**ON THE SCALE OF LUNAR MANTLE OVERTURN FOLLOWING MAGMA OCEAN FRACTIONAL SOLIDIFICATION: THE ROLE FOR MULTIPLE SCALES OF CONVECTIVE MOTION,** E.M. Parmentier, Department of Geological Sciences, Brown University, Providence, RI, 02912 (EM_Parmentier@brown.edu).

**Introduction:** In understanding the evolution of the Moon, a number of its fundamental magmatic characteristics must be explained in the context of other geophysical and geological observations. Volcanic activity subsequent to the formation of anorthositic crust was dominated by the eruption of mare basalt. (1) The main phase of mare volcanism began ~500 Myr after the crystallization of the anorthositic crust and continued for ~1 Gyr. (2) The picritic glasses, considered to be representative of primitive mare basalt liquid, were generated by melting, at 400-600 km depth [1,2], of a source containing components that, on the basis of the magma ocean hypothesis, should have crystallized at much shallower depth during fractionation of the anorthositic crust. (3) Mare basalts occur primarily in one region of the Moon. Recent topographic data [3] demonstrate that the earlier idea that mare basalt flooded all areas of sufficiently low elevation is not correct. Large areas of very low elevation do not contain mare basalt. The hemispheric asymmetry of mare basalt distribution on the lunar surface must be explained in some other way [4]. (4) A region of the surface roughly correlating with that containing mare basalts also is thought to contain high subsurface concentrations of KREEP which was excavated during the formation of large impact basins. This so-called Procellarum KREEP Terrane (PKT) [5] is responsible for the Imbrium basin centered thorium anomaly mapped by Lunar Prospector [6]. KREEP, as used here, refers to late stage ilmenite-bearing cumulates of the hypothetical magma ocean that would have crystallized near the base of the anorthositic crust. Interestingly, the region of mare basalt eruptions is near the equator of the Moon's rotational axis, as would be expected if this region is underlain by dense mantle.

**MO fractional solidification and overturn:** The Moon should have been significantly melted if it formed by a large impact with the Earth [7]. 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 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 resulting in a stably stratified mantle that would resist solid-state thermal convection and in which incompatible heat producing elements are carried to depth in the mantle with potentially fundamental implications for the Moon's long term evolution [8,9,10].

**Scale and rate of mantle overturn:** Factors controlling the rate of differentiation and the scale of mixing of dense residual cumulates into the underlying mantle may be complex. First, this layer, if it did not differentiate, would be only 20-40 km thick. Gravitational instability of such a thin layer by solid-state flow at a wavelength of $10^5$ km (the circumference of the Moon) to produce the global scale asymmetry would require an unrealistically low viscosity. A still liquid layer would have a very low viscosity relative to underlying solidified olivine-pyroxene mantle, but the density of residual liquid at pressures near the base of the anorthositic crust, based on estimates like those in [1], is not expected to exceed that of the underlying olivine-pyroxene mantle.

A mechanism allowing initially short wavelength instabilities to evolve into a much longer wavelength global overturn is illustrated by the simple model in Figure 1. Here an initially thin, dense layer at the surface of a sphere in which the viscosity increases with depth. Consistent with expectations from linearized stability analysis, instability begins at a wavelength comparable to the layer thickness; but at later times, a much longer wavelength spherical harmonic-degree-1 flow subsequently grows more rapidly because of its longer wavelength. The early short wavelength instability creates an effectively thicker dense layer that is then unstable at long wavelength [4]. The only requirement for such behavior is a modest increase in viscosity with depth.

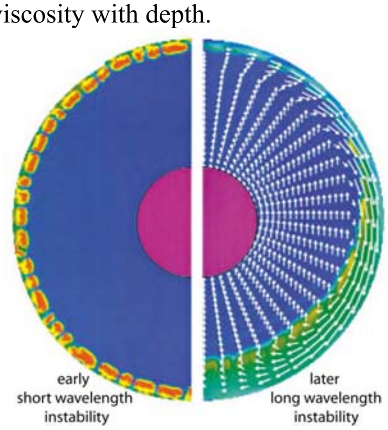


**Figure 1.** Finite amplitude R-T instability of an initially thin (40 km thick) dense layer at the surface of a sphere (with the radius of the Moon) with viscosity increasing by a factor of 5000 over a 400 km depth interval. Central region corresponds to a dense metallic core. Velocity vectors show the spherical harmonic-degree-1 flow pattern present at the later time. Instability begins at a wavelength comparable to the layer thickness; but rapidly evolves to a much longer wavelength flow [4].

While the later long wavelength instability explains the global scale asymmetry of lunar structure, early small scale instability controls the size of KREEP-rich mantle heterogeneities and so plays a fundamental role in subsequent mantle melting and volcanism. In a dense global scale mantle downwelling, melting would be a consequence of heating due to high U, Th, and K within KREEP-rich heterogeneities. Melt generated at depths >400-500 km apparently does not requilibrate with olivine-pyroxene mantle at shallower depth, making the mechanism(s) of melt migration a fundamental aspect of lunar evolution. Melt migration mechanisms should depend on the size of melt-generating heterogeneities relative to the compaction length of the region through which melt migrates.

