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Crustal recycling, mantle dehydration, and the thermal evolution of Mars

A. Morschhauser, M. Grott and D. Breuer
Institute of Planetary Research, German Aerospace Center (DLR), Berlin (Achim.Morschhauser@dlr.de)

Abstract

We have reinvestigated the coupled thermal and crustal evolution of Mars taking new data concerning the content and distribution of heat producing elements in the Martian interior, new laboratory data concerning the flow behaviour of iron-rich olivine, as well as dehydration stiffening of the mantle viscosity by the extraction of water from the mantle into account. We find that models satisfying the constraints posed by the crustal evolution of Mars and the absence of crustal recycling have low initial upper mantle temperatures, a primordial crust, and an initially wet mantle rheology. Water extraction from the mantle was found to be relatively efficient and close to 50 percent of the total inventory is lost from the mantle in most models. The amount of water extracted to the surface is equivalent to a 20 m thick global surface layer, suggesting that volcanic outgassing of H_2O could have significantly influenced the early Martian climate and increased the planet's habitability.

1. Introduction

The coupled crustal and thermal evolution of Mars is one of the outstanding problems in Martian geophysics and knowledge of the evolution of the crust can place important constraints on the thermal evolution of the planet. It is generally accepted that the bulk of the Martian crust formed early in Martian history [1] and Martian meteorite isotope data suggests an early mantle differentiation and the extraction of a primordial, enriched crust around 4.5 Gyr [2].

Recently, new data concerning the enrichment and concentration of radioactive elements in the Martian crust has been obtained from gamma-ray spectroscopy [3] and the crust was found to be more strongly enriched in heat producing elements than previously assumed. Furthermore, new laboratory data on the creep behaviour of olivine indicate that the relatively higher iron content of the Martian mantle with respect to the Earth's reduces mantle viscosity on Mars by approximately one order of magnitude [4]. Together with the thermal blanketing caused by the highly enriched crust, this promotes erosion of the stagnant lid from below and the stagnant lid thickness can thin below the crustal thickness in these models. Physically, this situation corresponds to a scenario in which crust is recycled back into the mantle, replenishing the mantle with enriched crustal material.

The new data indicates that crustal recycling should be the rule rather than the exception for a variety of models, justifying a reinvestigation of the crustal and thermal evolution of Mars. As crustal recycling is incompatible with an early separation of geochemical reservoirs [5,6], and we will use the requirement that no crust must be recycled back into the mantle to constrain our models. Furthermore, admissible models are required to reproduce the Martian crust formation history and to allow for the formation of partial melt under present-day mantle conditions.

2. Modelling

The thermal evolution of Mars is modelled starting from an initial temperature profile corresponding to the time after core formation and the evolution is followed to the present by solving the energy balance equations for the core, mantle and lithosphere. Partial melting in the mantle, melt extraction, and crustal formation is included in the model in a self-consistent manner and we explicitly take the increase of the mantle solidus upon depletion of crustal components into account. Water will preferably move to the liquid phase upon partial melting and by assuming water to behave as a regular trace element, the amount of water extracted from the mantle during the crust formation process is calculated. The concentration of water remaining in the mantle then follows from mass balance considerations and the successive dehydration of the mantle and the associated viscosity increase is taken into account in our models.

3. Results

Varying initial upper mantle temperatures and reference viscosities between 1600 to 1900 K and 10^{18} and 10^{21} Pa s, respectively, we find that the majority of models show phases of crustal recycling during the early stages of planetary evolution. Only very cool models or those with large mantle viscosities are compatible with the requirement that no crust must be recycled back into the mantle. However, models with large viscosities are incompatible with the crust formation history, as crustal production occurs too late in these models.

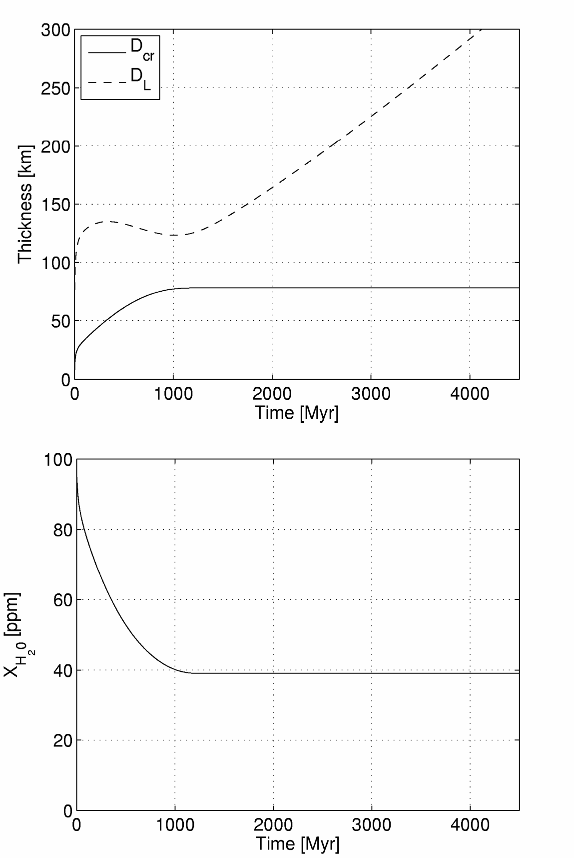

Figure 1: Top: Crustal thickness D_{cr} and stagnant lid thickness D_L as a function of time for a model with initial upper mantle temperature of 1700 K. Bottom: Mantle water content X_{H20} as a function of time for the same model.

Models satisfy all constraints including the possibility for present day mantle melting have an initially wet mantle and a successful model is shown in Fig. 1. In this model, 80% of the total crustal volume is produced before 500 Myr and the present day crustal thickness is 78 km. Although the presence of a primordial crust is not required, models having a primordial crustal thickness of 30 km fit the observed crustal evolution slightly better.

In most models, the amount of water extracted from the mantle is about 50 % of the total inventory and assuming that 10 % of this water is supplied to the surface, a 20 m thick global surface layer could be created. This suggests that volcanic outgassing of H_2O could have significantly influenced the early Martian climate and potentially increased the planet's habitability.

We conclude that admissible models have low initial upper mantle temperatures and an initially wet mantle, which becomes increasingly viscous due to volcanic outgassing of water during the crust formation process.

Acknowledgements

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