variability either between- or within-suite [e.g., 3,4,5,6,7,8]. This is also consistent with the observation that none of the high Ti-glasses are multiply saturated with a titanium-bearing phase [5].

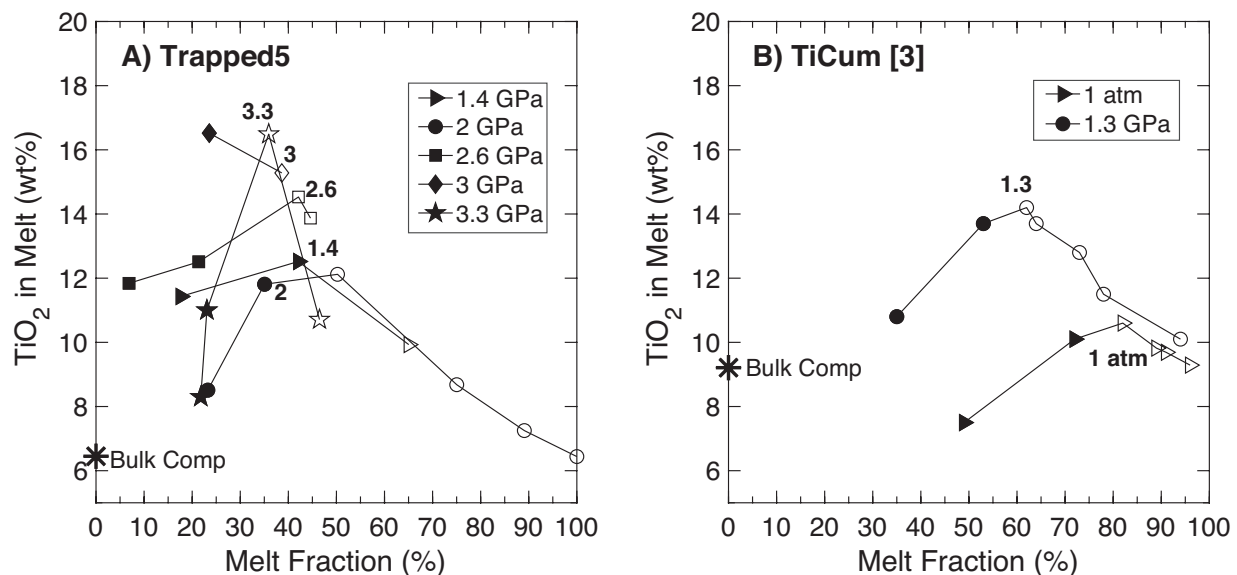
Instead of a single cumulate remelting, mixing melts from distinct cumulate source regions combined with fractional crystallization successfully explains the within-suite and between-suite variability of the glasses [5]. The data require that the cumulate sources of the component magmas must be: (1) an early olivine and orthopyroxene cumulate, (2) an ilmenite-bearing clinopyroxene layer and (3) a KREEP component [5].

To further constrain ultramafic glass petrogenesis, we need to first constrain the systematics of cumulate

remelting, especially that of the ilmenite-bearing clinopyroxene cumulate. Thus, we present the results of a new series of high-pressure, high-temperature cumulate remelting experiments on two proposed high-titanium, ilmenite-bearing clinopyroxene layers.

**Starting Materials:** We derived two cumulate compositions using [8], Trapped5 and Trapped6. Trapped5 is a late stage cumulate with 78% clinopyroxene, 11% ilmenite, 5% trapped plagioclase, 1% trapped silica, and 5% trapped melt with an Mg# of 0.34, which would be in equilibrium with a lunar magma ocean liquid with an Mg# of 0.10. Trapped6 is a very late stage cumulate with 37% olivine, 30% clinopyroxene, 22% ilmenite, 5% trapped plagioclase, 1% trapped silica, and 5% trapped melt with an extremely low Mg# of 0.12, which would be in equilibrium with a lunar magma ocean liquid with an Mg# of 0.05.

**Experimental Methods:** Remelting experiments were conducted on ½" Boyd-England piston-cylinders at MIT in graphite capsules ( $f_{O_2} = IW + 2$ ) at pressures from 1.4 - 3.3 GPa and temperatures of 1180° - 1460° C. We will conduct more experiments up to 4 GPa.



**Fig. 1.** TiO<sub>2</sub> concentration in cumulate remelts as a function of melt fraction by pressure in GPa for Trapped5 (this study) in panel A) and TiCum [3] in panel B). Experiments in which ilmenite are present are represented by filled markers. The TiO<sub>2</sub> concentration of the starting composition is shown as an asterisk at 0% melt. The concentration of TiO<sub>2</sub> is maximized near the point where ilmenite is exhausted. This concentration trends upwards as pressure increases. The highest concentration was 16.5 wt% in a 3.3 GPa experiment at a melt fraction of 23.06%.

**Results and Discussion:** Very late-stage cumulates such as Trapped 6 are not likely to be involved in the production of the lunar glasses. Increasing the amount of ilmenite in the source does not result in significantly higher  $\text{TiO}_2$  contents, and instead introduces more problems by making melts too low in CaO and MgO and too rich in FeO to be mixing end-members that can reproduce any of the erupted compositions. Trapped5 and TiCum [3] do have melt compositions that can explain at least some of the ultramafic glasses, but more experiments will be necessary to explain all glasses.

All cumulate starting compositions, including TiCum from [3], show that at a given pressure, the temperature at which ilmenite is exhausted coincides with the maximum liquid  $\text{TiO}_2$  content of all experiments at that pressure (Fig. 1). At higher pressures, this point occurs at temperatures corresponding to lower melt fractions (Fig. 1). In addition, there is a correlation between the maximum  $\text{TiO}_2$  content in the liquid and the pressure of the experiments (Fig. 1).

The highest concentration of  $\text{TiO}_2$  found in the lunar glasses is ~16wt.% [1]. If the high-titanium glasses are mixtures, then the high- $\text{TiO}_2$  mixing end-member must have more  $\text{TiO}_2$  in the liquid than the glass itself. Only experiments at pressures greater than 3 GPa were able to produce liquids with this amount of  $\text{TiO}_2$ . The highest  $\text{TiO}_2$  concentration was achieved at 3.3 GPa (~800 km deep), which suggests that, at least for the highest  $\text{TiO}_2$  rich glasses (the Apollo 12 red and the Apollo 14 black), 3.3 GPa is the minimum depth of melting of the ilmenite-bearing source. However, in this particular case, the proportion of the high-Ti end-member in the mixed magma would approach 100%, which is inconsistent with the other major elements of the high-titanium glasses. For example, the Apollo 12 red glass has 13.0 wt.% MgO, 23.9 wt.% FeO and 33.4 wt.%  $\text{SiO}_2$  [1] while experimental liquids with 16.5 wt.%  $\text{TiO}_2$  have 3.56 wt.% MgO and 28.86 wt.% FeO. Thus, depths of melting of greater than 800 km are required to generate the necessary high  $\text{TiO}_2$ -melt compositions.

The constraints on the depth of melting imposed by these results require that the gravitationally unstable, initially shallow, ilmenite-bearing layer overturn and melt at high pressures, in agreement with previous studies [9,12]. Overturn of ilmenite-bearing cumulates is highly efficient [12], and so Trapped6 should have also overturned. If it melted, its extremely high-FeO melts must have been too dense to erupt compared to the other ilmenite bearing cumulates.

**References:** [1] Delano, J. W. (1986) *JGR: Sol. Earth* 91, 201-213. [2] Snyder, G. A. et al. (1992) *GCA*

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