

VISCOSITY AND STRUCTURE OF A LATE LUNAR MAGMA OCEAN LIQUID: IMPLICATIONS FOR THE PURITY OF FERROAN ANORTHOSITES AND THE PARTIALLY MOLTEN LAYER AROUND THE CORE. N. Dygert¹, J.F. Lin¹, E.W. Marshall¹, Y. Kono², and J.E. Gardner¹, ¹Department of Geological Sciences, University of Texas at Austin (2275 Speedway Stop C9000, Austin, TX, 78705, ndygert@jsg.utexas.edu), ²HPCAT, Advanced Photon Source (Argonne National Laboratory, Argonne, IL 60439).

Introduction: 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 [1-3], formed by flotation of positively buoyant plagioclase on the residual liquid. Because plagioclase precipitated along with other phases (e.g., Fe-rich clinopyroxene and ilmenite) [e.g., 4], phase separation by plagioclase flotation and the sinking of dense ilmenite and mafic minerals must have been efficient. The newly formed, partially molten anorthosite flotation crust would have contained some trapped melt [5]. Compaction of the trapped melt out of the crust before solidification would be required to generate a very pure anorthositic crust.

The efficiency of phase separation and compaction of trapped liquid out of the flotation crust depend on the viscosity of the residual magma ocean liquid [5,6], which was unconstrained prior to this study. Phase separation efficiency determines the bulk density of late LMO cumulates that accumulated beneath the flotation crust. The less plagioclase they contain, the greater the driving force for cumulate mantle overturn, which would bring derivatives of the late LMO liquid (and possibly some of the late LMO liquid itself) deep into the lunar interior.

Experiments: We conducted falling sphere viscometry and diffuse scattering experiments at the Advanced Photon Source, Beamline 16-BM-B, Argonne National Laboratory on a synthetic Ti-rich ferrobasalt from Longhi (FR-1290) [7] (Table 1). *P-T* conditions explored are directly relevant to the Moon (1300-1600°C, 0.1-4.4GPa). Starting material was prepared from reagent-grade oxide powders, ground in an agate mortar for 5h in ethanol, then decarbonated in air at 800°C for 4h.

Experiments were conducted in a Paris-Edinburgh apparatus in graphite-lined BN capsules. An X-ray attenuating rhenium sphere is placed at the top of the sample charge. The experiment is heated to its estimated solidus temperature, then flash melted, causing the sphere to sink and accelerate to its terminal velocity. A high-speed camera located opposite the X-ray source images the path of the sphere. The viscosity of the liquid is calculated using Stokes' Law with wall and end effect corrections [e.g., 8]. Because the Paris-Edinburgh apparatus lacks a thermocouple, temperature is estimated

using an experimentally calibrated current-*T* curve; we estimate the uncertainty to be approximately $\pm 50^\circ\text{C}$.

Diffuse scattering data are obtained after the viscometry experiment. An X-ray detector on a mobile arm is rotated through a series of 2θ angles to collect energy dispersive X-ray diffraction spectra. The total structure factor of the melt is estimated from the diffuse scattering data using the aEDXD software, which employs methods described in [8].

Table 1. Nominal composition of starting material (wt%).

SiO ₂	TiO ₂	Al ₂ O ₃	FeO [†]	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O*
44.2	4.1	8.7	29.9	0.7	0.26	10.9	0.5	0.4	0.4	0.48

[†]Total iron reported as FeO.

*Characterized by FTIR assuming an absorption coefficient of 63 L/mol·cm [9].

