

THE FATE OF WATER IN THE MARTIAN MAGMA OCEAN AND THE FORMATION OF AN EARLY ATMOSPHERE. L.T. Elkins-Tanton and E. M. Parmentier, Brown University Department of Geological Sciences, Providence RI, USA (Lindy@brown.edu).

Introduction: The quantity and source of water that went into the initial formation of Mars, its distribution between the planetary interior, surface, and atmosphere, and the extent of its loss to space over time are critical to planetary evolution. We present here initial results from modeling efforts describing the fate of water during the fractional solidification of a magma ocean that formed with the heat of accretion of the planet and solidified within 30 million years of planetary formation. The fate of water during magma ocean crystallization is critical to the locations and quantities of water in later planetary evolution: water may be trapped in mantle cumulates, available for later release to the atmosphere through melting and degassing, or the magma ocean may largely degas before crystallization is complete. If a water fraction remains in the planetary mantle it would significantly decrease silicate viscosity and augment subsequent mantle convection [1], as well as lowering the melting temperature of the mantle and facilitating the magmatism that on Mars appears to have lasted to the present day.

The quantity of water on the surface and in the near-surface of Mars today is estimated at 6 to 27% of Earth's oceans, and because Martian water has a D/H ratio of 1.2 to 1.6 times SMOW no more than 10% of its water is thought to have come from comets [2]. As much as 99% of Mars' original volatiles are thought to have been lost by 3.8 GPa through escape following impacts, sputtering by the solar wind, and hydrodynamic escape [3], and loss has continued at a far lower rate to the present. These geochemical and remote sensing estimates form important comparisons for our model results.

Models: Vigorous convection in the low viscosity liquid magma ocean is assumed to maintain a homogeneous liquid composition (see [4]). Because adiabats are steeper than solidii, a solid region develops at the bottom of the mantle and thickens as the ocean cools (figure 1). Elkins-Tanton *et al.* [5] discusses the complete fractional solidification model.

The water content of accreting planetesimals and volatile loss during accretion are unknown. These models assume that all water was obtained in initial accretion, and that following any degassing from initial accretion, the water content of the whole-mantle magma ocean was 2%, approximately a chondritic value [6]. No later cometary input is assumed.

Only the nominally anhydrous phases listed in table 1 are considered. Water retention in the mantle

would be significantly higher if hydrous phases such as superhydrous B (≤ 6 wt% water, ≥ 16 GPa) or phase E (≤ 18 wt% water, ≥ 8 GPa) were stable, as they are in water-saturated peridotite experiments [7-9]. There is no experimental evidence that these hydrous phases are stable in undersaturated systems, and they are excluded.

Hydroxyls are partitioned into fractionating phases from the hydrous magma using the coefficients in table 1, up to the saturation limits listed. Though partitioning and saturation are known to be dependent upon oxygen fugacity, the simple model presented here uses constant partition coefficients. Results of the model are relatively insensitive to partition coefficients and completely insensitive to saturation limits because of the low water content of the magma ocean: increasing the olivine partition coefficient to 1 changes the final atmospheric mass by less than 1%.

Table 1. Mineral/magma ocean water partitioning [10-14].

Mineral	Solid-melt coeff.	Saturation limit
olivine	0.002	1000 ppm
clinopyroxene	0.02	1000 ppm
garnet	0.0008	700 ppm
ringwoodite	0.02	2.5 wt%
majorite	0.003	675 ppm

While the magma ocean is fractionally solidifying, magma is convecting. We assume that any magma that moves to pressures less than 0.5 GPa degasses all but 1% of its water to the atmosphere. Degassing is therefore a function of mass flux near the surface, which in turn is a function of convective velocity, which is directly driven by heat flux out of the planet, which is directly related to solidification rate. We use the following simple relation to calculate the kilograms of magma moving upward and degassing per second M during solidification:

$$M = Nu \left[\frac{\text{heatflux}}{\text{energypermass}} \right] [\text{area}] = Nu \left[\frac{k \frac{\Delta T}{l}}{C_p \Delta T} \right] [4\pi r^2] = Nu \left[\frac{k}{C_p l} \right] [4\pi r^2]$$

where thermal conductivity k is 2 W/mK, heat capacity C_p is 1,256 J/kgK, radius r is 3,396 km, the length scale of the remaining convecting magma ocean l is output by the model at each step, and Nusselt number Nu is 10 to 1000. The magma ocean is further assumed to solidify from $r = 1,396$ km to 2,696 km ($\sim 2/3$ of the radius) in 10,000 years, and to complete solidification by 30 Myr [15,16]. These solidification rates give a time scale to the mass degassing per second M . Given

the mass of magma degassing at each step of the model and the mass fraction of water in the magma, the growth of a water atmosphere can be measured.

