MELT-SOLID SEGREGATION, FRACTIONAL MAGMA OCEAN SOLIDIFICATION, AND IMPLICATIONS FOR LONGTERM PLANETARY EVOLUTION. E.M. Parmentier, L. Elkins-Tanton, and Shane Schoepfer, Department of Geological Sciences, Brown University, Providence, RI, 02912 (EM_Parmentier@brown.edu).

Introduction: Large planetary bodies are likely to have been significantly melted during their accretion, simply as a consequence of the potential energy of accretion if accretion occurs rapidly enough or possibly due to subsequent giant impacts [1]. Since the solidus and liquidus temperatures of mantle mineral assemblages increase with pressure more rapidly than temperature along an adiabat, solidification of a thermally well-mixed magma ocean (MO) is expected to occur from the bottom up.

Ideal fractional solidification of a MO would result in an unstable stratigraphy primarily due to increasing Fe/Mg of residual liquid as solidification proceeds. Highly incompatible elements, including heat producing U, Th, and K, would be progressively enriched in the residual liquid. The unstable stratigraphy resulting from fractional solidification would overturn on relatively short time scales with significant implications resulting in a stably stratified mantle that would resist solid-state thermal convection and in which incompatible heat producing elements are concentrated at the bottom of the mantle with fundamental implications for long term planetary evolution [2,3,4].

Fractional solidification requires the separation of solid from the liquid in which it forms. The rate of this separation may thus control how ideally fractional the MO solidification can be. Cooling of the MO is expected to be controlled by the radiative cooling of the planetary surface, thus depending on the pressure and composition of the atmosphere [5,6]. The rapidity of early planetary evolution is indicated by the presence of significant fractionations in the daughter products of isotopic decay that must have occurred during the earliest evolution, including variation in ^{182}W [7] and ^{142}Nd [8,9] that are produced from decay with half-lives of approximately 10 and 100 Myr, respectively.

Solid-melt segregation during MO solidification: Crystallization will occur in cool sinking plumes and thermals that develop from instability of the surface thermal boundary layer and in the thermal boundary layer itself if the surface temperature is below the liquidus. Figure 1 illustrates the case with solidification occurring only in downwelling plumes. Due to turbulent entrainment the plume radius increases as about 0.1 x depth [10,11]. Solids forming in the cool central region of the plume will impinge on the solidified floor of the MO and spread laterally to form a layer of solid containing interstitial melt with a melt fraction that increases upward. The rate of melt migration and compaction of dense solids in this layer will determine the how quickly melt and solid segregate. Since MOs are expected to be highly time dependent, deposition of partially molten material in layers beneath plumes will be episodic at an average deposition rate determined by the overall cooling at the surface. For an average solidification velocity V and a layer thickness H, the average time between depositions and the time for each layer to lose its melt before being buried beneath the next layer would be simply H/V. Previous studies [12] have addressed this competition between cooling and melt migration.

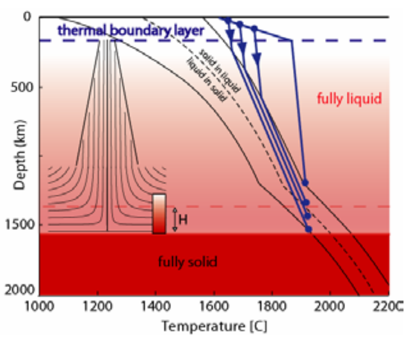

Figure 1. Temperature-pressure paths (bold blue) and flow lines (fine black) in a thermal plume emanating from the cold surface thermal boundary layer. Solidification that would occur by adiabatic compression decreases from the plume center where temperatures are lowest. The plume widens with depth due to turbulent entrainment. Each plume deposits a layer of thickness H that thins radially away from the plume. Depth scale would be appropriate for a deep magma ocean on Mars.

Turbulent suspension of solid mineral grains: As cool sinking plumes spread radially at the top of the mostly solidified layer, solid mineral grains in the overlying mostly liquid layer that are denser than the liquid will settle. This is one factor determining how well mixed the convecting portions of the MO can be.

Flow in turbulent eddies, generated as cold plumes impinge on deeper, higher viscosity, more solidified mantle will act to keep particles suspended thus reducing solid-liquid separation in the solidifying magma ocean or affecting the downward segregation of denser mineral phases [2]. Whether turbulent convective motions can keep dense particles suspended has been the subject of significant debate [10,11]. We believe the issue is not whether they can but for how long. A simple estimate can be obtained by assuming that mineral grains are transported diffusively with the eddy diffusivity $K = 0.4\ u^*\ y$ of shear driven turbulence. Here y is height above the top of the mostly solid layer and $u^*=(\tau/\rho)^{1/2}$ with shear stress τ. Mass balance also requires a region of upwelling surrounding the downwelling plume. The balance between this upwelling, gravitational settling of particles, and their turbulent diffusion determines the distribution of solid mineral grains. Since both the shear stress and upwelling decrease radially from the plume center and plumes are inherently time dependent, such an analysis does not indicate the perpetual suspension of solids during the solidification of a convecting MO.

