WEAKNESS OF ILMENITE REVEALED BY NEW RHEOLOGICAL MEASUREMENTS WITH IMPLICATIONS FOR LUNAR CUMULATE MANTLE OVERTURN. N. Dygert, C. Meyers, G. Hirth, and Y. Liang, Brown University (324 Brook Street, Providence, R.I., nicholas_dygert@brown.edu).

Introduction: Several lines of evidence suggest there was once a deep lunar magma ocean [1]. Experimental work [2] and studies of terrestrial layered intrusions [3] indicate that as the magma ocean crystallized the composition of the liquid evolved from a Mg-rich picritic liquid to an Fe-rich felsic liquid saturated in plagioclase, clinopyroxene, and ilmenite [4]. Because the intermediate and late stage pyroxene and ilmenite ($FeTiO_3$) minerals were more Fe-rich than the olivine cumulates that preceded them they were denser than the early cumulates, which led to a gravitationally unstable density stratification. It has been argued that the gravitational instability was relieved by solid-state cumulate overturn [5,6], where early ultramafic cumulates rose to the top displacing the denser layer of ilmenite-bearing cumulates that crystallized late at the base of lunar crust.

The rheology of the lunar cumulates is perhaps one of the most important parameters determining whether cumulate overturn is possible and under what conditions it can occur. While the mechanical properties of olivine (and to a lesser extent, pyroxene and plagioclase) are well studied, no measurements of ilmenite rheology have been made. Although ilmenite represents only a small fraction of the mineralogy of the Moon, the ubiquity of high-Ti lunar basalts suggest that ilmenite is present in relatively high abundances in the lunar mantle [7]. Interactions among phases in mineral aggregates can generate different rheologies than those possessed by the single phase constituents [8]. For these reasons, characterizing the rheological properties of ilmenite and ilmenite bearing cumulates (*IBC*) is important. The goals of this study are to define a flow law for ilmenite as a single phase, then investigate the rheologies and deformation mechanisms of ilmenite + olivine ± orthopyroxene aggregates. The data will be used to develop more realistic dynamic models for convection in the lunar interior and ultimately models for the thermal and chemical evolution of the Moon.

Methods: Deformation experiments were conducted in axial compression in a Griggs apparatus at Brown University using molten salt assemblies similar to [9] at a confining pressure of 1GPa and 1000-1100°C. Starting material is 99.5% pure synthetic ilmenite powder purchased from Sigma Aldrich. Grain size separation was conducted using Stokes' settling in ethanol. After the powder was separated into 4 grain size brackets and dried, the materials were baked at 800°C in a mixed gas furnace at ~Fe-FeO to drive off any residue. The experiments reported here used ilmenite powder with a target grain size of 20-30µm (Fig. 1a) as their starting material. To minimize water adsorption, the powders were stored in an oven before preparation of the experimental assemblies. Experiments were annealed overnight at pressure and temperature before deformation. Run conditions are listed below.

Experiment	T (°C)	Strain rate(s)	Total Strain
W1776	1100	10^{-5}	30%
W1780	1000	10^{-5},$10^{-4.5}$,10^{-5},$10^{-5.5}$	25%

Results: Differential stress vs. % axial strain curves are shown in Fig. 2. In our first experiment (W1776), a nominally steady-state stress was achieved after 5% strain that persisted until 12% strain. While it appears some grain size modification occurred (Fig. 1b), no strain rate step was attempted and therefore the deformation mechanism of the experiment is unknown. In our second experiment (W1780), microstructures indicative of dynamic recrystallization are observed (Fig. 1c) and we determined a stress exponent of 3.4 (±0.6) using data from 4 strain rate steps. Differential stresses recorded at the 10^{-5} strain rate steps are indistinguishable within the estimated uncertainty in stress resolution (±10MPa), Fig. 2b.

Discussion: Our experiments demonstrate that ilmenite is more than an order of magnitude weaker than olivine deforming in dislocation creep at the same strain rate and temperature [10]. Because of the power law dependence of viscosity on stress in dislocation creep, we expect that ilmenite will be even weaker relative to olivine at lunar mantle stresses. While the implications of these results for the rheology of IBC are not yet understood, it is likely IBC will be considerably weaker than pure olivine. It has been shown that the viscosity contrast between ilmenite-free and ilmenite-bearing cumulates (and their temperature sensitivities) can have a strong effect on the spatial and temporal distribution of ilmenite in the lunar mantle [11]. A lower IBC viscosity will facilitate cumulate mantle overturn and help to stabilize the overturned IBC at the lunar core-mantle, which has important implications for the basalt volcanism on the Moon.

