

Volatile Retention from a Crystallizing Martian Magma Ocean

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We present a dynamic magma ocean crystallization model that predicts the H₂O and CO₂ concentrations of the crystallized Martian interior. We employ a scaling relation between the rate of crystallization of the MO and compaction within a thin freezing front, as the MO crystallizes in a bottom-up fashion. We show that rapid crystallization prevents expulsion of melt from the mushy freezing front, thus trapping volatiles in frozen-in melts. We consider three primordial volatile reservoirs, the magma ocean, the residual mantle, and the primitive atmosphere. The distribution of volatiles in each reservoir evolves as the magma ocean cools and crystallizes.

Our scaling results indicate that the amount of trapped melt volume fraction can be as high as 30 vol%, the limit of disaggregation in partially molten rocks, and a substantially higher fraction than typically assumed values of 1-5 vol%. This ‘dynamic melt trapping’ leads to a solidified Martian mantle containing a substantial portion of the initial volatile content. For example, for a constant rate of crystallization, a bulk composition containing 1 terrestrial Ocean’s equivalent (1.6×10^{21} kg) of H₂O in the bulk, and an H:C ratio of 0.4, leads to a Martian mantle containing 1600 ppm H₂O.

In contrast, evolution of CO₂ in the reservoirs is strongly dependent on the fO_2 . Under relatively oxidizing conditions ($f_{CO_2}/f_{O_2} = 0.01$), a thick CO₂ rich atmosphere with pressure exceeding 400 bars forms within the first thousands of years. For more reducing conditions ($f_{CO_2}/f_{O_2} = 100$), CO₂ release in the atmosphere is much more gradual and graphite saturation in the solid leads up to 1200 ppm C in the residual mantle. In summary, our results demonstrate that the evolution of volatiles in the Martian atmosphere and the mantle is strongly dependent on dynamic melt trapping and the state of oxidation.