RHEOLOGY OF ILMENITE AND ILMENITE-OLIVINE AGGREGATES: IMPLICATIONS FOR LUNAR CUMUALTE MANTLE OVERTURN. N. Dygert[1,2], G. Hirth[1], and Y. Liang[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University; [2]Jackson School of Geosciences, University of Texas at Austin (ndygert@jsg.utexas.edu).

Introduction: Lunar basalts have TiO_2 abundances that range from <1 wt% to >16 wt% [1,2,3]. Lunar petrologists have argued that high-Ti basalts can be produced by (1) partial melting an ilmenite-bearing cumulate lunar mantle [4] or (2) partial melting of the lunar mantle followed by assimilation of ilmenite as the melt migrated to the lunar surface [5]. In either scenario, ilmenite is an important component of the lunar basalt source region.

Lunar basalt petrogenetic models have been used to make inferences about the dynamic evolution of the lunar mantle [e.g., 4]. Currently favored models of lunar formation propose the Moon originated from a giant impact between the Earth and another large body [e.g., 6,7] that left a deep magma ocean on the nascent Moon. The magma ocean crystallized from the bottom up, causing its composition to evolve from Fe and Ti poor to Fe and Ti rich [e.g., 8]. Eventually the magma ocean reached ilmenite saturation and precipitated ilmenite and Fe-rich clinopyroxene enriched in incompatible trace elements beneath an anorthositic flotation crust [8,9]. Instead of forming a uniform layer, these cumulates may have sank into underlying olivine rich cumulates as they crystallized, forming a thicker layer of ilmenite-bearing cumulates (IBC) [9]. Ilmenite-bearing magma ocean cumulates were denser than the early mafic cumulates, and the resulting unstable density stratification may have been relieved by solid state cumulate mantle overturn [e.g., 4,9].

Because the viscosity of ilmenite and ilmenite-bearing lunar mantle cumulates was previously unknown, efforts to model lunar cumulate mantle overturn and its aftermath have relied on olivine viscosity [10,11], or explored the effects of different viscosities on lunar mantle convection patterns during or after cumulate overturn [9,12,13,14]. [9] proposed that IBC mix with underlying harzburgites which then flow to the center of the Moon, producing a hybrid cumulate mantle by subsequent melting. [10] proposed that IBC are too viscous to overturn as solids and instead may melt where they crystallized beneath the anorthositic crust. [11] found the IBC rapidly flow to the lunar core and may be stable there, forming an ilmenite core or outer core. [12] investigated whether spherical harmonic degree-one upwelling of previously overturned IBC at the lunar core could concentrate ilmenite-bearing cumulates beneath the Procellarum KREEP terrane (PKT). They found models where the cumulates are more viscous than overlying mantle are most likely to form a single large upwelling plume. [13] investigated the thermochemical evolution of the lunar mantle and core after cumulate overturn with a wide range of temperature dependent IBC viscosities. They observed that weaker IBC layers surrounding the core tend to form multiple upwelling plumes, and that very weak IBC layers are highly stable (i.e., internally convecting but stationary) at the core-mantle boundary to the present day. [14] investigated whether degree-one downwelling could spatially concentrate IBC beneath the PKT. Assuming a scenario where a layer of IBC overlies a thicker layer of ultramafic cumulates, they found that low viscosity IBC layers are capable of generating degree-one downwelling plumes. The wide range of outcomes from these models demonstrates the importance of constraining the viscosity of the IBC for understanding the thermochemical evolution of the Moon.

Experiments: We examined the rheology of ilmenite ($FeTiO_3$) and ilmenite-olivine aggregates through laboratory deformation experiments in a Griggs apparatus at Brown University. We used molten salt assemblies (a eutectic KCl-NaCl mixture) as the confining medium, which helps to minimize thermal gradients and friction in the assembly, thereby maximizing the stress resolution of the deformation apparatus. Grain size separated (20-30μm and 30-50μm) cold pressed synthetic ilmenite powders (Sigma Aldrich) were deformed in axial compression after annealing overnight at run conditions. Aggregates of ilmenite and San Carlos olivine were prepared by mechanically mixing grain size separated (10-20μm) mineral powders in ethanol. Two different ratios of ilmenite:olivine were used and the powders were deformed in shear between Al_2O_3 pistons cut at a 45° angle. Shear experiments were annealed for 1-3 days at run conditions before deformation. The nominal confining pressure of all experiments was 1GPa. A summary of experimental conditions are presented in the table below.

