Viscosity and Structure of a Late Lunar Magma Ocean Liquid: Implications for the Purity of Ferroan Anorthosites and the Dynamics of a Crystallizing Magma Ocean


The current paradigm argues the Moon formed after a giant impact that produced a deep lunar magma ocean (LMO). After a period of turbulent convection, the LMO experienced fractional crystallization, causing the initially peridotitic liquid to evolve to a plagioclase-saturated ferrobasalt. The lunar crust, much of which comprises 93-98% pure anorthosite [1,2], formed by flotation of positively buoyant plagioclase on the residual liquid. A flotation crust would contain some trapped melt; compaction of the melt out of the crust before solidification may be necessary to generate a very pure anorthitic crust. The efficiency of this process depends on the previously unmeasured viscosity of the residual liquid [3].

To characterize the viscosity and thermal equation of state of a late LMO liquid, we conducted experiments at the Advanced Photon Source, Beamline 16-BM-B, Argonne National Laboratory on a nominally anhydrous Ti-rich ferrobasalt [4]. X-ray radiography and diffuse scattering experiments were conducted in a Paris-Edinburgh apparatus in graphite-lined BN capsules, allowing in-situ observation of viscosity and derivation of thermal EoS at P-T conditions relevant to the Moon (1300-1600°C, 0.1-4.4GPa). We calculated viscosities of 0.23-1.45 Pa·s for the melt; based on 11 observations, we find that viscosity is pressure insensitive under the conditions explored. Viscosity can be modeled by an Arrhenius relation with an activation enthalpy of 66 kJ/mol. Composition-dependent predictive models [5] overestimate our observations by roughly a factor of 2.

Preliminary analysis suggests no pressure-dependent structural transition over the conditions explored. Late LMO liquids brought to the lunar core-mantle boundary by cumulate mantle overturn may be positively buoyant, implying the seismically attenuating layer around the lunar core contains a denser, higher-Ti melt. Our results suggest that efficient phase segregation in the lunar magma ocean and compaction in the anorthositic flotation crust can produce a high-purity crust under physically reasonable conditions.