WATER IN THE LUNAR MANTLE: RESULTS FROM MAGMA OCEAN MODELING. L.T.. Elkins-Tanton[1], [1]MIT Dept. Earth, Atmospheric, and Planetary Sciences, 77 Massachusetts Ave., Cambridge MA, ltelkins@mit.edu

Introduction: The Moon is posited to have formed by reconsolidation of materials produced during a giant impact with the Earth early in solar system evolution [1-3]. The young Moon appears to have experienced a magma ocean of some depth, which resulted in the formation of an anorthosite flotation crust. The hypothetical energetics of such an impact and cooling process, combined with the low oxygen activity implied by lunar petrology, has lead investigators to believe that the Moon was free of water.

Recent results indicating water in lunar volcanic glasses produced by fire fountaining [4] and in surface materials [5-7]. The volcanic glasses are reported to contain 4 to 46 ppm water, thought to be the remnant after degassing an original minimum 260 ppm [4]. This water suggested to be in the lunar interior may be at odds with the pervasive existence of native iron in lunar rocks [*e.g.*, 8,9].

The lunar magma ocean hypothesis forms a framework for assessing these data about water on the Moon. Lunar sample suites indicate fractional crystallization of a lunar magma ocean, including efficient flotation of anorthosite to its surface, unimpeded by high crystal fractions or crystal networks [1,2]. Modeling lunar magma ocean solidification including a small amount of initial water produces predictions for the locations and quantities of water that should be found in the lunar interior, and which would have been degassed and possibly interacted with the lunar surface.

Models: At the beginning of magma ocean solidification the dense iron- and magnesium-rich olivine and pyroxene crystallizing from the cooling magma are believed to have sunk to the bottom of the magma ocean. When approximately 80% of the lunar magma ocean solidified, anorthite began to crystallize and float upward through the more dense magma ocean liquid; anorthite will continue to be added to this flotation crust until the last dregs of the magma ocean solidify [1,2,10].

Our models include fractionation of magma ocean cumulates in assemblages determined *a priori* and shown in Figure 1. Compositions of mineral phases are calculated in equilibrium with the magma ocean liquid composition at that stage of solidification, using experimentally-determined K_Ds for major elements and partition coefficients for hydroxyl and trace elements; for methods and tables of experimental data see [11].

Following solidification the lunar mantle has a gravitationally unstable density gradient and will undergo compositionally-driven overturn to stability [12, 13].

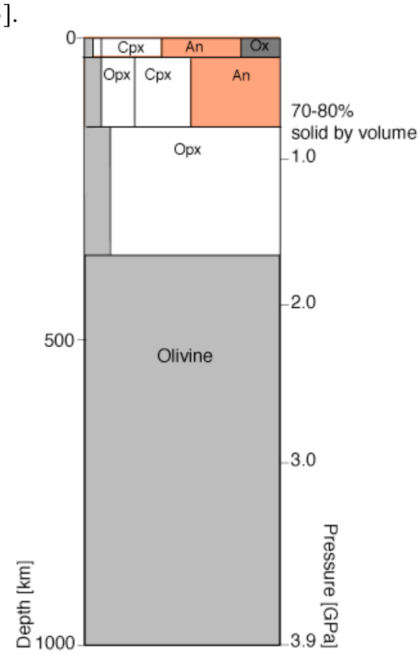

Figure 1: Cumulate minerals assumed to solidify from the hypothetical 1,000 km-deep lunar magma ocean. Opx = orthopyroxene; Cpx = clinopyroxene; An = Anorthite; Ox = titanium-bearing oxides. Anorthite is assumed to float and the other minerals to sink.

Results: Models including convection in the remaining magma ocean, conduction through the growing anorthosite lid, and radiation into space indicate that the magma ocean may freeze to the point of anorthosite formation in less than 10^4 years, and perhaps as little as 10^3 years. After this brief free-surface cooling period the growth of the anorthosite lid radically slows heat loss, and complete solidification of the magma ocean will require additional tens of millions of years.

Any water in the lunar magma ocean will partition in minute quantities into the solidifying cumulate minerals, all of which are nominally anhydrous phases. Water, and all other incompatible elements, is therefore progressively enriched in the evolving magma ocean liquids as solidification progresses. Progressive enrichment of water in magma ocean liquids produces increasing water contents in solidifying cumulate minerals. A model beginning with 100 ppm water in the bulk lunar magma ocean produces a cumulate mantle containing the water contents shown in figure 2.