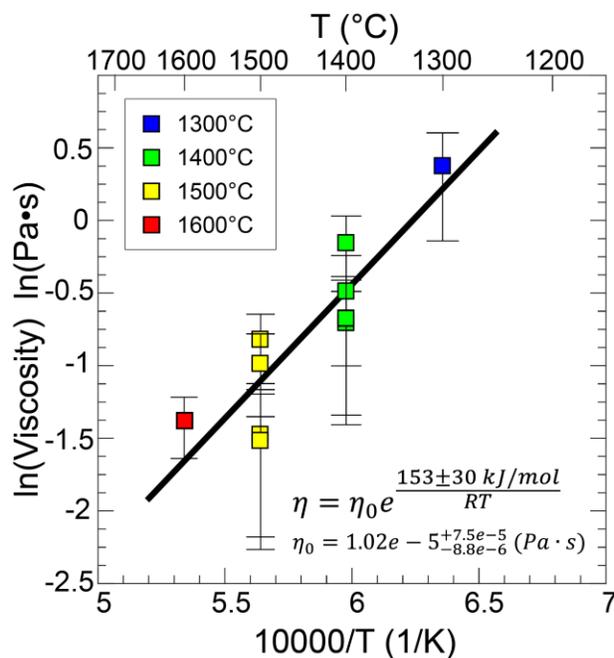


Figure 1. Log viscosity plotted against inverse temperature. Viscosity can be modeled by the Arrhenius relation shown in the inset; coefficient uncertainties are 1σ . Error bars are calculated assuming a $\pm 50^\circ\text{C}$ temperature uncertainty.

Results: We measured viscosities of $0.23^{+0.12}_{-0.08}$ to $1.45^{+0.58}_{-0.38}$ Pa·s for the melt. Based on 11 observations, viscosity is pressure insensitive within the experimental uncertainty. Viscosity can be modeled by an Arrhenius relation with an activation energy of 153 ± 30 kJ/mol (black line, Figure 1). Viscosities are lower than those of most silicate melts at the experimental temperatures (see Figure 2 for a few relevant examples). The composition-dependent predictive models of [10,11] overestimate our

observations by roughly a factor of 2; within error, the model of Hui & Zhang [12] reproduces the results.

Implications: *Phase separation in the crystallizing magma ocean.* To first order, the efficiency of crystal separation in the crystallizing LMO can be thought of as a competition between Stokes flow and the LMO solidification rate. In reality the process is more complicated as convection continued throughout LMO solidification, and interactions among crystals affect their floating and sinking rates [6]. Fluid dynamic experiments show that the length scale of hydrodynamic interactions between suspended crystals increases with increasing fluid viscosity [13]; higher liquid viscosities tend to slow down crystal separation owing to these interactions. The very low measured viscosity of the late LMO liquid promotes efficient phase separation during magma ocean crystallization. Measured LMO liquid viscosities are consistent with assumptions of the model of [6], who argued the LMO approximates a fractionally crystallizing body. A fractionally crystallizing LMO would produce an anorthositic flotation crust with few rafted mafic minerals, and a relatively pure layer of dense cumulates beneath the flotation crust. Owing to its high density, this layer would efficiently drive cumulate mantle overturn.

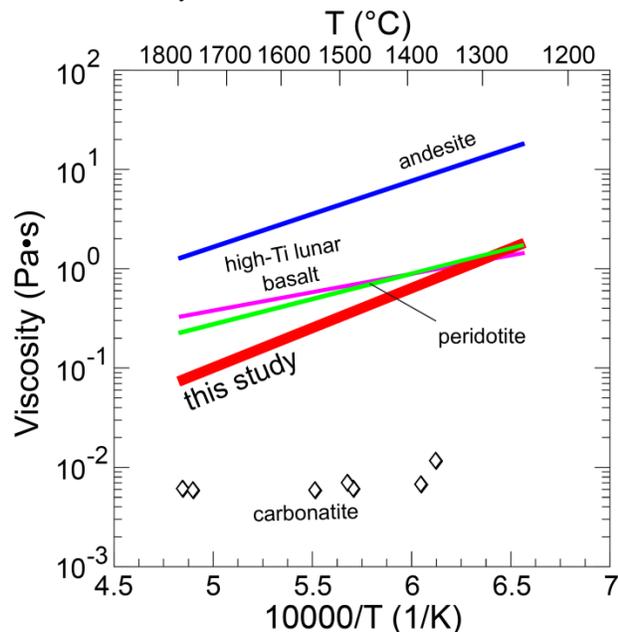


Figure 2. Viscosities of silicate melts [11,14,15] and carbonatite [16] compared to the results of this study. Late LMO liquid is less viscous than other silicate melts and is low viscosity (~ 2 Pa·s) at plagioclase saturation temperatures.

