

ON THE PRESENCE OF A TITANIUM-RICH MELT LAYER IN THE DEEP LUNAR INTERIOR. A. Khan¹, A.Pommier² and J.A.D. Connolly¹ ¹Institute of Geochemistry and Petrology, ETH Zuerich, Switzerland (amir.khan@erdw.ethz.ch, james.connolly@erdw.ethz.ch), ²School of Earth and Space Exploration, Arizona State University, Tempe, USA (Anne.Pommier@asu.edu).

Introduction: It has been postulated that lunar magma-ocean crystallization led to formation of dense Ti-rich cumulates near the base of the crust [1]. This cumulate pile would be gravitationally unstable and convectively overturn to cause settling of TiO₂-rich phases, including melt, to the bottom of the mantle [2]. Melt trapped by this mechanism might remain as a partially molten layer in the present-day Moon [3]. Thus, if a TiO₂-rich melt-layer is indeed present, then it would provide an important constraint on lunar evolution. Dissipation-related data obtained from LLR [4] and orbiting spacecraft [5] provide evidence for an attenuating region deep within the Moon. The lack of farside moonquakes is also considered to indicate the presence of an attenuating, possibly molten, region in the lunar interior [6, 7]. Recent analysis of the Apollo lunar seismic data for core-related phases is suggestive of an outer molten core [8, 9] overlain by a partially molten layer [8]. The absence of recent volcanic activity on the lunar surface indicates that if melt is present within the mantle it must be neutrally buoyant. Experimental investigation of densities of lunar melts derived from the most primitive lunar material available (picritic glasses) has shown that TiO₂-rich melts (~16 wt% TiO₂) are neutrally buoyant [10, 11]. These results are consistent with earlier work based on more limited experimental data [12].

Purpose: Here we invert a set of diverse geophysical data bearing on different physical rock properties in combination with phase-equilibrium calculations to 1) assess whether such a layer is geophysically required; and 2) determine the likely composition, thermal state and physical properties of the layer.

Method of analysis: The geophysical data include mass (M), moment of inertia (I), frequency-dependent electromagnetic sounding data (Apollo lunar day-side transfer functions, T) and Love number (k₂). These data are sensitive to different physical properties (density, conductivity, shear modulus) and depth ranges (M, I and k₂ sense integral properties). By using thermodynamic methods (free energy minimization) to compute local physical properties within the mantle [13], the data sets are linked directly to the mantle temperature and composition by the inversion. For this purpose we model the mantle mineralogy in the chemical system CaO-FeO-MgO-Al₂O₃-SiO₂-TiO₂ (CFMASTi). Computation of bulk rock conductivity from the computed phase equilibria relies on

combining the predicted mineralogy with laboratory-based estimates of mineral conductivities [e.g., 15]. Our model Moon is comprised of spherically-symmetric layers from the surface to the core that are parameterized by composition and temperature. The crust is physically parameterized in terms of P-, S-wave speed, density, and fixed thickness (45 km), whereas the core is parameterized by variable size, density, P-, and S-wave speed.

Results – 1. Presence of melt layer: We conducted several independent inversions to assess whether a melt-layer is required by the geophysical data. While we found that models without deep melt-layers could accommodate M, I and T within uncertainties, such models were unable to fit k₂ within one standard deviation. This result is evidence that lunar rigidity decreases in the deep lunar interior and shows that a dissipative region, such as a partially molten layer is required to fit LLR data [4].

2. Melt-layer composition: The melt-layers typically appear at depths of 1150-1450 km. The amount of melt present ranges from a few to several tens of vol% in the deepest layers (>1250 km depth). Mantle compositions derived here (figure 1) generally agree with independent estimates of lunar bulk silicate composition [e.g., 16-19]. Melt, when stable, has a composition (figure 1) enriched in FeO and TiO₂ relative to bulk mantle, with TiO₂ content of 2-9 wt%, which is within the range reported for picritic lunar glasses (0.26-16.4 wt%) [20]. We do not seek to match the lunar glass compositions derived from the lunar glasses because the melt compositions obtained in the inversion are in equilibrium with the mantle host rocks, whereas the melts represented by lunar glasses were almost certainly modified during ascent through the mantle

3. Phase equilibria and physical properties: Phase equilibria for probable compositions indicate a lunar mantle consisting of olivine, pyroxenes, an aluminous phase (anorthite->spinel->garnet), and ilmenite and/or a melt phase. For the most probable model (figure 2), melt appears at ~4.4 GPa and reaches a volume of ~50 vol%, in line with earlier suggestions [8]. Shear-wave speed and conductivity profile are controlled mostly by variations in temperature, while with the appearance of melt toward the base of the mantle strong variations in both properties occur.

