CRYSTAL SETTLING IN A VIGOROUSLY CONVECTING MAGMA OCEAN. W. B. Tonks and H. J. Melosh, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ. 85721.

Fractional crystallization of a cooling magma ocean is the generally accepted explanation of the observed dichotomy between the Europium-enriched anorthositic crust and the Europium-depleted basaltic source regions of the moon (i.e. Wood, 1970). The accretion theory of Safronov (1972) as extended by others (i.e. Kaula (1979)), coupled with the energetics of core formation strongly suggest that the earth underwent early extreme energy events; thus if the moon had a magma ocean the earth should have had one also. This is especially true if the moon was formed by the giant impact of a Mars-sized body as noted in the works of Melosh and Kipp (1988) and Cameron and Benz (1988).

On the other hand, a number of workers (i.e. Kato et. al. (1988) and Drake et. al. (1988)) have argued that the earth could not have had a deep magma ocean since fractionating phases such as perovskite and majorite garnet would have a large effect on the ratios of elements such as Sc/Sm and Ni/Co (present in the mantle in nearly chondritic abundances). However, it seems possible that vigorous convection may cause crystals to remain in intimate contact with the magma and the permit the ocean to cool via equilibrium crystallization. We investigated this possibility using the relatively simple model shown below.

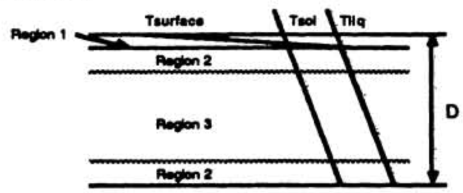

Figure 1. Model showing 3 distinct regions of behavior at the start of the computation.

It is assumed that the liquidus and solidus temperature profiles of the planet have the same slope as the adiabat. This is only strictly valid for a very small planet although recent experiments on the melting curves of peridotite at very high pressures (Takahashi, 1986) indicate that this simplification may not be too unrealistic even for the earth. The planet is melted uniformly to depth D, and is originally at the liquidus. The temperature difference between the surface and the magma sets up free convection. The model considers only the effect of the cooling magma. After a time Δt, the ocean has lost an amount of energy equal to $h\Delta t$, where h is the heat flux. The heat flux h is derived from the Nusselt number, Nu ($h=h_c Nu$, where h_c is the heat that would be conducted through a slab of thickness D), which itself is related to the Rayleigh number of the convection though the following relationship:

$$Nu = 0.089 \cdot Ra^n$$

where n has been shown theoretically to be 0.3333 but experiments indicate it should be 0.289.

It is presumed (McBirney and Murase, 1984) that the magma behaves as a viscous liquid until the concentration of crystals in the crystal-magma mush exceeds about 50%, at which point the mush locks up, the crystals and liquid are unable to separate, and any further motion occurs by the mechanisms of subsolidus convection. The magma will thus solidify into the same chemical composition as the starting material since the liquid and solid fraction remain intimately mixed. Note that in this study we explicitly exclude consideration of liquid-mush separation. We are well aware that this effect may be important, but limit our work to the question of crystal settling now.

The convective regime of such a system breaks into 3 distinct regions as described by Kraichnan (1962). Region 1 is the normal conductive boundary layer. Region 2 is a layer where the flow is dominated by viscous forces but is still highly turbulent. In region 3 the flow is dominated by inertial forces, causing the formation of large scale eddies having spatial dimension of the order of the depth of the ocean. These eddies sweep into region 2 at the bottom of the ocean (where the mean convective velocities go to 0 as pointed out by Martin and Nokes, 1988) and give rise to upward directed forces which have the potential to entrain crystals which have already settled or are about to settle out (Bagnold, 1965). In particular, if the effective friction velocity arising from these large eddies is about the same as the terminal velocity of settling crystals, the crystals should stay in suspension. Thus the ratio of the fall velocity of crystals to the effective frictional velocity (known as the Rouse number, S) was calculated, using Kraichnan's equations and a routine that calculated the Stoke's fall velocity if the local Reynold's number of the crystals was <1 (which is normally the case) and invoked the drag coefficient if the local Reynold's number was >1. Thus if S<1 and region 3 exists, the magma ocean remains well stirred with a steady state fraction of its crystals remaining in suspension. According to Kraichnan (1962), region 3 exists if the following condition is met:

