Ilmenite Solubility In Lunar Basalts As A Function Of Temperature And Pressure: Implications For Petrogenesis. A. R. Beck and P. C. Hess, Department of Geological Sciences, Brown University 324 Brook St. Providence, RI 02906. Alyssa_Beck@Brown.edu, Paul_Hess@Brown.edu

Introduction:

The picritic glasses are among the most primitive lunar basaltic liquids, and thus most useful in constraining the depth and composition of their source region [1-3] despite having undergone a certain degree of shallow level olivine crystallization. The bulk of the lunar volcanic glass suite can be modeled as the partial melting products of an olivine + orthopyroxene source region deep within the lunar mantle [3-7]. TiO$_2$ contents vary from 0.2 wt % - 17.01 wt%. Values that extreme would seem to require a Ti-bearing phase such as ilmenite in the source of the high-Ti (but not in the VLT source). A source region of primitive LMO olivine and orthopyroxene, even when melted in small degrees cannot account for these compositions. The picritic glasses are undersaturated with respect to ilmenite at all pressures investigated therefore ilmenite must have been consumed during melting, leaving an ilmenite free residue and an undersaturated melt.

Multisaturation pressures for the glasses potentially represent the last depths at which the liquids equilibrated with a harzburgite residue before ascending to the surface. These occur at great depths within the lunar mantle. Because the liquids have suffered some amount of crystal fractionation, this is at best a minimum depth. If the melts are mixtures, then it is only an average depth of melting [4]. Multisaturation is still a strong constraint on source mineralogy, revealing that the generation of the lunar basalts was dominated by melting of olivine and orthopyroxene.

Hess and Parmentier [8] argued that the late stage ilmenite cumulate layer created during LMO crystallization was gravitationally unstable and would sink into the mantle, moving heat producing elements and ilmenite + clinopyroxene to great depths. Others argue that overturn is impossible due to viscosity constraints [9] though if melts could be generated from the ilmenite layer, they may sink into the mantle.

In order to better understand the nature of melts derived from the phase assemblage of olivine + orthopyroxene + ilmenite, this study investigates the composition and pressure-temperature stability of lunar basaltic liquids which are saturated with ilmenite.

Experimental Procedure:

We performed a series of piston cylinder experiments in which ilmenite was dissolved into a high Ti synthetic red glass [1] to the point at which the glass reached ilmenite saturation. The experimental charges were constructed as dissolution couples: a layer of glass was placed on top of synthetic ilmenite powder in a graphite capsule. The charges were annealed at 1100°C and then brought to final run temperatures, held for 0.5 – 8 hours and quenched. The experiments were performed over a pressure range of 1 – 2.5 GPa, and temperatures varied from 1215°C – 1475°C. Run products included glass, ilmenite, Cr-ulvospinel and olivine and were analyzed with a Cameca microprobe.

Figure 1. The TiO$_2$ content of ilmenite saturated glasses as a function of temperature. Dashed lines are linear regressions: blue is 1.0 GPa data, black is 1.5 GPa and red is 2.0 GPa. Each data point is an average value over an experimental charge. Error bars represent one standard deviation from the average.

Results:

All charges were cut in half lengthwise, and concentration profiles were measured in the glasses. Charges that had uniform oxide component profiles in the melt (from the boundary with ilmenite to the end of the capsule) were interpreted to have reached equilibrium and become fully saturated with ilmenite.

Ilmenite solubility in basalt (represented by the TiO$_2$ content of the saturated glass) is a function of temperature and pressure. Figure 1 shows the TiO$_2$ content in the liquid (and ilmenite solubility) increasing linearly with temperature and decreasing with increasing pressure. Temperature dependence is strong, for example, at 1.0 GPa the TiO$_2$ content...
increases from 14.1 wt% at 1250°C to 26.47 wt% at 1350°C, a 0.12 wt%/°C. This agrees with previously reported values from [10]. The pressure effect on solubility is -6.7 wt%/GPa. Figure 2 shows ilmenite saturation as a function of both temperature and pressure. Dashed lines are contours representing constant TiO₂ in a liquid in equilibrium with ilmenite. The dT/dP slopes of the saturation surfaces are 67°C/GPa. If the high Ti lunar picritic glasses began as partial melts in equilibrium with olivine + orthopyroxene + ilmenite (± clinopyroxene ± garnet) then this saturation data provides insight into the composition, density and viscosity of the melts during the initial stages of melting, prior to consumption of ilmenite. We can also constrain the composition of the melts at multisaturation pressures and temperatures. and also the degree to which to the high Ti picritic glasses have been diluted with ilmenite-free liquids. For example, the Apollo 15 red glass multisaturation point is 1450°C and 2.45 GPa [1]; at these conditions a liquid in equilibrium with ilmenite has more than 20% TiO₂. Figure 2 includes a lunar mantle adiabat estimated from [11] using a potential temperature of 1350°C. If this dense liquid was able to rise adiabatically (perhaps in a diapir [12]) the amount of TiO₂ in the ilmenite saturated liquid becomes progressively higher, leading to further ilmenite dissolution. When ilmenite is exhausted the liquid becomes undersaturated and diluted by further melting of olivine and orthopyroxene. Further experiments will allow us to refine our saturation data. We plan to extend the dataset to higher pressures and test effects of liquid composition on ilmenite solubility.

These results also indicate that if the picritic glasses had initial elevated TiO₂ contents at depth, the melts may have been so dense and fluid that they would have sunk deeper into the mantle. This has interesting implications for trace element concentrations in the glasses. TiO₂ has a strong effect on certain trace element partition coefficients. Delano, (1980) [1] and [13] showed that FeO/MgO Kds between olivine and basalt decrease with increasing TiO₂ in the liquid. Nakamura et al. (1986) [14] measured partition coefficients for Zr and Hf between ilmenite and a synthetic high-Ti basalt (TiO₂ = 8.6 wt%). They found D_{Hf} and D_{Zr} were 4 and 8 times lower (respectively) than D₅ measured from natural ilmenite in a Kimberlite megacyrst. This large variation suggests that the TiO₂ content of the liquid is a critical parameter controlling the behavior of HFSes. Hf and Zr, (also Nb and Ta) like Fe²⁺ have a strong affinity for Ti, perhaps even more so, as they are more chemically similar. HFSE-Ti complexes are likely stabilized in the high TiO₂ melt. Models of partial melting and disequilibrium porous flow in the high TiO₂ source may be refined by new measured partition coefficients in these extreme Ti-rich liquids. It may be possible to determine which models best fit the picritic glass data; those where high TiO₂ melts are lost as they sink deep into the moon or those where the high TiO₂ melts are diluted by melting of olivine and pyroxene.

Figure 2  Ilmenite solubility in a high Ti red glass as a function of temperature and pressure. Dashed lines are contours of constant TiO₂ in saturated glass in 5% increments (from 10% - 30% TiO₂). Red triangles are experimental glass data (also shown on figure 1) labeled with their TiO₂ content. The solid arrow is an estimated lunar mantle adiabat. The adiabat dT/dP slope is significantly shallower than the ilmenite ‘saturation surfaces’ illustrating that a partial melt in equilibrium with ilmenite at depth will have a very high TiO₂ content but become undersaturated as it rises to the surface.

References: