MAGMA OCEAN SOLIDIFICATION PROCESSES ON VESTA. L. T. Elkins-Tanton, E. Maroon, M.J. Krawczynski, and T.L. Grove, MIT, Dept. of Earth, Atmospheric, and Planetary Sciences, Cambridge MA, 02139, ltelkins@mit.edu.

Introduction: The small size of Vesta creates significant physical differences in magma ocean solidification and overturn from those of a larger planet. The different physics of solidification and gravitational equilibrium on a small body produce non-fractional solidification processes. These processes may help explain the compositional paradoxes of eucrites and diogenites: Some diogenites have olivines and orthopyroxenes that are not in Mg# equilibrium, and others have pyroxenes with varying minor and trace element compositions at constant Mg#s [1-3]. The compositional variations are not consistent with a single-stage igneous process, and have lead to conclusions that they require unusual source regions or melting conditions [4,5]. In addition, some diogenites exhibit negative Eu anomalies (e.g., [6]), perhaps explained by magma ocean processing as on the Moon, while other diogenites have no such anomalies.

Magma Ocean Solidification on Larger Bodies: On larger bodies gravity produces a significant crystal settling rate during solidification. Solomatov et al. [7] suggested that particles smaller than diameter *D* with density difference $\Delta\rho$ between themselves and the magma ocean liquids would remain entrained in a magma ocean with viscosity η and surface heat flux *F*, as given by

$$D \approx \frac{10}{\Delta\rho g}\left(\frac{\eta\alpha g F}{C_p}\right)^{\frac{1}{2}}, \qquad 1.$$

scaled by thermal expansivity α, gravity *g*, and heat capacity C_p. In the case of Mars, most mineral grains will settle out of the magma ocean; only those smaller than a fraction of a millimeter will remain entrained, according to this scaling.

Compositional models of magma ocean solidification show that both fractionally-solidified minerals and coexisting liquids become denser through iron enrichment as solidification proceeds. In the case of bodies the size of the Moon and larger, this process has lead to the model of overturn in the solid state following fractional solidification [8-11].

Solidification of a 2,000-km deep magma ocean on Mars or the Earth can be complete in ϑ(10,000) to ϑ(100,000) years, depending upon the atmospheric thickness [12, 13]. The onset of Rayleigh-Taylor instability and overturn of an unstably stratified layer thickness d of fluid with viscosity η is given as

$$t = \frac{4\pi^2\eta}{\gamma g d^2}, \qquad 2.$$

where γ is the compositional density and *g* is gravity [8]. For bodies the size of the Moon or larger, solidification of the magma ocean is largely or entirely complete before the timescale of instability.

Magma Ocean Solidification on Vesta: Perhaps most significantly for Vesta, because of its low pressure gradient an adiabat in a solidifying Vesta magma ocean will lie between the solidus and liquidus for the entire depth of the magma ocean throughout solidification. Over the ~0.6 kbar pressure range of Vesta's mantle the solidus will change by only about 10°C, and the adiabat by only ~2°C. In the absence of other forces, therefore, the entire depth of the magma ocean will contain some crystal fraction (Fig. 1).

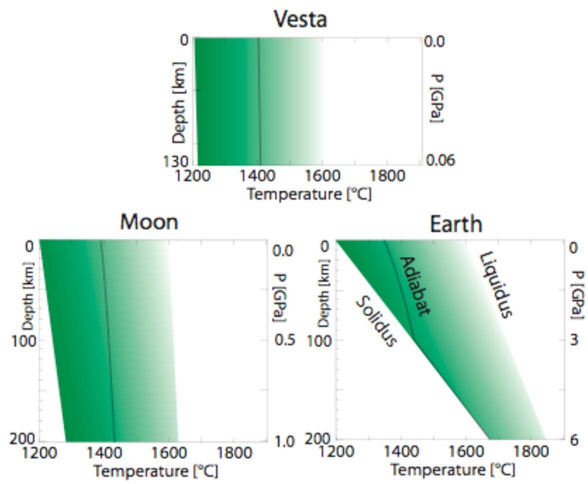

Figure 1: Using identical depth scales but appropriately varying pressure scales, the relationships between an adiabat and an approximate peridotite solidus and liquidus for Vesta, the Moon, and the Earth. Shading indicates the degree of crystallinity between the liquidus and solidus.

As cool downwellings sink from the surface boundary layer on the Earth, increasing pressure and the slopes of the solidus and liquidus mean that the material in the downwelling will attain larger and larger crystallinities as they sink, and as they strike the solid bottom of the magma ocean, the remaining small fraction of liquid will be expelled through compaction [14]. On Vesta, by comparison, downwellings sinking along adiabats will retain roughly the solid fraction they began with at the cool upper boundary (Fig. 1). Downwellings will be denser because of temperature and the slightly higher solid fraction created by the cooler temperature of the upper boundary layer.

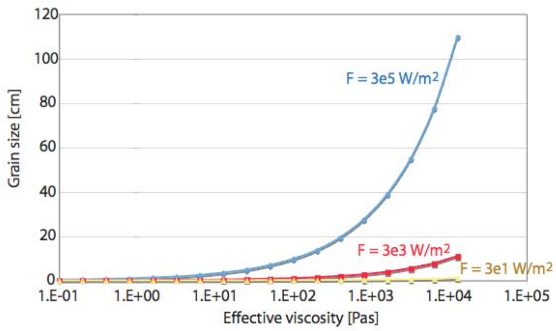

Figure 2: Following eq. 1, grains larger than the values shown for a given heat flux will settle out of convective flow, while smaller grains remain entrained. At high initial heat fluxes a Vestan magma ocean may be able to maintain large grain sizes and grain fractions in the convecting liquid, effectively suppressing fractionation.

Vesta's far smaller gravity field (0.26 m/s^2, [15]) and higher heat flux due to the lack of atmosphere conspire to allow larger particles to remain entrained rather than settling as they would on larger bodies (Fig. 2). Calculations based on methods from Elkins-Tanton [13] indicate that Vesta's solidification will begin at surface heat fluxes of $\vartheta(10^5)$ W/m^2. Over a range of viscosities from 0.1 to 100 Pas, particles from 0.3 to as much as 10 cm may remain entrained in the magma ocean. As heat fluxes from the surface lessen to $\vartheta(10^3)$ W/m^2 later in solidification, all particles larger than a few millimeters will settle out. This scenario raises the possibility that overturn of a compositionally unstable density stratification may occur in material that is a crystal mush overlying a solid, rather than in a completed solid. These numbers also indicate that flotation of a plagioclase crust is less likely than on the Moon.

Compositionally-driven Overturn on Vesta: Assuming internal convective heat transport, the time to solidification of a whole-mantle magma ocean can be calculated from radiative surface heat fluxes using a Stefan-Boltzmann law, as given in Elkins-Tanton [13]. Vesta is expected to solidify in $\vartheta(100)$ years in the absence of a conductive lid or radiogenic heating, though models by Ghosh and McSween [16] indicate that ^{26}Al decay could keep the planet hot for longer periods. In contrast, the timescale for overturn in the solid state for Vesta given by equation 2 is $\vartheta(1{,}000{,}000)$ years, likely after sufficient conductive cooling has occurred to make Vesta's viscosity too high to allow flow in the solid state. Vesta is therefore unlikely to reach gravitational stability in the solid state.

A strong opportunity for overturn exists between these timescale extremes, however, and may offer the physical scenario necessary to create both diogenites and eucrites. When Vesta has completed olivine crystallization and begun orthopyroxene crystallization, consistent with diogenite and olivine-diogenite formation (Krawczynski et al. [3]), heat flux will have reduced to the point that olivine and orthopyroxene will settle, while newer, smaller crystallites will remain entrained in the increasingly compositionally-stratified remaining crystal mush. The crystal mush is likely to have reached or neared a critical crystal fraction, and thus may have a viscosity of 10^{13} Pas or more; interstitial liquids may make up as much as a few tens of percent. The surface of Vesta is therefore well-defined. At this point, the 50 km of crystal mush will have a density gradient of ~3×10^3 $kg/m^3/m$, consistent with overturn according to equation 2 in $\vartheta(10)$ years.

When overturn initiates, perturbations form near the surface and sink as drips into the interior, creating return flow in the form of plume-like upwellings. In a crystal mush environment this produces magmatic processes that are at best uncommon on the Earth: downwelling drips solidify with increased pressure, while upwelling plumes may melt adiabatically. In this simultaneously mixing, solidifying, and melting environment, eucrites may be produced and erupted onto the Vestan surface. Simultaneously, late-solidifying material will be denser than the previously-formed diogenites, and may sink through the diogenites, pushing them closer to the surface and creating the apparent spatial relationship shown by compositional maps of Vesta [17], but belied by the incompatible compositions of the two types of rocks.

Conclusions: The effects of low gravity and low pressure gradient on Vesta make crystal-liquid segregation and gravitationally-driven overturn slower processes than on larger bodies. While diogenites are consistent with solidification of the first 50-60% of a magma ocean, the eucrites require multi-step igneous processes that may be produced in crystal mush toward the end of magma ocean crystallization. This hypothesis separates diogenite and eucrite production in time, but allows them to remain spatially related on Vesta.

References: [1] Fowler *et al.* (1995) *GCA 59*, 3071. [2] Mittlefehldt *et al.* (1996) *GCA 60*, 867. [3] Krawczynski *et al.*, this meeting. [4] Stolper (1977) *GCA*, *41*, 587. [5] Jurewicz *et al*. (1995) *GCA*, *59*, 391. [6] Barrat *et al* (2006) *MAPS 41*, 1045. [7] Solomatov *et al*. (1993) *EPSL 120*, 387. [8] Hess and Parmentier (1995) *EPSL 134*, 501. [9] Solomatov (2000) In *Origin of the Earth and Moon*, U. Arizona Press. [10] Elkins-Tanton *et al.* (2003) *MAPS*, *38*, 1753. [11] Elkins-Tanton *et al*. (2005) *JGR 110*, doi:10.1029/2005JE002480. [12] Abe and Matsui (1985) Proc. 15th LPSC., *JGR 90*, C545. [13] Elkins-Tanton (2008) *EPSL*, in review. [14] Parmentier *et al.* (2007) LPSC abstract. [15] Ruzicka *et al.* (1997) abstract *LPSC 28*, 1215. [16] Ghosh and McSween (1998) *Icarus 134*, 187. [17] Thomas *et al.* (1997) Science 277, 1492.