**Relating the scale of instability to solidification rate:** The model shown in Figure 1, treating only the instabilty of an initially prescribed density stratification, does not account for the progressive solidification and accumulation of unstably stratified mantle. A simple numerical experiment designed to understand the generation of small scale heterogeneity in an accumulating, unstably stratified fluid layer is illustrated schematically in Figure 2. Suppose that a layer (representing solidified lunar mantle) thickens by continuous addition of progressively denser material at a velocity $V$ to the top of the layer. The density of this depositied material is taken to increase linearly with a prescribed, constant value $\delta\rho/\delta z$. In a coordinate system attached to boundary at which deposition occurs, the material in the layer moves downward at the velocity $V$ corresponding to the MO solidification rate. The numerical experiments are based on a finite volume formulation in which buoyantly driven viscous flow is calculated using a multigrid iterative solver, and the density field is advected using the van Leer method. Results reported here are obtained on 512x512 grids with at least 50 grid volumes in each wavelength of stability.

In this simple model, no natural, time independent length scale exists so that a similarity solution (independent of the length scale of the length scale $L$ of the numerical experiment) is to be expected.

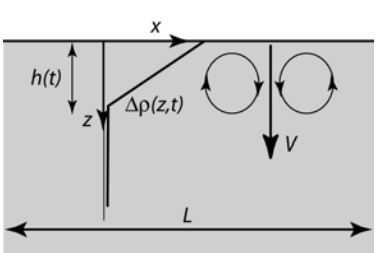


**Figure 2.** Numerical experiment to evaluate the scale of R-T instability in an unstably stratified layer being deposited from above at rate $V$.

As the layer of progressively denser material thickens with time, gravitational instability should first develop when the growthrate of instability $\propto \Delta\rho g h/\mu$ exceeds the rate of layer thickening $V/h$ where $h = V\,t$ is the thickness of the layer at time $t$ and density difference $\Delta\rho = (\delta\rho/\delta z)\ t$. The wavelength at which instability occurs is proportional to $h$ at the time of stability, resulting in a wavelength $\lambda \approx 20 \{\mu V/(\delta\rho/\delta z)g\}^{1/3}$ where the factor of proportionality in this expression is determined from numerical experiments, with results shown in Figure 3.

**Estimates of the range of wavelengths of instability to be expected in the Moon:** From [9], $\delta\rho/\delta z \approx 4\mathrm{x}10^{-3}$ kg/m$^4$. The final stages of MO solidification controlled by heat conduction through the anorthositic crust would have occurred over a time of ~100 Myr resulting in $V \approx 3\mathrm{x}10^{-10}$ m/sec. With a $\mu \approx 10^{19}$ Pa-sec and an appropriate value of $g$ for the Moon, $\lambda \approx 50$ km with a layer thickness $h \approx 10$ km at the time of instability. The radius of spherical inclusion containing the material volume in one wavelength of instability $\lambda^2 h$ would be about 20 km. Among the parameters controlling this size, the viscosity is the one of the least certain. Since inclusion size is proportional to $\mu^{1/3}$, increasing or reducing the viscosity by a factor of 10 changes the inclusion size by only about a factor of 2.

On 100 Myr time scales, KREEP-rich inclusions of the size indicated would become warmer than the mantle in which they are embedded. Inclusions will thus preferentially melt because they are both hotter and have a lower melting temperature. The inclusions should also be large compared to the compaction length for melt migration, and this will control the extent to which melt derived from inclusions metasomatizes olivine-pyroxene mantle into which it migrates, ultimately providing a suitable source for mare basalts.

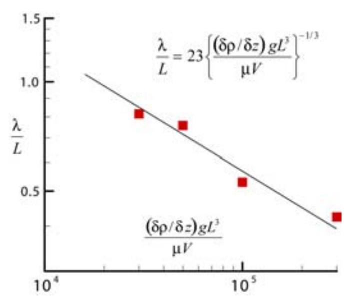


**Figure 3.** Wavelength of gravitational instability in numerical experiments of Figure 2. Selfsimilarity indicates that the domain size $L$ is arbitrary as discussed in the text.

**References:** [1] Delano, J.W., *Proc. Lunar Planet. Sci. Conf.* 20 (1990) 201-213. [2] Elkins, L.T., et al., *Geochim. Cosmochim. Acta* 64 (2000) 2339-2350. [3] Zuber, M.T., et al., *Science* 266 (1994) 1839-1843. [4] Parmentier, E.M., et al. *Earth and Planet. Sci. Lett.* 201 (2002) 473-480. [5] Haskins, L.A., *J. Geohys. Res.* 103 (1998) 1679-1689. [6] Lawrence, D. , et al., *Science* 281 (1998) 1484-1489. [7] Melosh, H.J., in *Origin of the Earth*, Oxford U. Press, 69-83, 1990. [8] Ringwood, A.E. and Kesson, S.E., *Proc. Lunar Planet. Sci. Conf.* 7 (1976) 1697-1722. [9] Hess, P.C., and Parmentier, E.M., *Earth Planet. Sci. Lett.* 134 (1995) 501-514. [10] Stegman, D.R., et al., Nature 421 (2003) 143-146.