CRUSTAL GROWTH AND DEGASSING OF THE MARTIAN MANTLE: CONSTRAINTS FROM NUMERICAL EXPERIMENTS

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Several problems regarding Mars geology have been addressed in the past by analyzing the results of planetary thermal evolution simulations. Since each problem comes with its own set of assumptions, reconciling the many hypotheses and constraints still remains a challenging task. Particularly in this study we address the relationship between the mantle degassing and melt production with constraints based on crustal evolution and mantle water content. The model employed includes the feedbacks between water loss and thermal evolution through the use of a wet olivine rheology and of wet peridotite melting.

We used a 1D parameterized convection thermal evolution model to calculate the thermal evolution of Mars and the effect of degassing and water content on the crustal and degassing evolution. The model couples mantle convection with volatile cycling, and accounts for the dependence of viscosity on temperature and water concentration. The effect of changing water concentration on the viscosity was estimated from the experimentally-determined olivine rheology of Mei and Kohlstedt [1] coupled with the relationship between water concentration and water fugacity of Li et al. [2]. The mantle solidus and thus the magma production rate also depend on the water concentration. This double dependence induces strong negative feedbacks that act as regulators. A key process in the system is the development and evolution of a partial melt zone, whose extent varies with the concentration of water in the mantle and thus evolves with time. The parameterization is based on the model of Sandu et al. [3], which was altered to account for stagnant lid convection and to include the evolution of the core temperature and heat flux [4]. The relationships between the internal Rayleigh number (*Ra*), convective heat flux, and convective velocity are based on the stagnant lid convection scaling of Grasset and Parmentier [5]. The melt zone is calculated based the size of the area between the thermal profile and the variable solidus. The solidus and liquidus change as water is extracted from the mantle based on the model of Katz et al. [6]. The melting process is quantified in terms of the fraction of the planetary surface affected by the melting and by the escape efficiency of water, which are combined into a degassing efficiency parameter, X_d [4]. Its value is difficult to derive directly but we will try to constrain it based on simulation results. Water and the radioactive elements partition into the melt and are transferred from the mantle to the crust or in the case of water escape to the surface. The amount of melt produced integrated over the planetary surface is used to derive the crustal thickness.

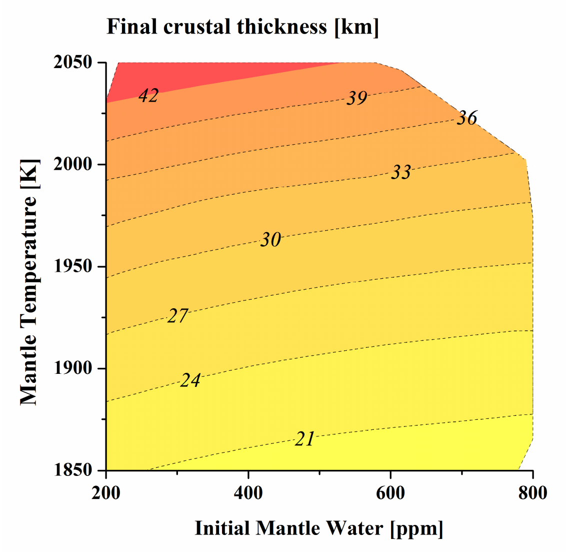

Fig. 1. *Crustal thickness for various initial temperatures and water concentration in the mantle.*

We analyzed the thermal evolution of Mars for varying initial water content in the mantle and a range of initial temperatures (Fig. 1). The results show the final crustal thickness at a degassing efficiency factor X_d =0.005. The amount of crust generated is highly dependent on the initial temperature and only slightly dependent on the initial amount of water in the mantle. The combination of high temperature and low water content produces the highest amount of crust. While high temperature is expected to produce more melt, the water effect is counterintuitive. Water lowers the solidus temperature and increases the melt production. However, a wet mantle has low viscosity and a high convective cooling rate. The reduction in temperature decreases the magma production rate, and this effect turns out to be more important than the reduction in the solidus from the added water. The present day average crustal thickness is estimated at about 50 km [7-8], some of which may have formed during an initial magma ocean phase. The plausible range for initial mantle temperature is in the upper half of the range shown in Figure 1 unless a higher degassing efficiency is used.

