OVERTURN OF UNSTABLY STRATIFIED FLUIDS: IMPLICATIONS FOR THE EARLY EVOLUTION OF PLANETARY MANTLES. S. E. Zaranek, E. M. Parmentier and L.T. Elkins-Tanton, Brown University (Department of Geological Sciences, Providence, RI 02912 , Sarah_Zaranek @brown.edu)

Introduction: Models for Mars and the Moon that treat a deep magma ocean predict that magma ocean fractional crystallization creates initial density stratification in the solidified mantle. This stratification is gravitationally unstable with respect to overturn. Subsequent overturn to a stable configuration may have important implications for the production of the earliest crust. The final stable compositional configuration would also control the subsequent evolution of the planet through the distribution of heat producing elements and compositional controls on density and rheology. These factors will influence the vigor and depth extent of subsequent solid-state thermal convection. Deep, stable, dense layers that founder during overturn may remain sequestered from convective mixing and melting, thus effectively changing the apparent bulk compositional of the mantle.

Numerical Experiments: 2D numerical experiments are used to characterize overturn. Conservation equations for mass, momentum and energy for a very viscous, infinite Prandtl number fluid are solved numerically. The density of the fluid is determined by composition, which is advected but not diffused. In our numerical experiments, composition begins as an unstable linear gradient. In some of the numerical experiments an additional denser layer is placed deep in the fluid, similar to the dense garnet layer hypothesized to form as the Martian magma ocean crystallized [1].

Because, as shown below, overturn is likely to be rapid, conductive temperature changes are not considered in this initial study. Both isoviscous and exponentially temperature dependent viscosity are examined. In cases with varying viscosity, the initial viscosity profile is based on a cold top surface boundary layer of a prescribed thickness. Viscosity and temperature fields advect with the fluid.

Results: The Rayleigh-Taylor overturn of a constant viscosity, unstable layer to a stable linear configuration occurs on time scales $t_{RT} = 4\pi^2\mu/\gamma g d$ where μ is viscosity, γ the initial density gradient, g is gravitational acceleration, and d is the layer thickness [2]. For Mars, a gradient of 0.1 kg/m^3 similar to that calculated in the models of [1] and for a magma ocean 2000 km deep, t_{RT} ranges from 0.004-4 Myr for a range of μ from 10^{18}-10^{21} Pa s. Times in our numerical experiments are non-dimensionalized by t_{RT} with a viscosity chosen equal to a reference viscosity μ_{ref}.

Overturn at the largest scale occurs rapidly on a time scale of the order of ~10 t_{RT}. For no-slip top boundaries, either prescribed in the isoviscous cases or at the base of the high viscosity lid in cases with temperature dependent viscosity, material gets “stuck” on the top boundary creating a second stage of overturn. This second stage, consisting of removal of smaller amounts high density material from the upper boundary, occurs at shorter wavelengths and starting at times of the order ~25-100 t_{RT}. Subsequent motion in the fluid on time scales ~500-2000 t_{RT} flatten the undulations in the stable stratification caused by small-scale downwellings.

Introducing temperature-dependent viscosity creates a region of high viscosity material adjacent to the upper boundary that resists overturn. This delays the second stage of overturn which now includes removal of cold, very viscous material from the upper boundary. Interestly, the material even though of very high viscosity, is gradually removed.

If the mantle before overturn were at its solidus temperature, it would have a much larger scale temperature stratification than that of the adiabatic case. This larger temperature stratification in our numerical experiments slows the second stage of overturn because more viscous material is present at the base of the stagnant lid. In the absence of conduction, this temperature gradient is completely inverted and fairly uniform by ~1000 t_{RT}.

In cases with a deep dense layer with a higher viscosity (x 10μ_{ref}), similar to that proposed for garnet [3], the layer is entrained into larger scale overturn motions but sinks to the base of the fluid fairly quickly. However, it has considerable topography at the base of the fluid at 60 t_{RT} unlike the case with no increased viscosity. Viscosity of the deep dense layer strongly affects it ability to sink into an uniform layer at the base of the fluid.

Implications: Timescales of large-scale overturn are rapid enough, except for a very shallow magma ocean or very high mantle viscosities, to consider cases when the unstable crystallized magma ocean has fully overturn before thermal convection has begun. The gradual incorporation of the stagnant lid in overturn motions allows for the possibility of additional melting and resurfacing not previously thought possible with overturn in the presence of temperature-dependent viscosity.

References: [1] Elkins-Tanton L.T. et al, (2003), *MAPS ,38* [2] Hess P.C. and Parmentier E.M., (1995), *EPSL*, *134*, 501-514 [3] Karato S. et al. (1995) *EPSL*, *130*, 13-30

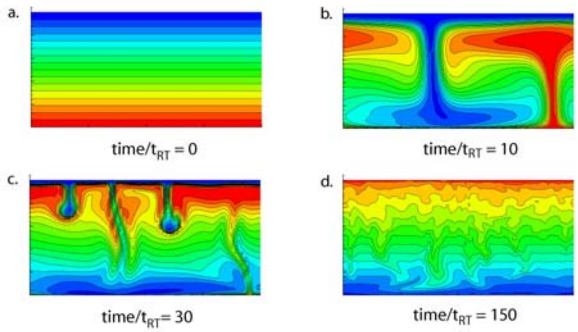

Figure 1. Contours of composition as a function of time for the overturn of an isoviscous fluid illustrating the timescale and wavelength of the two stages of overturn.

