DEGASSING OF THE MARTIAN MANTLE AND ITS EFFECTS ON THE THERMAL EVOLUTION AND MAGNETIC FIELD HISTORY

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The volcanic and magnetic activity on the surface of Mars is directly related to its thermal evolution and to the melting potential of its mantle. In this study we analyze various Martian thermal evolution scenarios obtained using a parameterization that includes the effect of chemical composition and especially of water concentration. Based on the results we analyze the potential effects on the early magnetic field on the planet.

Fig. 1. General settings of the model showing the thermal profile between surface temperature ($T_s$) and mantle potential temperature ($T_p$). Degassing is scaled with the extent and concentration of partial melt zone, which is calculated by comparing the temperature of any given point with the pressure-dependent solidus and liquidus.

The simulations are performed using a 1D parameterized model [1] that couples mantle convection with volatile cycling and crustal evolution. The model accounts for the decay of radiogenic elements in the mantle and crust, and for the dependence of viscosity on temperature and 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 with variable extent that has implications for the crustal formation, surface magmatism and degassing history. A thermal profile is calculated anytime, along with the position of solidus and liquidus lines (Fig 1). Degassing is then quantified in terms of the amount of water extracted in the melt, the thickness of the partial melt zone and the intensity of convection. The melt fraction and concentration of water in the melt are calculated according to Katz et al. [2]. It is known that water increases the strain rate for solid state creep at a given stress level and thus decreases the viscosity. The mantle viscosity is thus parameterized in terms of both the temperature and water concentration. In this work we used a relation proposed by Li et al. [3], which allows us derive the viscosity consistently from the water concentration.

Fig. 2. Thermal evolution models for different degassing efficiency values ($X_d$) showing average bulk mantle temperature as well as core temperature evolution. The increased degassing efficiency leads to drier mantle that evolves at higher temperature.

We analyzed the thermal evolution of Mars for different initial water content in the mantle, and various degassing efficiency parameters (Fig. 2). The mantle temperature constrains the outgassing process from both directions. If the mantle is too hot, an extended melt zone is generated but the melt would be depleted in volatiles. On the other hand, cold mantle would produce a melt rich in volatiles but a shrunken melt zone. The results show also that water lowers the viscosity and makes the heat removal process more efficient. Consequently, a wet mantle cools more quickly than a dry one. However, the wet mantle also creates more melt which increases the degassing flux making the mantle drier. This negative feedback is superimposed on the temperature feedback and regulates the mantle temperature. The cooling and degassing efficiency were calculated as a percentage of the difference between the initial and final values reported to the initial one. Both cooling
and degassing efficiency increase with the initial value of the water concentration.

Fig. 3. Heat flux out of the core for different degassing efficiency values. The results show that increasingly wet mantle (less efficient degassing) is able to maintain a convective core for a longer period, controlling the planet’s magnetic field lifespan.

Geologic evidence constrains the magnetic field on Mars to be active only for about first 500-700 Ma of its evolution [4-7]. Previous work investigated as possible scenarios an initial plate tectonics phase, an initial superheated core, and the effects of large impacts on the thermal structure and flow of the core and mantle [8-12]. We examine the possible relation between degassing histories and the existence and lifespan of the Martian geodynamo (Fig 3). This condition is present when heat flux out of the core exceeds a critical value. The process needs an efficient cooling of the mantle to lower the temperature fast enough to require convective core cooling. Since degassing removes water and other volatiles from the mantle increasing its viscosity, the process is thus affecting the convection intensity and heat removal efficiency in the system. The results from our numerical simulations with various values of the free degassing efficiency factor ($X_d$) show that certain combinations of initial bulk water concentration value and degassing efficiency factor are able to generate enough heat flux of the core to ensure the generation of a magnetic dynamo (Fig 4). The factors that constrain the solution are represented by the information regarding ancient volcanism on the planet and the final water concentration in the Martian mantle, which is considered based on analyses on SNC meteorites. This restricts the solution to a narrow zone. Further simulations showed that the initial mantle temperature plays an important role too. Thus, small variations of this parameter can significantly affect the thermal and melt-zone evolution and extend the magnetic field window.

Fig. 4. Isochrones to core convection shut-off ($q_c > 5$ mW/m²). The colored areas represent the possible combination of initial water and degassing efficiency that produce the magnetic field cessation within a timeframe from 500 to 700 MA.

The degassing history of Mars is controlled mainly by the magmatic processes associated with the melt-zone characteristics. Our results show that the process played an important role not only in the mantle cooling but in the core cooling too. This has further consequences for the early planetary magnetic field. The water composition of mantle regulates the thermal evolution of the planet and this opens the perspective for other elements that make the Martian mantle distinct from that of Earth’s to play a significant role too.