Name	Material	T (°C)	Axial strain rate(s)
ID-1	Ilmenite	1100	10^{-5}
ID-3	Ilmenite	1100	10^{-5},5×10^{-5},1×10^{-4},5×10^{-5}
ID-12	Ilmenite	1100	10^{-5},5×10-5,1×10^{-4},5×10^{-5}
ID-2	Ilmenite	1000	10^{-5},5×10^{-5},10^{-5},5×10^{-6}
ID-13	Ilmenite	950	10^{-5},5×10^{-5},10^{-5},5×10^{-6},5×10^{-5}
ID-5	Ilmenite	900	10^{-5},5×10^{-6},1×10^{-6},5×10^{-6}
W1866	0.5Ilm:0.5Ol	1000	10^{-5} (shear experiment)
W1867	0.1Ilm:0.9Ol	1000	10^{-5} (shear experiment)
W1870	0.1Ilm:0.9Ol	1000	10^{-5} (shear experiment)

Results: Force and displacement were corrected to account for apparatus distortion and using the frictional force measured during initial advancement of the load piston. Efforts are underway to correct the data for the strain rate dependence of friction, so the differential stresses and flow law parameters presented here should be treated as preliminary. Neglecting this friction correction exaggerates the strength of the samples and we believe our results capture the first order characteristics of ilmenite rheology. Differential stress versus axial strain curves are shown in Figure 1. Each plateau represents a strain rate step. Differential stresses approach steady state at each strain rate except in experiment ID-13. ID-13 demonstrated strain weakening over the first two strain rate steps, so mechanical data from the first step was excluded from the flow law determination.

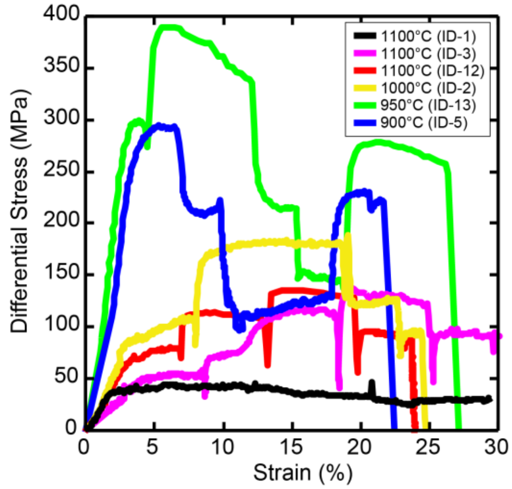

Figure 1. Differential stress-strain paths for pure ilmenite experiments processed assuming constant volume shortening.

A flow law for ilmenite in dislocation creep was parameterized in the standard form. Parameters in the flow law were estimated by simultaneous nonlinear inversion. We find an activation energy of 290±28 kJ/mol and a stress exponent of 2.9±0.2, consistent with deformation by dislocation creep. Extrapolating the flow law to mantle stresses and temperatures, we predict a viscosity more than four orders of magnitude lower than dry olivine [15].

Aggregate Viscosities: Ilmenite is expected to be a minor phase in the IBC (~5 vol. % [9,13]) so determining the effect of low modal abundance on aggregate viscosities is critical. The mixing model of [16] can be used to predict a volume-weighted aggregate flow law based on end member flow laws. Predicted viscosities for ilmenite-olivine aggregates at the differential stress condition of experiment W1870 are shown in Figure 2. The dashed line is the isostrain bound and the dash-dotted line is the isostress bound which are robust upper and lower limits for aggregate viscosities. In all of the aggregate experiments the measured viscosities are intermediate to the model prediction of [16] and the isostress bound.

Implications: Just 5 volume % ilmenite in a harzburgitic lunar mantle may halve the viscosity of the aggregate,

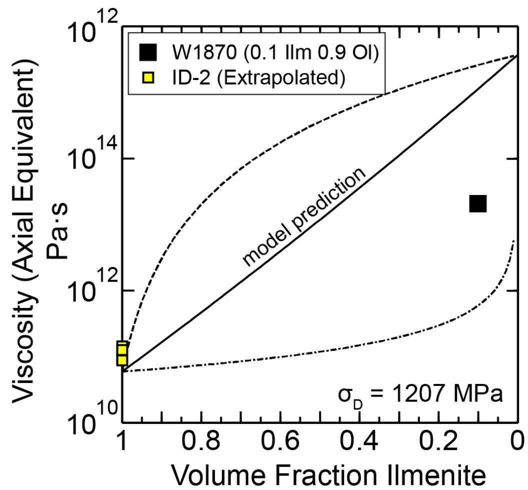

Figure 2. Mixing model [16] calculated for ilmenite and olivine end-member flow laws (this study, [15]) compared to the measured viscosity of experiment W1870.

making long wavelength cumulate mantle overturn more likely [14]. The presence of overturned ilmenite around the lunar core can explain an ultralow viscosity zone that may surround the core [17]. Ilmenite makes transport of pyroxene-hosted heat producing elements to the core easier, providing a mechanism for partial melting of lowermost mantle which can explain a zone of seismic attenuation there [e.g.,18,19]. Overturned IBC around the lunar core may be highly stable (i.e., internally convecting but stationary) [12,13], suggesting the formation of upwelling diapirs of overturned IBC is unlikely. Thus, the petrogenesis of high-Ti lunar basalts may require entrainment of overturned IBC by an overlying, convecting harzburgite mantle, or incomplete cumulate mantle overturn. A hot stable blanket of IBC around the lunar core may cause negative heat flux at the core-mantle boundary, suppressing convection in the core and the development of a convection-driven core dynamo [13].

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