WATER IN THE LUNAR MAGMA OCEAN.

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Introduction: Lunar sample suites indicate fractional crystallization of a lunar magma ocean (*1-6*). The last dregs of the magma ocean, the ur-KREEP, would have been highly enriched in incompatible elements, including any water or hydroxyl; this simple observation forms a base for this study.

After fractional solidification and gravitational solid-state cumulate overturn, secondary melting of cumulate source regions produced mare basalts and picritic glasses. Here we present results from modeling fractional solidification of a lunar magma ocean with traces of water, and thermodynamic calculations of oxygen, hydroxyl, water, and iron metal co-existence, as found in many lunar samples.

Models: Compositions of mineral phases are calculated in equilibrium with the magma ocean liquid composition at each fractionation step using experimentally-determined partition coefficients for water; a full model description is given in (*7*).

Results and discussion: To recreate the inferred melting source region water contents from (*8, 9*) (100 to 700 ppm) through a fractionally solidifying magma ocean, the bulk magma ocean must have contained at least 100 ppm with a high fraction of retained interstitial melt in the cumulates, or, more likely, over 1000 ppm water with a smaller retained melt fraction. The smaller hypothesized melting source region water contents of (*10-12*) (10 ppb to 10 ppm) can be created with a bulk magma ocean with 100 ppm water or less.

Magma oceans that began with 100 ppm or more of water would likely produce KREEP with water concentrations in the weight percent abundance range (Table 1). Further, if KREEP originally resided at the base of the anorthosite flotation crust, it would have formed at a pressure around 2 kbar, sufficient for water saturation near 5 wt% (*13*). Thus degassing is not a sufficient explanation for drying KREEP.

The existence of water or hydroxyl in magma implies this reaction relationship $H_2 + \frac{1}{2} O_2 \Leftrightarrow H_2O$, which is controlled by an equilibrium constant *K*; see (*14*). Maintaining a magma with 1 wt% water at an f_{O_2} below the iron-wüstite buffer requires hydrogen fugacity between 1 and 100 bars. At low f_{O_2} and high magmatic temperature, f_{H_2} has to be equal to or greater than f_{H_2O}. At low f_{O_2} and low magmatic temperature, f_{H_2} can be as much as two orders of magnitude less than f_{H_2O} but never less than about 0.1 bar on the Moon. We therefore conclude that significant water contents in magmas are unlikely on the low-gravity Moon.

Conclusions: We conclude that (1) KREEP signature and water should be positively correlated if the water was processed through the original magma ocean, and (2) producing a picritic glass source region with water consistent with the results of Saal et al. (*8*) creates KREEP too wet to be consistent with lunar petrology. We further suggest that the measurements made in lunar samples are largely explained by hydrogen rather than hydroxyl or water. Additionally, water may have been delivered to the lunar shallow mantle by later impacts, and non-water volatiles may have been degassed from the lunar magma ocean and trapped in the lunar conductive lid, providing a later driving mechanism for fire fountains.

Initial water content of magma ocean [ppm]	Water in KREEP (final 2 vol% of magma ocean) [wt%]
1000	~4.7
100	~0.5
10	~0.05

Table 1. KREEP water contents resulting from magma ocean fractional solidification with 1% retained interstitial melt.

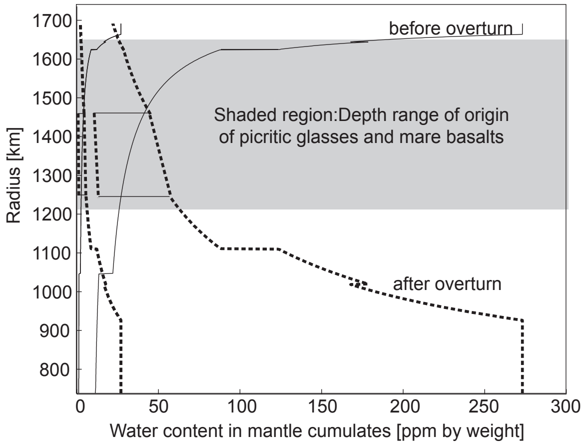

Figure 1. Effect of initial bulk magma ocean water on cumulate mantle composition. 100 and 1000 bulk ppm water, with 1% retained melt.. Depth range of picritic glasses and mare basalts from experiments referenced in (*15*).

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