



Water In The Lunar Mantle: Results From Magma Ocean Modeling

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The Moon is posited to have formed by reconsolidation of materials produced during a giant impact with the Earth. The young Moon appears to have experienced a magma ocean of some depth. 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, however, indicate that lunar volcanic glasses produced by fire fountaining contain small amounts of water (Saal et al., 2008). The volcanic glasses are reported to contain 4 to 46 ppm water, thought to be the remnant after degassing an original minimum 260 ppm.

Lunar sample suites indicate fractional crystallization of a lunar magma ocean, including efficient flotation of anorthite to its surface, unimpeded by high crystal fractions or crystal networks. 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 water that would have been degassed. Compositions of mineral phases are calculated in equilibrium with the magma ocean liquid composition at that stage of solidification, using experimentally-determined KDs for major elements and partition coefficients for hydroxyl and trace elements; for methods see Elkins-Tanton (2008).

Water and all other incompatible elements are 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. Between 0.2 and 1% of the magma ocean liquid water content will be incorporated into solidifying cumulates, enhanced by trapped interstitial liquids. Upon later melting about 99% of cumulate source region water moves into the melt phase. Finally, upon eruption, Saal et al. (2008) estimate that 98% of magmatic water is degassed.

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 10 ppm water, insufficient to explain the suggested source water contents in Saal et al. (2008). With an initial 1,000 ppm water, the relevant mantle cumulates obtain about 50 ppm water. If volcanic glasses represent 20% melting, then the magma begins with 250 ppm that is reduced to 5 ppm upon eruptive degassing, matching measurements from Saal et al. (2008).

Such a high initial magma ocean water content, however, would produce exceptionally water-rich final magma ocean liquids (KREEP). Water enrichment in later-forming cumulates may not be consistent with observed lunar petrology, which includes iron metal. Further, high water contents suppress plagioclase solidification and would work against formation of the observed anorthositic flotation crust.

Water enrichments in volcanic glasses, therefore, may not be a primary source characteristic. The time of highest volatile degassing is at the end of magma ocean solidification when residual liquids are beneath the conductive anorthositic lid. This lid, therefore, may have been fluxed with volatiles. Cold temperatures in the lid would act as a volatile condensation trap. When the lid begins to form the magma ocean is hot and liquid; cooling in the lid proceeds slowly over millions of years, allowing substantial time for the growth of crustal volatile reservoirs. Magmas would later percolate upward into the lid and assimilate water-rich reservoirs.

This hypothesis predicts that water and non-volatile trace elements would be decoupled, and magmas would only

assimilate volatiles without attendant trace element enrichments found in KREEP materials. This hypothesis may be tested by measuring volatile contents in KREEP-rich materials and in crustal materials, and by producing experimentally-determined equilibrium calculations for the water contents allowed in mare basalt magmas.