Laboratory fluid tank experiments are being carried out to address these processes (see Figure 2). Water, with small amounts of salt added to adjust the buoyancy of small (300-500μm) particles, in a 10 cm thick layer is heated from below at a prescribed rate generating hot turbulent plumes that rise to impinge on the top boundary. Since fluid properties, other than density, do not depend strongly temperature, the hot rising plumes in our experiments can be used to mimic cool

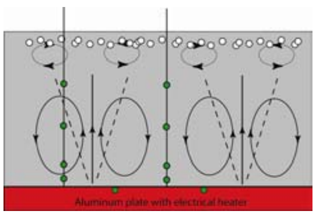

Figure 2. Schematic of experiment. Green symbols show thermcouples. Heater shown in red. White symbols are buoyant particles

sinking plumes in a MO. Temperatures are measured on two vertical columns of thermocouples. Time series of the deviation of temperatures from a uniform secular heating rate provide a measure of plume structure with height. High temperature is measured as a plume migrates past a thermocouple, so that the skewness of the temperature histograms, shown in Figure 3, show high plume temperature. Plume ΔT decreases with height so that skewness decreases. At any height, the highest temperature recorded represents the peak temperature in the plume and the skewness reflects the ration of radius to spacing of plumes. The thermal boundary layer thickness, as shown in mean temperature, and the rms temperature fluctuation as a function of height follow scaling laws expected for turbulent plumes [13,14]. For a heatflux F, thermal boundary layer thickness δ is consistent with a variation as $F^{-1/4}$ and $\Delta T \propto F\delta$ as expected based on similarity analysis [13,16] and boundary layer scaling [15]. Velocities scale approximately as $F^{1/3}$. In our experiments, the Rayleigh number (based on F and layer thickness) $\sim 10^{10}$ and the Reynolds number (based on the convective velocity and layer thickness) $\sim 10^{3}$.

Particle densities are measured as a function of time and position from digital images of scattered white light. The first convective motions mix particles initially at the top boundary into the fluid. Particle densities are highest near the top boundary and decrease with time following this initial increase as shown in Figure 4. The decay with time appears to be longer than the buoyant rise time suggesting, as described above, that turbulent convective motions are acting to suspend particles. This should allow an estimate of the turbulent diffusivity K discussed above. Higher heating rates should generate larger shear stresses τ, larger K and longer decay times. At a heating rate one-half that in Figure 3, the number of suspended particles is much smaller, suggesting the existence of a critical shear stress to lift particles.

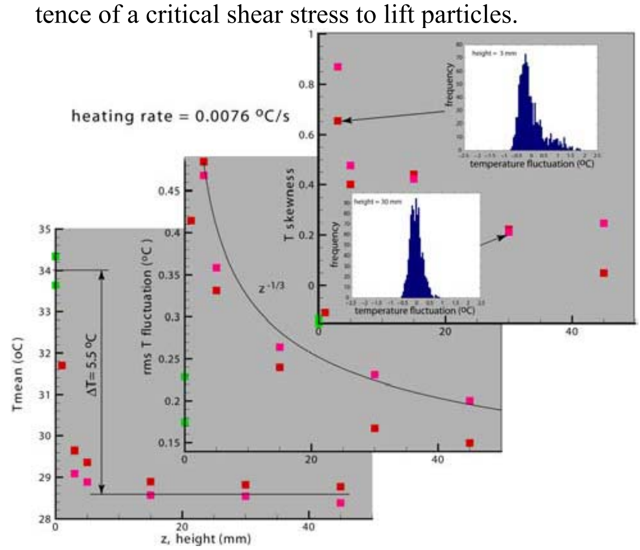

Figure 3. Mean temperature, root mean square temperature fluctuation, and skewness of temperature time series as a function of height above heated bottom boundary.

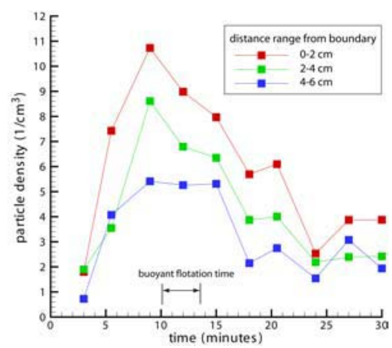

Figure 4. Particle densities as a function of time in three distance ranges from the top boundary.

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