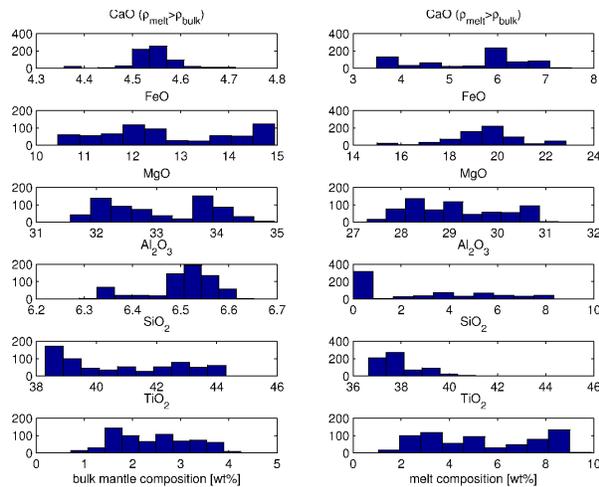


Figure 1: Sampled bulk mantle (left column) and melt-layer (right column) silicate compositions for those models where melt density > bulk density (the reverse case is not shown here for brevity). Melt layers encompass the depth range ~1150-1450 km, while bulk mantle comprises the entire silicate mantle.

4. Implications: The densities of the melts corresponding to the green, orange, and black lunar glasses [10-12] are bracketed by our results (figure 3). Models producing negatively- to neutrally-buoyant melt-layers have high FeO-contents relative to the

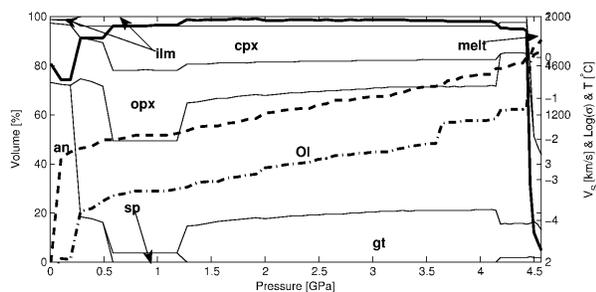


Figure 2: The model mineralogy and selenotherm (dashed line) for the most probable composition. Corresponding physical properties are also shown (shear-wave speed - solid line, conductivity - dot-dashed line). Phases are an (anorthite), ol (olivine), opx (orthopyroxene), cpx (clinopyroxene) ilm (ilmenite), gt (garnet), and melt (melt phase).

surrounding mantle and are not necessarily those with high TiO₂-contents. The effect of increasing melt density with increasing TiO₂ content is most evident in positively buoyant melts. Gravitationally stable melts have densities of 3.3-3.4 g/cm³, whereas the positively buoyant melts are 3.1-3.4 g/cm³.

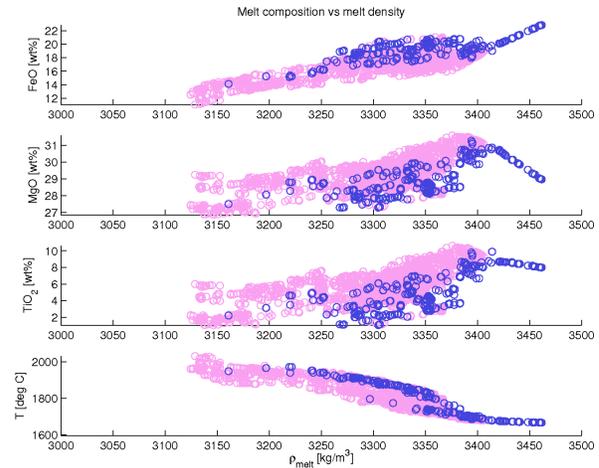


Figure 3: Compositional and thermal dependence of melt density. Blue and pink dots indicate models for which melt density > bulk density and melt density < bulk density, respectively.

5. Summary: The data investigated here require significantly reduced rigidity within the deep Moon. This result suggests the presence of partial melt somewhere in the deep lunar interior. However, as a large fraction of our obtained models result in melts that are less dense than the surrounding mantle and thus positively buoyant, in line with earlier results [12], we infer that a deep lunar melt-layer as modeled here is most probably not present. If this is indeed the case it suggests that dissipation within the Moon takes place in the core. Resolution of the question as to whether the partially molten zone encompasses the entire core or only part of it as suggested by [e.g., 6] will most likely have to await the acquisition of new lunar seismic data.

References: [1] Snyder et al., *Geochim. Cosmochim. Acta*, 1992. [2] Hess & Parmentier, *EPSL*, 1995. [3] de Vries et al., *EPSL*, 2010. [4] Williams et al., *LPSC 43*, 2012. [5] Goosens et al., *PSS*, 2010. [6] Nakamura et al., *Science*, 1973. [7] Nakamura, *JGR Planets*, 2005. [8] Weber et al., *Science*, 2010. [9] Garcia et al., *PEPI*, 2011. [10] Van Kan Parker et al., *Nat. Geo.*, 2012. [11] Sakamaki et al., *EPSL*, 2010. [12] Delano, *LPSC 20*, 1990. [13] Connolly, *EPSL*, 2005. [14] Khan & Shankland, *EPSL*, 2012. [15] Taylor et al., *Geochim. Cosmochim. Acta*, 2006. [16] Khan et al., *JGR Planets*, 2006. [17] Kuskov & Kronrod, *Phys. Sol. Earth*, 2009. [18] Warren, 2005. [19] Delano, *LPSC 16*, 1986. [20] Saal et al., *Nature*, 2008. [21] Shearer. [22] Elkins-Tanton et al., *MAPS*, 2003. [23] Wyatt, *Contrib. Mineral. Petrol.*, 1977.