The results of the same set of simulations showing the final amount of water in the mantle are presented in Fig. 2. The amount of water left in the mantle at the end of each simulation increases with the amount of water that was initially present. Because hotter mantles convect more vigorously, increasing the initial temperature increases the rate of degassing and decreases the final mantle water abundance.

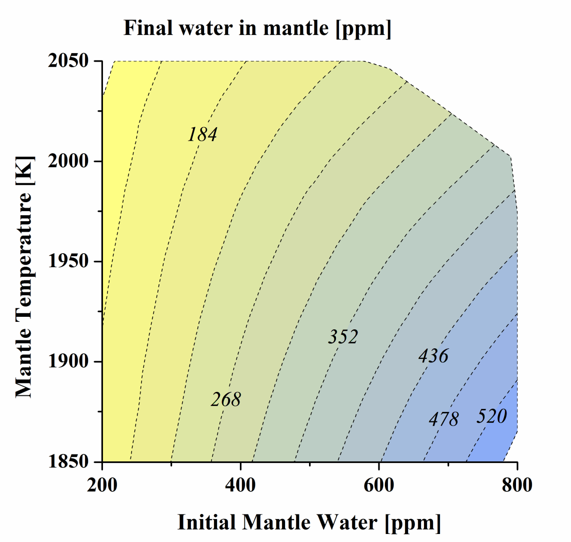

Fig. 2. *Final water in mantle for various initial temperatures and water concentration in the mantle.*

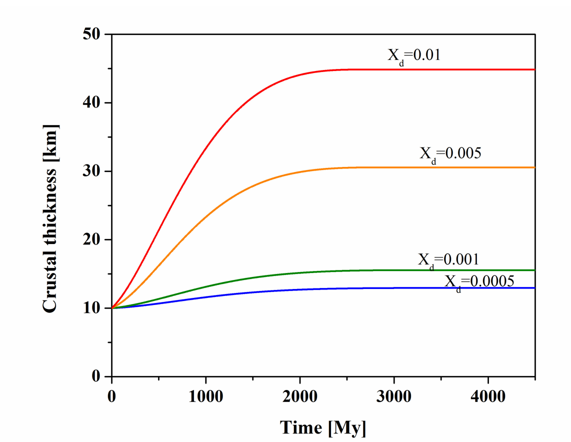

Fig. 3*. Crustal thickness for various degassing factors.*

Measurements of water in the martian meteorites [9-11] are consistent with a few hundred ppm water in the geologically recent (degassed) martian mantle and measurements by the Mars Odyssey Gamma Ray Spectrometer suggest that about half of the radioactive elements such as Th and K have been partitioned into the crust [12] along with the same ratio for water. These results are also compatible with models of recent plume volcanism [13]. All these suggest an initial water content situated in the middle of the range shown in Fig. 2.

A plot of the crustal thickness evolution for various degassing efficiency factors (Fig. 3) shows that most of the crust is formed during the first billion years of evolution with basically the entire crustal layer formed by 2 Gy. These values are consistent with results based on volcanism modeling [14]. The simulations were run for a similar set of parameters as previous runs with 500 ppm initial water and 1950 K initial mantle temperature.

The crustal gain per each 10^{-3} X_d factor is on average about 3 km but the gain is not linear. The crustal evolution has consequences for the thermal evolution too since the growth is associated with two secondary effects. As more crust is developed there are more radioactive elements (heat sources) removed from mantle and accumulated in the crust along with the heat removed as latent and advective heat. Oppositely, as the crust grows on top of the convective system it adds to the insulation of mantle convection by slowing down the cooling of its upper boundary.

Preliminary results of thermal evolution on Mars with mantle degassing suggest a narrow zone for the initial temperature and water content. Based on several constraints a lower limit for the initial mantle temperature of ~1950 K is suggested. The initial amount of water is likely to be in the 400 – 600 ppm range. These parameters are also consistent with the timing for the end of the martian magnetic dynamo [4]. Lower values of both parameters will not produce enough crust; higher values will lead to crustal erosion and top heating the mantle. The degassing factor is also important, and the possible effects of larger values are being assessed in on-going work.

References:

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