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The influence of variable thermal conductivity on Mercury's thermal evolution

N. Tosi (1), A.-C. Plesa (1, 2) and D. Breuer (1)
(1) Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany (nic.tosi@gmail.com), (2) Institute of Planetology, University of Münster (WWU), Münster, Germany

Abstract

After MESSENGER's three flybys, clear evidence has emerged of a widerspread presence of pyroclastic deposits on Mercury's surface, which indicates the presence of volatiles in the interior and a prolonged volcanic activity and crustal production. Considering a composition that allows for the presence of volatiles, we show numerical simulations of mantle convection, focusing on the influence of variable thermal conductivity on the planet's thermal evolution. Our results indicate that if a primordial crust enriched in radioactive elements and with a low thermal conductivity is taken into account, the production of secondary crust due to partial melt can last longer than 1 Byr, or even more if an essentially insulating thin megaregolith layer covering the planet's surface is considered.

1. Introduction

The latest analyses of the images taken by MESSENGER during its three flybys reveal an essentially global distribution of pyroclastic deposits [5]. These observations require Mercury's volatiles content to be much greater than predicted by traditional highly-refractory and Thorium-rich compositions. Furthermore, they suggest that the planet's volcanic activity with its associated crustal production postdates the period of heavy bombardment and may have continued for a time-span significantly longer than previously thought [3].

Using a meteoritic mixing model for the bulk composition, because of the Potasium ascertained presence in Mercury's exosphere [7], [2] used parameterized convection models to investigate the thermal evolution of Mercury. With the aim to predict the small amount of global radial contraction as inferred from MESSENGER data [9], they showed that models featuring a weakly conductive crust along with a dry olivine rheology allow for a prolonged phase of crustal production and imply an amount of contraction close to the observations.

Previous studies have been caried out using parameterized models. However these models have the disadvantage of using scaling laws which are based on parameter studies done for a radius ratio other than that of Mecury's. Here we model the thermal evolution of Mercury using fully numerical simulations of mantle convection. Building upon the study of [2], we study how the formation of a secondary crust due to partial melting is influenced by the presence of a primitive crust, enriched in radioactive heat sources, with a low thermal conductivity and overlaid by a thin and even more insulating megaregolith layer of fractured rocks.

2. Method

To model the thermal evolution of Mercury's mantle, we have employed the 2D-3D spherical code GAIA [4]. GAIA solves the conservation equations of thermal convection for an incompressible, Boussinesq fluid with infinite Prandtl number, cooling boundary conditions and decaying radioactive elements. We have assumed the presence of a primordial crust [1] with a thickness ranging from 10 to 25 km. While the mantle thermal conductivity k is set to 4 W/mK, the primordial crust is modeled as a weekly conductive layer with $k = 1.5$ W/mK enriched by a factor of 4 in radioactive elements. The effect of megaregolith is modeled by adding on top of the crust a 5 km thick layer with a thermal conductivty value of 0.2 W/mK, as suggested by [8] for the lunar megaregolith.

Besides the conservation equations of mass, momentum and thermal energy with consideration of latent heat, we solve an additional equation to track variations of a composition field C due to the occurrence of partial melt:

$$\frac{\partial C}{\partial t} + \vec{u} \cdot \vec{\nabla} C = \frac{1}{Le} \nabla^2 C + \frac{\partial F}{\partial t}, \qquad (1)$$

where $\vec{u}$ is the velocity vector, Le the Lewis number, which is assumed to be large enough to ensure a negligible chemical diffusion ($Le = 10^3$), and F is the melt fraction. The latter is calculated by comparing local temperatures with the solidus temperature of peridotite, which, in turn, is determined in a self-consistent way, being allowed to increase, due to mineralogical changes, in regions where partial melting has already occurred.

3. Results

We have started from simple models of thermal evolution in which no partitioning of heat sources between crust and mantle is considered. For these, the effects of a poorly conductive primordial crust are dramatic. Its insulating character, along with the large contribution from mantle radioactive heating cause the planet to cool very slowly and its temperature to remain above solidus, and hence to produce secondary crust, until present day. If a primordial crust enriched in radioactive heat sources is considered, the smaller amount of heat generated in the mantle results in a faster cooling rate. In our models convection lasts the entire evolution while the crustal production ceases within 1.8 Byr. The thickness of the secondary crust is calculated in a postprocesing step at the end of the simluation. An overall thickness of the final crust ranging from about 130 km for models with a 10 km thick primordial crust (Fig. 1), to 150 km for models with a 25 km thick primordial curst and a 5 km thick insulating regolith layer. These values agree well with those derived by [6] who used the depth of faulting of lobate scarps to constrain the crustal thickness and heat flow at the base of Mercury's crust.

4. Summary and Conclusions

As the latest MESSENGER observations of pyroclastic deposits on Mercury's surface require the presence of volatiles and a prolonged period of volcanic activity and crustal production, we have carried out numerical simulations of mantle convection to show the effecs of heat partitioning and crustal insulation on the planet's thermal evolution.

The presence of a low-conductive primordial crust, possibly overlaid by a megaregolith layer of fractured rocks similar to that on the Moon, allow us to keep the crustal production active for up to 1.8 Byr of evolution, in agreement with recent parameterized models of [2], and to produce an overall crustal thickness ≤ 150 km that matches the values predicted by [6].

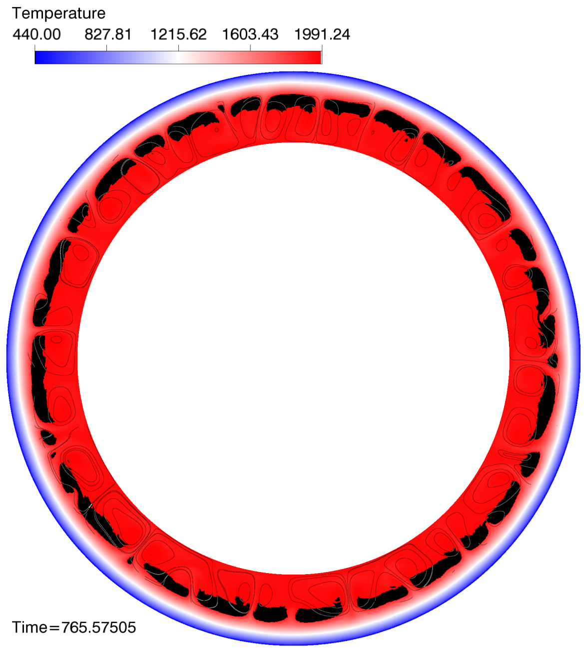

Figure 1: Snapshot of the temperature field and streamlines taken after 765 Myr of evolution for a 2D cylindrical model having 10 km of weakly conductive primordial crust. The black spots mark the occurrence of partial melt.

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