Resolving the origin of lunar high-Ti basalts by petrologic experiments

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The origin of the most primitive, picritic lunar basalts, sampled as pyroclastic glass beads in the lunar soils [1,2], remains poorly constrained. Especially the petrogenesis of high-Ti glasses ($TiO_2 > 6$ wt%) seems enigmatic. Three hypotheses have been proposed for the origin of these exotic samples: I) Ascent of a primary, undifferentiated melt from the lunar interior and assimilation of clinopyroxene and ilmenite in the upper section of the not overturned lunar mantle [3]. II) Melting of a hybridized lunar mantle after lunar mantel overturn [4,5]. III) Reaction of sunken low-degree high-density melts of the hybrid magma ocean source with high Mg-cumulates in the deep interior of the lunar mantle and subsequent ascent [5,6,7]. This study re-investigates hypothesis II with the aim to assess whether a one stage melting process of a heterogeneous lunar mantle can cause the compositional variabilities of lunar (high-Ti) picritic glasses. Specifically, the effect of modal mineralogy of different cumulate layers in the hybrid lunar mantle is investigated.

The overturn of the lunar mantle stratification due to Rayleigh-Taylor instabilities will have caused the so-called "Ilmenite-bearing cumulate (IBC)" to sink into the underlying harzburgite lunar mantle [7]. Therefore, an IB cumulate and a harzburgite cumulate appear to be the major components of a hybrid lunar mantle [7]. In this study, the first batch of starting material compositions was mixed similar to [5] using a fixed composition the harzburgite mantle. An IBC was designed by mixing ilmenite, clinopyroxene, and small amounts of plagioclase. These minerals are the basic components of the bulk lunar mantle after cumulate overturn [2]. We investigated how the ilm/cpx ratio within an IBC will affect the melt compositions and melting conditions. A such, we assumed that modal proportions of crystallization were not preserved in the cumulate [e.g., 5,9]. In a second batch of experiments, we slightly adjusted olivine and orthopyroxene ratios in the harzburgite layer. A third component of a hybrid lunar mantle in some of our starting material composition was an urKREEP component [10], which has been proposed to participate in the overturn and melting process [7,11].

To investigate the composition and modal amounts of partial melts from several different starting materials, we conducted high-pressure and high-temperature experiments in an endloaded Piston cylinder apparatus at the University of Münster. Most runs were conducted at a pressure of 1.5 GPa, which corresponds to the lower end of the depth range suggested for the source depth of high-Ti lunar picritic basalts [6]. Run temperatures were varied between 1300 and 1450 °C to investigate the effect of changing melting degree on melt compositions [3]. In order to control fO_2 and to minimize Fe-loss in the runs, we used graphite-lined Pt capsules [3,4]. The characterization of experimental runs was conducted by the means of scanning electron microscopy (SEM) and energy

dispersive x-ray spectroscopy (EDS). Mineral and melt proportions were determined via mass balance calculations using the major element chemistry of the phases present in each experiment.

