FORMATION OF PURE ANORTHOSITE DURING LUNAR MAGMA OCEAN SOLIDIFICATION: IMPLICATIONS FOR THE MELT-SOLID SEGREGATION PROCESS. E.M. Parmentier and Yan Liang, Department of Geological Sciences, Brown University, Providence, RI 02912.

Summary: SELENE remote sensing data indicate that anorthosite consisting of nearly pure plagioclase is exposed in the central peaks of lunar craters. A mafic mineral content of less that 2% inferred from this data places an important constraint on the mechanisms of solid-solid and solid-melt segregation in the lunar magma ocean (MO). Segregation of plagioclase from denser mafic mineral grains can occur by shearing in the granular flow at the top of the low viscosity, convecting, liquid- rich region of the MO. Segregation of residual mafic liquid from a compacting solid plagioclase-rich matrix should occur by the buoyant downward migration of the melt. We will explore the role of both mechanisms in the formation of lunar anorthosite.

Introduction: Anorthositic crustal rocks on the Moon have long been attributed to plagioclase segregation in a magma ocean (MO); in fact, anorthite-rich Apollo samples provided a primary motivation for the MO hypothesis [cf. 1]. While other mechanisms to generate lunar anorthosites have been explored [2,3], plagioclase flotation in a MO remains a frequently cited hypothesis. Recent results from the Multiband Imager on the KAGUYA (SELENE) spacecraft indicate the presence of anorthosite with plagioclase abundance exceeding 98% [4] in the central peaks of lunar craters. These occurrences of nearly pure anorthosite motivate the need to explore whether plagioclase segregation in a MO can produce lithologies that are almost free of mafic minerals; and, if so, the conditions under which this might occur.

The magma ocean setting for anorthosite formation: Figure 1 illustrates schematically temperature distributions expected in a cooling, solidifying lunar MO. The separation of plagioclase has frequently been thought of as crystal flotation in a mafic liquid. However, as recognized previously [5,6], the lunar MO during crystallization of the anorthositic crust is not expected to be fully liquid at any depth, but rather mixture of liquid and solid in varying proportions. The column inset in Figure 1, reproduced from [7], shows the composition of solids that would crystallize at each depth during the progressive fractional solidification of a particular lunar bulk composition. Liquid fractions are likely to exceed 50% during a significant fraction the plagioclase crystallization interval.

Figure 2 shows that the MO should consist of two regions: a deeper mostly liquid region in which the viscosity is close to that of the liquid. Cooling at the top of this region combined with its low viscosity should allow vigorous convection [12]. In the mostly solid region at shallower depths mafic liquids can be segregated from a compacting plagioclase-rich solid matrix by buoyantly driven melt migration.

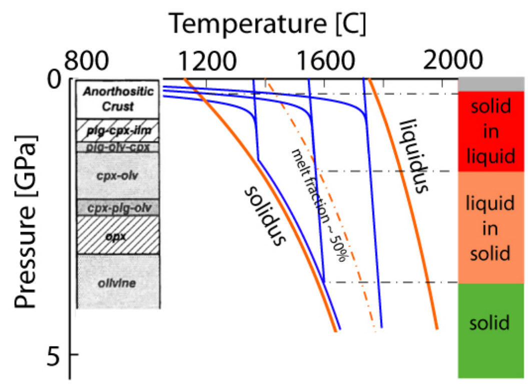

Figure 1. Idealized thermal structure of a cooling solidifying lunar MO. The region of the MO in which plagioclase crystallizes is expected to be mostly solid.

Segregating liquid from solid by compaction and melt migration: Downward migration of denser, mafic, interstitial liquid by porous flow through a deformable solid matrix that compacts as the liquid segregates can have important implications for both purity and geochemistry of anorthosites. These liquids should be rich in incompatible and heat producing elements that are important for the longer term thermal evolution of the Moon.

Melt migration driven by buoyancy may be limited by resistance due to viscous flow through small pore spaces or by the compaction of the solid matrix. The relative magnitude of these two effects depends on the compaction length $L = (K\xi/\mu)^{1/2}$ where μ and ξ are viscosities of liquid shear and matrix compaction, respectively, and K is the matrix permeability [8,9,10]. We adopt a laboratory-derived permeability $K = b^2\phi^3/300$ [11] that depends on the liquid fraction ϕ and the grain size b. ξ is usually approximated by the matrix shear viscosity; however, recent laboratory measurements suggest that the compaction viscosity depends on both ϕ and the excess pore fluid pressure [15]. As a first estimate, we simply adopt a typical value of ~10^{19} Pa-s for shearing of anorthite near MO melting temperatures, but recognize this as an important aspect for further study. For ϕ = 1% and b = 1 mm, L ~ 200 m. For a compacting layer thicker than L, dense melt will migrate downward with a velocity $\Delta\rho g K(\phi)/\mu\phi$, except in a compacting boundary layer of thickness L as shown in Figure 2.

