THE EFFECT OF THERMAL CYCLING ON CRYSTAL-LIQUID SEPARATION DURING LUNAR MAGMA OCEAN DIFFERENTIATION. R. D. Mills (ryan.d.mills@nasa.gov), NASA-ARES, JSC, Houston TX 77058.

Introduction: Differentiation of magma oceans likely involves a mixture of fractional and equilibrium crystallization [1]. The existence of: 1) large volumes of anorthosite in the lunar highlands and 2) the incompatible-rich (KREEP) reservoir suggests that fractional crystallization may have dominated during differentiation of the Moon. For this to have occurred, crystal fractionation must have been remarkably efficient.

Several authors [e.g. 2, 3] have hypothesized that equilibrium crystallization would have dominated early in differentiation of magma oceans because of crystal entrainment during turbulent convection. However, recent numerical modeling [4] suggests that crystal settling could have occurred throughout the entire solidification history of the lunar magma ocean if crystals were large and crystal fraction was low. These results indicate that the crystal size distribution could have played an important role in differentiation of the lunar magma ocean. Here, I suggest that thermal cycling from tidal heating during lunar magma ocean crystallization caused crystals to coarsen, leading to efficient crystal-liquid separation.

Thermal cycling and crystal coarsening:. Coarsening of crystals is typically thought to occur during: 1) slow cooling with limited nucleation and 2) aging under isothermal conditions owing to the inverse relationship between crystal size and surface energy (i.e. Ostwald ripening). However, another process that can greatly enhance development of large crystals is thermal cycling. Melting and crystallization experiments on basalt [5, Fig. 1] demonstrate that thermal cycling increases the mean size of olivine and plagioclase crystals and decreases the crystal number density. These results are in agreement with studies of ice coarsening in ice cream [6] and coarsening of ammonium thiocyanate in a magma analog [7], and demonstrate that thermal cycling can coarsen silicate minerals in silicate melts.

Melting and crystallization experiments were performed at a mean temperature of 1150ºC and near the Ni-NiO buffer to investigate the role of amplitude, period and duration on crystal size distributions of plagioclase and olivine. Results indicate that amplitude positively correlates with coarsening (Fig. 1) and that coarsening appears to be insensitive to the period of the oscillation over the range of periods investigated (10 to 60 minutes). Although these experiments were not designed to investigate crystallization of a lunar magma ocean, they do show that crystal coarsening during temperature cycling appears to be a universal process in magmas of varied compositions.

Temperature cycling in the lunar magma ocean: Large lunar orbital eccentricity would create significant tidal heating early in the Moon's history [8]. Oscillations in the magnitude of tidal heating would be likely if the Moon was not tidally locked during magma ocean solidification. Under those conditions, any single portion of the Moon would have experienced cycling of tidal heating as the Moon rotated relative to the Earth. The cycling of heat could have coarsened the crystals in the magma ocean if the amplitude was not too large, leading to complete dissolution. Certainly depth in the magma ocean would be an important variable with regards to heating [9], and the subsequent coarsening of crystals.

Crystal size and chemical evolution of a magma ocean: [3, 10] show that there is a critical grain size for a given heat flux that defines whether crystals will settle from turbulent flow. For a heat flux of 10^4 (J m^{-2} s^{-1}) that critical diameter is ~ 0.001 cm and for a heat flux of 10^5 (J m^{-2} s^{-1}) the critical diameter is ~ 0.002 cm.

Plagioclase size distributions (Fig. 2) from [5] and Fig. 1 show that after temperature cycling a much larger fraction of the total plagioclase mass is concentrated in crystals greater than the critical diameters listed above (note: plagioclase crystal shapes are not spheres and so the critical values will likely be slightly different). For instance ~85% of the plagioclase mass of the cycled runs is in crystals greater than 0.002 cm whereas only 55% of the plagioclase mass of the static temperature run was in crystals > 0.002 cm. These results indicate that chemical fractionation would have been much more efficient during lunar differentiation if temperature cycling coarsened the crystallizing minerals.

References: [1] Sha L. (2012) GCA 86:52-75. [2] Tonks W. and Melosh H.J. (1990) Origins of the Earth 151-174. [3] Solomatov V.S. (2000) Origin of the Earth and Moon 323-338. [4] Suckale et al. (2012) J. of Geo. Res. 117:E08005. [5] Mills R.D. and Glazner A.F. (in revision) Contrib. Mineral. Petrol. [6] Donhowe D. P. and Hartel R.W. (1996) *Int. Dairy Journal, 6,* 1191–1208. [7] Mills et al. (2011) *Geology, 39,* 1139–1142. [8] Touma J. and Wisdom J. (1998) The Astronomical Journal 115:1653-1663. [9] Meyer et al. (2010) Icarus 208:1-10. [10] Elkins-Tanton L.T. (2012) Annu. Rev. Earth Planet Sci. 40:113-139.