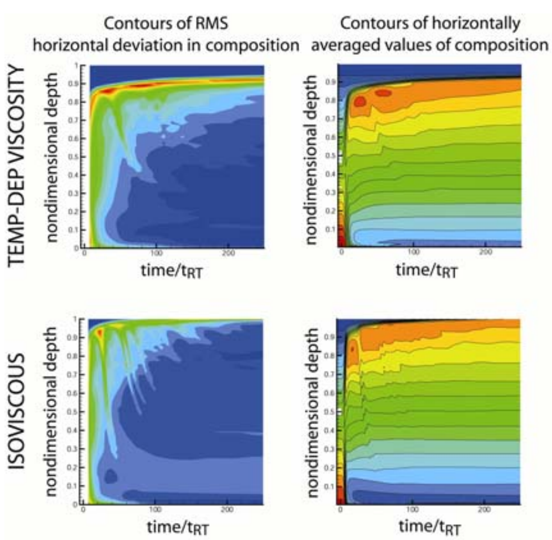

Figure 2: Horizontally averaged composition as a function of time showing the slow integration of the high viscosity stagnant lid in the overturn motions compared to the overturn of the isoviscous fluid. RMS of horizontal deviations of compostion show that horizontal variations persist even after ~200 t_{RT} .

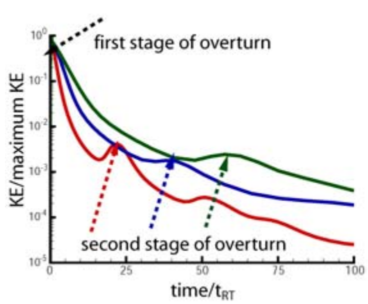

Figure 3: Plot of normalized kinetic energy as a function of time shows distinct peaks with the two stages of overturn. The introduction of temp-dependent viscosity (blue) delays the second stage of overturn compared the isoviscous results (red). An additional temperature gradient (green) increases that delay.

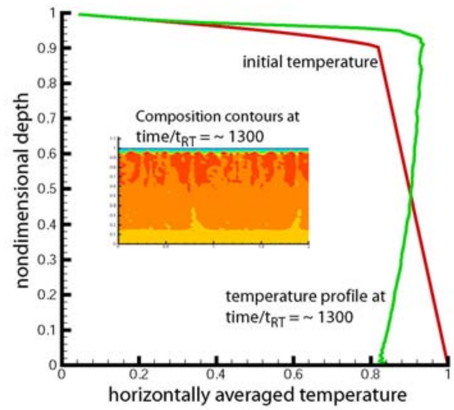

Figure 4: In the absence of heat conduction, the temperature profile in the fluid after ~1000 t_{RT} is nearly completely inverted and fairly uniform horizontally. In this case, the temperature gradient is less steep than expected for the actual solidus. Adiabatic overturn should result in partial melting.

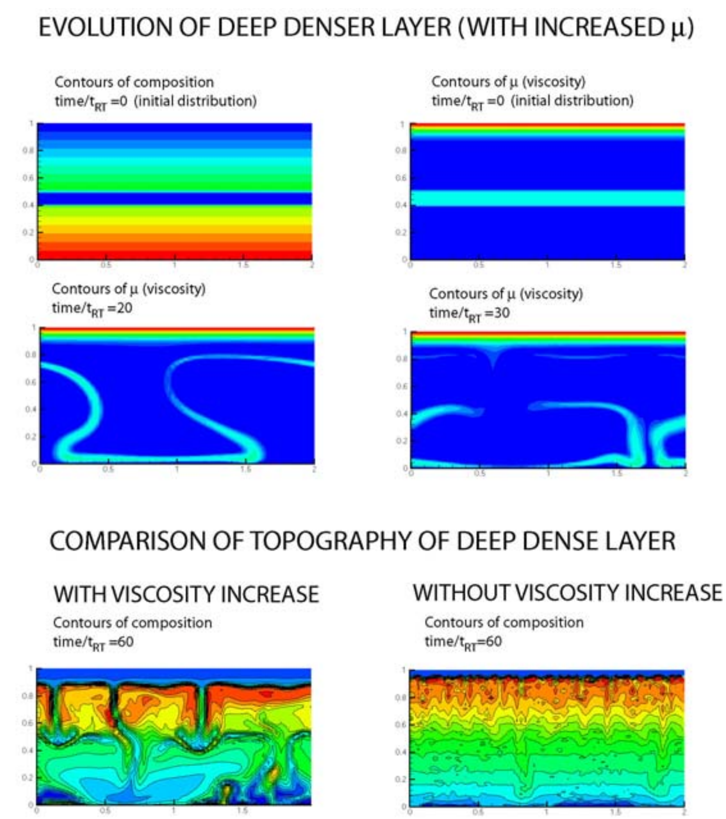

Figure 5: *Top*: Time evolution of a more viscous, dense, deep layer. The evolution of the layer can clearly seen in the viscosity field. *Bottom:* Increasing the viscosity of the layer, delays the second stage of convection and creates a larger amount of topography of this deep layer on the base of the fluid after overturn.