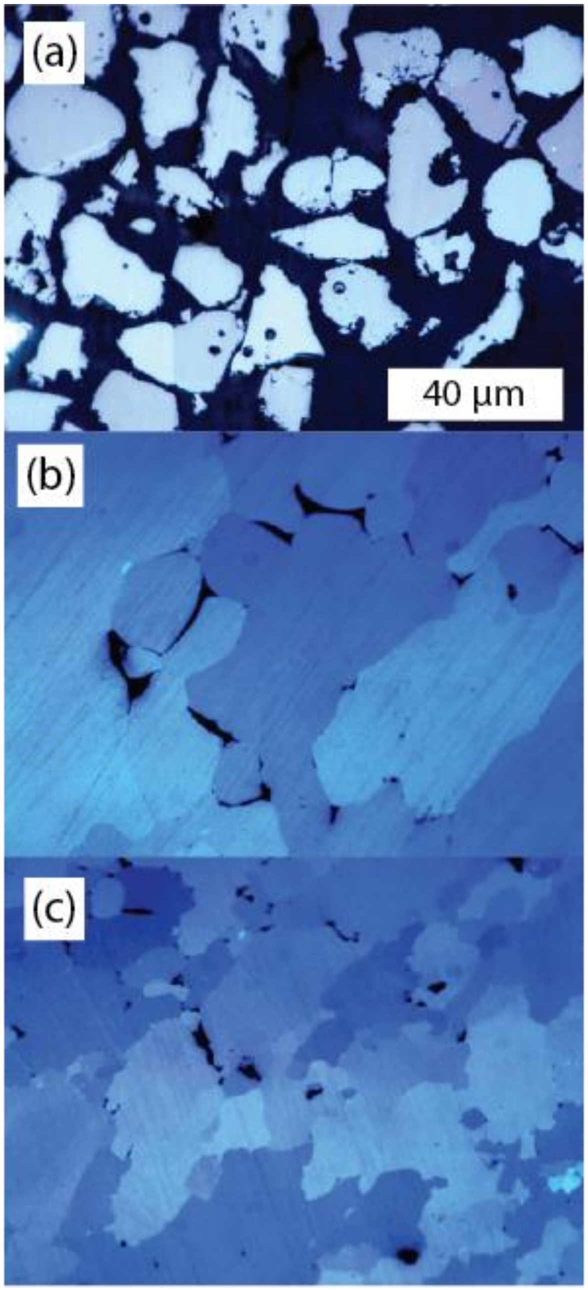

Figure 1. Reflected light micrographs of uncompressed experimental starting material (a), and microstructures in constant strain rate experiment (W1776) (b) and strain rate stepping experiment (W1780) (c). Scale bar is applicable to all images. The differences in contrast among grains are likely due to different orientations. Black areas in (b) and (c) are either porosity or voids where grains were plucked during polishing. The evolution of grain size in (c) is indicative of dynamic recrystallization suggesting the experiment was conducted in the dislocation creep regime.

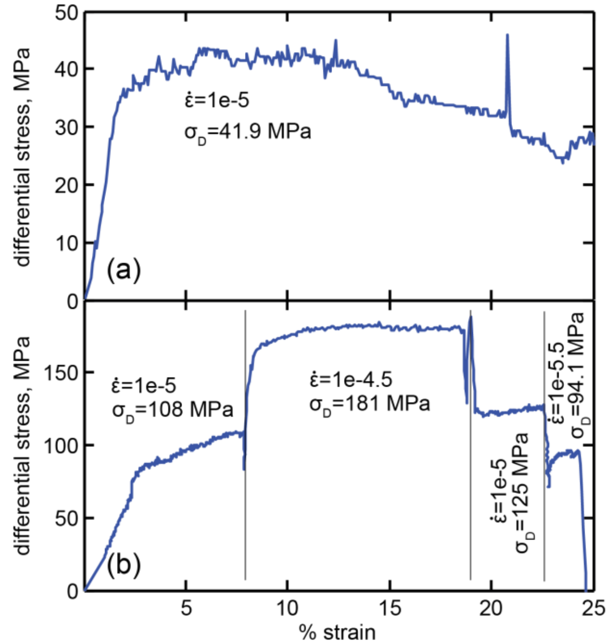

Figure 2. Differential stress vs. axial strain for runs W1776 (a) and W1780 (b). Strain rates and differential stresses are indicated for each strain rate step in (b). Reported differential stresses are averaged over intervals where approximate steady-state behavior is reached.

Future Work: The rheology of pure ilmenite will be explored in the diffusion and dislocation creep regimes and appropriate flow laws will be defined. The inherent weakness of the mineral should make it highly accessible to the pressure and temperature conditions of the experimental apparatus. Two-phase flow laws will be modeled [e.g., 12] and tested experimentally. Physical deformation mechanisms of olivine-ilmenite aggregates will be investigated. Finally, measured flow laws will be incorporated into three-dimensional convection models that explore the thermal and chemical evolution of ilmenite bearing cumulates in the lunar mantle.

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