Results: At Nusselt numbers between 10 and 100, water content in the solidified cumulates ranges from about 0.04 wt% at the bottom of the majorite + ringwoodite layer, to about 0.25 wt% at the top of the olivine + pyroxene layer (fig. 1 in blue).

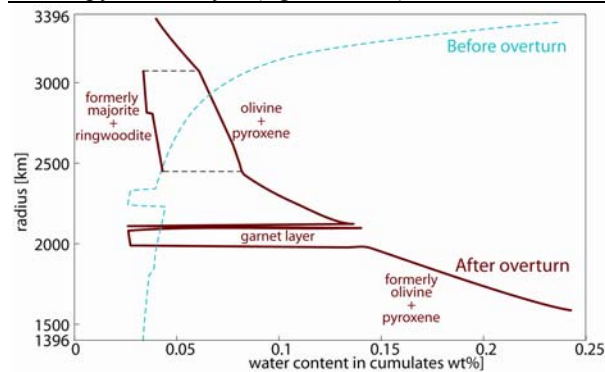


Fig. 1. Water content of cumulates before overturn (dashed blue line) and following overturn (solid red line) for $Nu \sim 10$ to 100. Post-overturn profile does not include effects of wet adiabatic melting or water exsolution due to phase changes.

Throughout the process of solidification the magma ocean liquid becomes increasingly enriched in water, despite the degassing at the surface to form the early water atmosphere. When crystallization has reached $\sim 95\%$ by mass the remaining magma ocean liquid has a water content between 10 and 20%, depending upon Nu . As the water content in the magma ocean increases, the water content in the fractionating minerals also increases, though their saturation limits are not reached at any point in this model.

Degassing to the atmosphere speeds significantly during the crystallization of the more slowly solidifying, anhydrous upper mantle (fig. 2). Nusselt number is the controlling factor in degassing: at Nu higher than ~ 500 more degassing occurs during crystallization of the lower mantle, and upper mantle minerals are accordingly depleted (100 to 300 rather than $\geq 1,500$ ppm); these minerals then fall to the lower mantle during overturn. Regardless of degassing rates the final mass of water in the atmosphere is $\sim 7 \times 10^{23}$ kg.

The mantle cumulate stratigraphy from fractional solidification is gravitationally unstable [5] and will overturn to a stable profile with intrinsically densest materials at the bottom (fig. 1, red). During overturn the most hydrous cumulates fall to the core-mantle boundary, where their water content may facilitate later convection by maintaining a lower viscosity.

The water degassed to the initial atmosphere of Mars in this model is about 60% of the initial water in the magma ocean, about 6 times the mass of one Earth

ocean. Estimates of water on the surface and near-surface of Mars today are equal to only 1 to 5% of the modeled mass of the initial wet atmosphere, implying 95 to 99% loss over the lifetime of the planet, in good agreement with the estimate of 99% based on isotopic arguments [3].

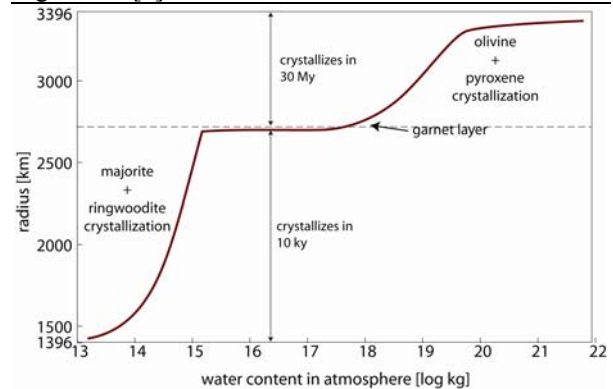


Fig. 2. Log kilograms of water in atmosphere from magma ocean degassing during solidification as a function of radius of the magma ocean solidified for $Nu \sim 10$ to 100.

Conclusions: Degassing an initially chondritic Martian magma ocean during fractional solidification can create an initial water atmosphere on the planet consistent with current estimates for the planet's water content and with estimates for volatile loss over the planet's evolution. Fractional solidification of nominally anhydrous minerals at $Nu = 10$ to 100 results in a planetary mantle with 0.05 to 0.25 wt% water, sufficient to lower viscosity and enable convection to maintain volcanic activity. At Nu higher than ~ 500 the post-overturn mantle has only 0.015 to 0.05 wt% water.

The results of this simple model are robust within assumptions; the initial water content of the magma ocean prevents even the nominally anhydrous minerals in the model from reaching water saturation, and the majority of degassing to the atmosphere occurs at the end of crystallization when all the remaining magma ocean liquid is presumed to be at shallow depths and low pressures. The high water contents of late magma ocean liquids would largely eliminate plagioclase instability [17], perhaps explaining the lack of an anorthositic crust on Mars, Venus, and the Earth.

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