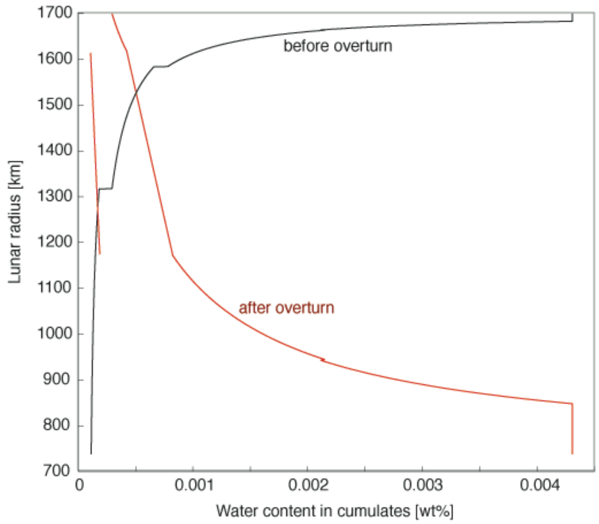

Figure 2: Water contents of lunar mantle cumulates after solidification but before gravitationally-driven overturn (black) and after overturn to stability (red). Note that this image does not include the overlying ~40 km of anorthosite crust, which is assumed to remain in place and not to participate in overturn.

Fractional solidification of the lunar magma ocean beginning with 100 ppm water would result in a source region for lunar picritic glasses and mare basalts with less than 1 ppm water ("after overturn" curve). The water contents indicated in this model result are not sufficient to explain the suggested source water contents in [1].

Higher initial magma ocean water contents can be considered. If the picritic glasses erupted with 500 ppm water and they were a 20% melt of their source region, then the source region contained about 100 ppm of water. This level requires an initial magma ocean with 1 wt% water, probably an unrealistic value.

Summary The magma ocean model produces several predictions:

1. Significant water contents in picritic glasses or mare basalts were not likely obtained from primary, unaltered source regions within the lunar mantle.

2. The ubiquity of iron metal in lunar samples must be reconciled with any models for water activity.

3. Enrichment of water in evolving lunar magma ocean liquids predicts the highest water contents would be in KREEP materials; though KREEP basalts also contain iron metal [9] they are an important target for water measurements.

4. At initial water contents under 300 ppm the lunar magma ocean does not reach saturation and so degassing may be minimal.

5. Highest water contents in the magma ocean, and therefore the time of highest volatile degassing, is at the end of magma ocean solidification when residual liquids are beneath the conductive anorthosite lid. This lid, therefore, may have been fluxed with some volatiles and contain heterogeneous incompatible element and volatile reservoirs. When the lid begins to form the magma ocean is hot and liquid; cooling in the lid proceeds slowly over millions of years. Cooling curves are shown in Figure 3.

6. Water in picritic glasses may therefore have been diffused into the beads from a later compositional addition from one of the other, more volatile-rich reservoirs possibly available during the process of rise and eruption.

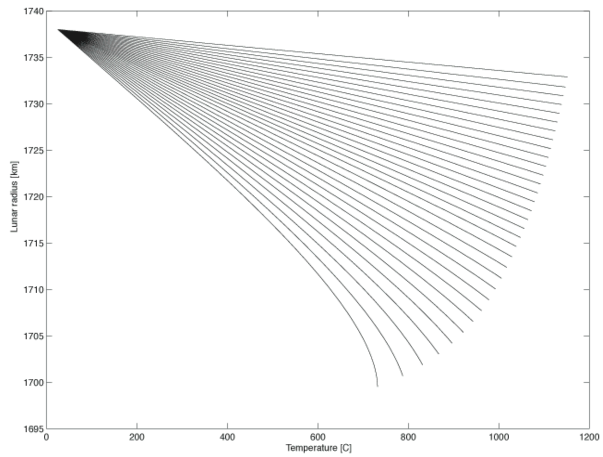

Figure 3. Temperature profiles through the growing, conductive anorthosite lid on the solidifying lunar magma ocean. The top curve shows the thinnest, initial lid; lid growth from the bottom is shown in each subsequent curve that begins at greater depth.

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