Compaction of trapped liquid out of the flotation crust. Any interstitial melt remaining in the flotation crust as it cools below its solidus will precipitate mafic minerals and Fe-Ti oxides. The amount of trapped melt depends on the relative rates of compaction and solidification. The solidification rate is probably determined by

thermal conduction through the accumulating crust. Piskorz and Stevenson [5] developed a compaction-solidification model, finding that at relatively low compaction viscosities ($<10^{20}$ Pa·s), $<2\%$ trapped melt would remain in the flotation crust, consistent with a 98% pure anorthositic crust. However, this model assumes a melt viscosity of 100 Pa·s, ~ 2 orders of magnitude higher than our measurements. How sensitive is the amount of trapped melt to viscosity? The flotation crust scenario differs from the familiar example of a compacting cumulate pile where advecting melt partially supports the crystalline matrix and compaction length scales with the square root of melt viscosity [17]. In the lunar flotation crust pressure in the interstitial melt network is low and the compaction viscosity of the crust predominantly determines the trapped melt fraction (unless trapped melt is as viscous as a rhyolite). Our experimental results confirm the findings of [5]; provided that compaction viscosity is sufficiently low, the trapped melt fraction in the flotation crust will be $<2\%$.

A late LMO liquid layer around the lunar core? Because farside moonquakes were not observed by the Apollo seismic network on the nearside, it is inferred the lunar core is surrounded by a seismically attenuating partially molten layer [e.g., 18]. The liquid in this layer must be negatively buoyant relative to the lunar mantle to be stable at or near the core-mantle boundary. Could this liquid be a late LMO melt brought into the interior by cumulate overturn? Preliminary analysis suggests no major structural transition in our silicate melt over the conditions explored. Late LMO liquids may remain positively buoyant at all depths in the Moon's interior, implying the seismically attenuating layer around the core contains a denser, higher-Ti melt. Future efforts to investigate this problem will use diffuse scattering data to parameterize a thermal equation of state for the LMO liquid [e.g., 19].

References: [1] Warren P. (1990) *Am. Min.*, 75, 46-58. [2] Donaldson Hannah K. et al. (2014) *JGR*, 119, 1516-1545. [3] Ohtake M. et al. (2009) *Nature*, 461, 236-241. [4] Hess P. C. & Parmentier E. M. (1995) *EPSL*, 134, 501-514. [5] Piskorz D. & Stevenson D. J. (2014) *Icarus*, 239, 238-243. [6] Suckale J. et al. (2012) *JGR*, 117. [7] Longhi J. (2003) *JGR*, 108. [8] Kono Y. et al. (2013) *PEPI*, 228, 269-280. [9] Mandeville C. et al. (2002) *Am. Min.*, 87, 813-821. [10] Giordano D. et al. (2008) *EPSL*, 271, 123-134. [11] Sehlke A. & Whittington A. G. (2016) *GCA*, 191, 277-299. [12] Hui H. & Zhang Y. (2007) *GCA*, 71, 403-416. [13] Koyaguchi T. (1990) *Nature*, 343, 447-450. [14] Vetere F. et al. (2006) *Chem. Geol.* 228, 233-245. [15] Liebske C. et al. (2005) *EPSL*, 240, 589-604. [16] Kono Y. et al. (2014) *Nat. Comm.*, 5:5019. [17] McKenzie D. (1984) *J. Pet.*, 25, 713-765. [18] Nakamura E. et al. (1974) *GRL*, 1, 137-140. [19] Eggert J. et al. (2002) *Phys. Rev. B*, 65.