All experiments contain glass and forsteritic olivine. Some experiments contain olivine and orthopyroxene. The degree of partial melting (F_{melt}) is 0.18–0.75. The experiments that contain both olivine and orthopyroxene were run at lower temperatures (< 1400 °C) and low degrees of partial melting (F_{melt} < 0.5).
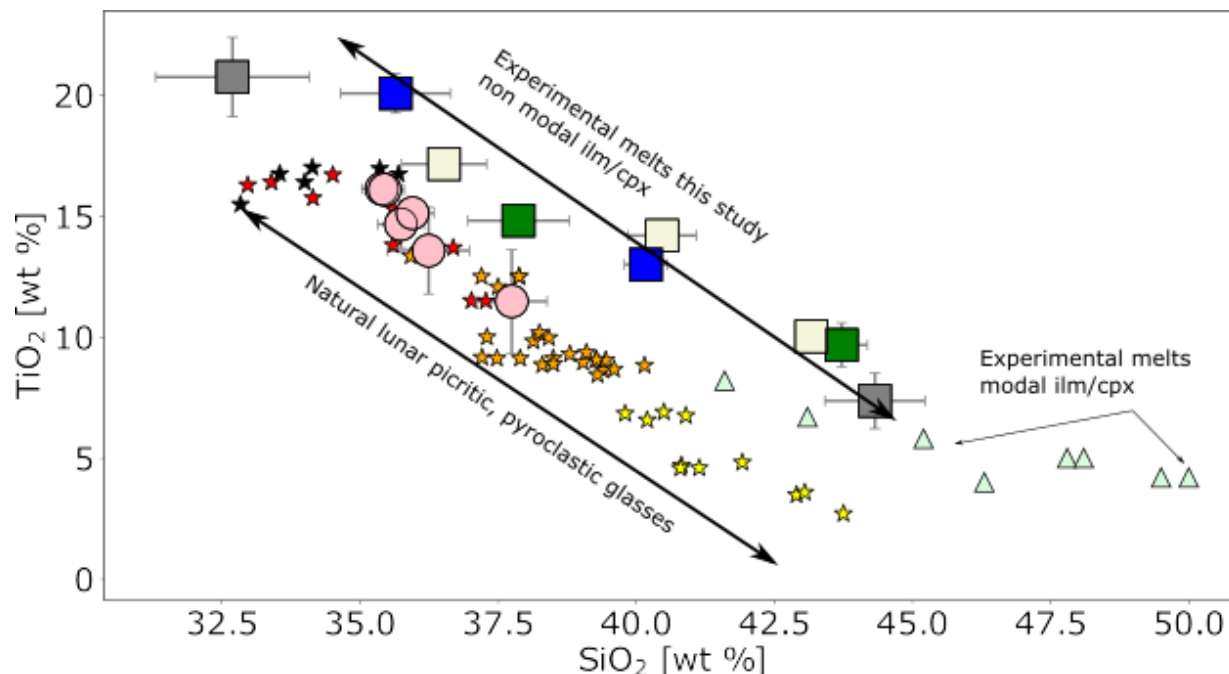

Figure 1: SiO$_2$ vs. TiO$_2$ of lunar Apollo picritic glasses (yellow, orange, red, black – colored accordingly) from [8,9] and our experimental melts (squares and circles). Indivudual symbols correspond to different starting material compositions.Triangles correspond to melting experiments of a hybrid lunar mantle with modal ilm/cpx from fractional crystallization experiments [5]

Comparing the composition of experimental melts and natural lunar picritic glasses (Fig. 1), it can be stated that the melting of a heterogeneous lunar mantle produced by the overturn of lunar stratification after the solidification of the lunar magma ocean can generate melts in the range similar high-Ti picritic melts. Experimental temperatures and pressures agree with the temperatures and depth of origin predicted by previous experimental studies [3,5]. A partial melting process of a cumulate-bearing mantle, as modeled by our experiments, is shown to be a viable and simple alternative to the currently accepted complex melting model [5,6]. In our experimental setup, a ratio of ilm/cpx of 1/1 or 4/1 in the IBC layer reproduces high-Ti compositions, similar to the picritic lunar basalts. Good matches are achieved in runs with lower temperatures, which correspond to the comparably lower degree of melting.

The most suitable ol/opx is 3/2. We further find that, following the constraints of [12], some plagioclase has to be entrained in the IBC layer, in order to reproduce Al$_2$O$_3$/CaO in the cumulate mantle melting experiments. Additionally, the presence of urKREEP in the cumulates strongly influences Al$_2$O$_3$/CaO, driving it too high in melts originating from cumulates containing that component.

In the light of our experiments, it is possible to shed some new light on the origin of exotic lunar basalt samples, such as the picritic, high-Ti lunar basalts. We explored the feasibility of a simple melting process of a hybrid lunar mantle after overturn.

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