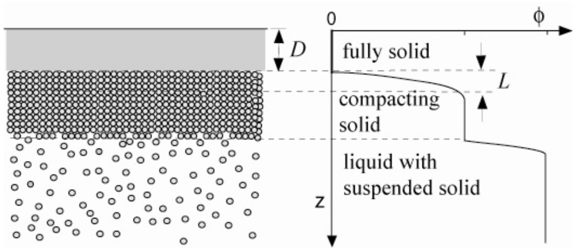

Figure 2. Schematic illustration of the structure near the top boundary of the MO. Segregation of plagioclase from mafic residual liquid will occur due to buoyantly-driven downward migration of mafic melt in the compacting plagioclase matrix. Segregation of mafic minerals from plagioclase can occur due to shearing in the granular flow at the bottom of the mostly solid compacting layer (Figure 4).

Heat conduction through the fully solidified layer will cause the top of the partially molten region to migrate downward with a velocity $2\kappa/D$. Here D is the solidified layer thickness and κ is the thermal diffusivity. Equating the buoyant melt migration velocity with the rate of thickening of D yields an estimate of ϕ at which melt freezes before it can segregate downward. This ϕ value is shown in Figure 3 as a function of D for a range of grain sizes. A trapped melt fraction, corresponding to the mafic mineral content of the anorthosite, less than 2%, as indicated SELENE measurements, is possible if grain size is sufficiently large > 3mm. Note also that the calculated trapped melt fraction decreases as the solidified layer thickens, because a thicker layer thickens more slowly. This suggests that the mafic mineral content should be less in the central peaks of larger impact craters that excavate to greater depth - a prediction that could perhaps be tested with high resolution remote sensing data.

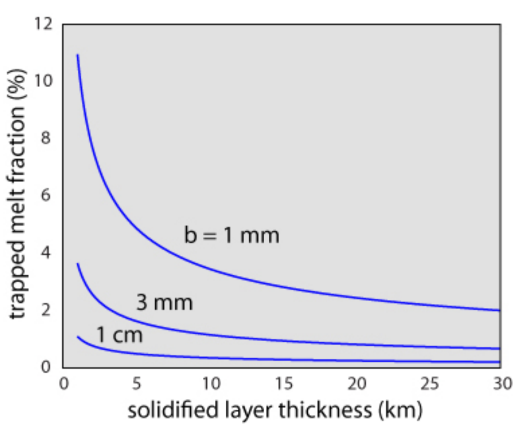

Figure 3. Calculated trapped melt fraction due to freezing at the top of the MO shown for several grain sizes and with a liquid viscosity of 10 Pa-s.

Segregating solids by granular shearing: Segregation of solid grains may occur near the base of the compacting layer due to shearing produced by strong convective motion in the low viscosity, mostly liquid region beneath. As illustrated in Figure 4, shearing allows dense (mafic) mineral grains to settle through a granular aggregate of less dense (plagioclase) grains. Estimates of rates of segregation by this mechanism [13,14] can be applied to the lunar MO. In constrast to melt migration, this mechanism will become less effective as the solidified lid thickens. As the solidified lid thickens, thus reducing heat flux to the surface, convective motions will weaken resulting in less shearing and slower segregation by this mechanism.

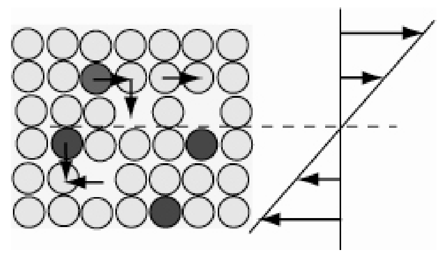

Figure 4. Segregation of dense solid grains (dark) in a sheared granular flow near the top boundary of the layer of solid suspended in liquid. In this idealization, relative motion of layers of particles due to shearing allow dense grains to fall into space between less dense grains (light). Buoyant grains do not. Here the shearing rate will control the rate of segregation. Shearing is a consequence of convective instability in this low viscosity region.

References: [1] Taylor, S. R. (1982) *Planetary Science: A Lunar Perspective* (Lunar and Planetary Institute. [2] Warren, P. H. (1990) *Am. Mineral.* **75**, 46–58. [3] Longhi, J. (2003) *J. Geophys. Res.* **108** doi:10.1029/2002JE001941. [4] Ohtake, M., et al. (2009) *Nature* 461, 237-241. [5] Solomon S.C. and Longhi J (1977) *Proc. Lunar Sci. Conf* . 8, 583–599. [6] Tonks W.B. and Melosh H.J. (1993) *J. Geophys. Res.* 98:5319–5333. [7] Snyder G.A., Taylor L.A., Neil C.R. (1992) *Geochim. Cosmochim. Acta* 56:3809–3823. [8] Ribe, N.M. (1985) *Earth Planet. Sci. Lett.*, *73*, 361–376. [9] Shirley D.N. (1986) *J. Geol*. **94**: 795-808. [10] Shirley D.N. (1983) *J. Geophys. Res.* 88, A519–A527. [11] Wark, D.A. and Watson, E.B. (1998) *Earth Planet. Sci. Lett.*164, 591-605. [12] Solomatov, V.S. (2000) *Origin of the Earth and Moon.* Canup RM, Righter K (eds) Univ Arizona Press, p 323–338. [13] Ottino J.M. and Kakhar, D.V. (2000) *Ann. Rev. Fluid Mech.* 32, 55-91. [14] Paterson, M.S. (2001) *Tectonophysics* 335, 51-61. [15] Renner, J., Viskupic, K., Hirth, G. and Evans B. (2003) *Geochem. Geophys. Geosyst.* 4, doi:10.1029/2002GC000369.