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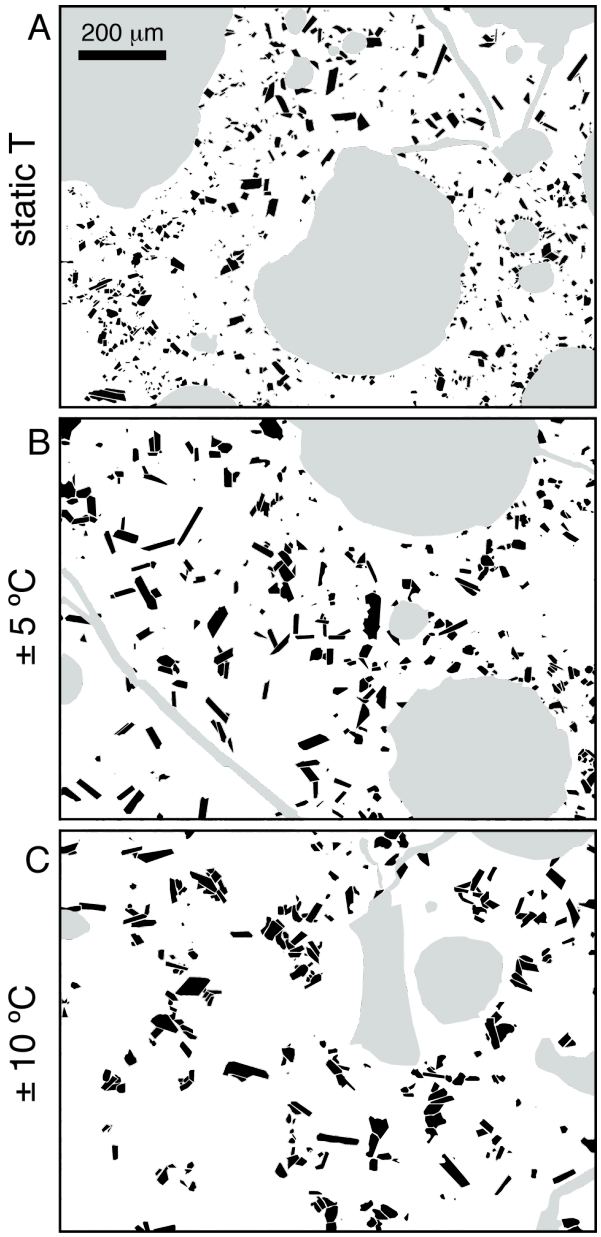

Fig. 1. Figure modified from [5]. Phase maps of plagioclase (black) and void space (gray). All three of the experiments shown had duration of 120 hours and the cycled experiments had a period of 20 minutes. The plagioclase mode for all three experiments is ~ 10%, excluding void space. Scale bar applies to all three images. Crystal density in: A is 984 mm^{-2}, B is 361 mm^{-2}, and C is 231 mm^{-2}. Median plagioclase size in: A is 53μm^2, B is 210 μm^2, and C is 298 μm^2.

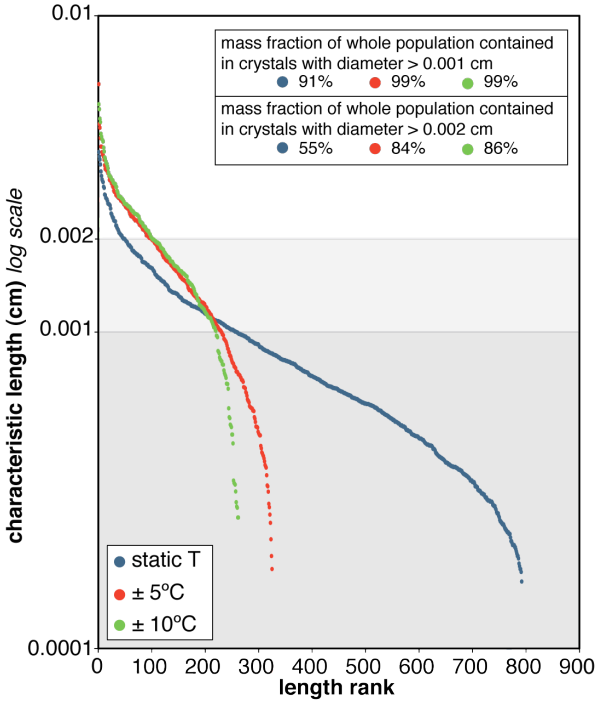

Fig. 2. Characteristic length ($area^{1/2}$) of plagioclase crystals from Fig. 1 plotted in order of decreasing length. Crystal populations from cycled experiments (red and green) have a much higher fraction of the total mass contained in crystals greater than critical values (0.001 or 0.002 cm). Mass fractions were obtained by cubing the characteristic length for each crystal to obtain volume. However, this assumes a cube shape, so it is only a basic estimate of volume or mass.