$$Ra^{.3333} \geq 35 \cdot Pr^{0.5}$$

In our magma ocean models, region 3 existed for the entire cooling history, except for a 1 km magma chamber in which region 3 disappeared at about 48% crystallization. Thus it seems probable that convection can keep a magma ocean from separating, but a magma chamber may fractionate by the mechanism discussed by Martin and Nokes (1988). The only parameters that were varied between the Earth and Moon models were the bulk compositions and the acceleration of gravity. The liquidus and solidus temperatures, among other parameters, were intentionally kept constant.

Results of the modelling showed that small crystals (with diameters of the order of a few centimeters or less) should remain suspended in the magma, but larger crystals should settle out from both a 1000 km magma ocean on earth and a 400 km ocean on the moon. Both have very similar Rouse numbers for a given crystal diameter. This surprising result can be understood by deriving the dependence of the Rouse number on the variables in the model assuming the fall velocity is given by Stokes law and using Kraichnan's equations. These dependences are:

$$S \propto D^{-n} g^{\frac{2-n}{3}} \nu^{-\left(1-\frac{n}{3}\right)} d_{cry}{}^{2}$$

where D is the depth of the magma ocean, g is the acceleration due to gravity, d_{cry} is the crystal diameter, and n defined above. The strongest dependence is on the crystal diameter--large crystals are more difficult to suspend than small ones. As the ocean crystallizes, crystals become less likely to separate due to the increase in viscosity. The Rouse number increases as gravity increases: even though a higher acceleration of gravity increases convective vigor, the Stoke's law increase in the settling velocity overcomes it, allowing crystals to more easily separate. Thus the effect of the difference in acceleration due to gravity between the earth and moon on the Rouse number is insufficient to create the geochemical disparity between them. However, the difference in g would result in different temperature profiles. On the moon, the adiabat is nearly parallel to the liquidus and solidus profiles. Thus in a lunar magma ocean crystallization can occur anywhere in the ocean. Crystals will not melt anywhere in the ocean but will continue to grow larger until they are able to settle out. On the earth, however, the liquidus and solidus are steeper than the adiabat. Thus on the earth, crystals would grow in the region between the solidus and liquidus near the bottom then be swept into the main body of the ocean which is superliquidus where they would melt. The mean size of the crystals would then be kept smaller and crystals might not settle out. This concept needs to be tested in detail.

REFERENCES: Bagnold, R. A. (1965) *U. S. G. S. Prof. Pap* **422 I**; Cameron, A. G. W. and W. Benz (1988), *Abstracts submitted to the Origin of the Earth Conference*; Drake, M. J., Malvin, D. J., and Capobianco, C. J. (1988), *Abstracts submitted to the Origin of the Earth Conference*; Kato, T., Ringwood A. E., and Irifune T. (1988) *Earth Planet. Sci Let.* **89**, 123-145; Kaula, W. M. (1979) *J. Geophys. Res.* **84**, 999-1008; Kraichnan, R. H. (1962) *Phys. Fluids* **5**, 1374-1389; Martin, D. and Nokes, R. 1988. *Nature* **332**, pp. 534-536; McBirney, A. K., and Murase, T. (1984), *Ann. Rev. Earth Planet. Sci.* **12**, 337-357; Melosh, H. J. and Kipp, M. E. (1988), *Abstracts submitted to the Origin of the Earth Conference*; Safronov, V. 1972. *NASA translation by Israel Program for Scientific Translation*, NASA TT F-677; Takahashi, E. (1986), *J. Geophys. Res.* **91**, 9367-9382; Wood, J. A. (1970) *J. Geophys. Res.* **32**, 6497-6513.