The Thermo-Chemical Evolution of Mercury revisited.

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Introduction: The thermal evolution of Mercury and the history of volcanism on the planet critically depend on the abundance of heat producing elements and the rate of heat transport in the planetary interior. With MESSENGER in orbit around Mercury since March 2011, new data on the surface abundance of radioactive elements as well as the planet's moment of inertia have been obtained. Data from the gamma ray spectrometer indicate an average surface abundance of 1150$\pm$220 ppm K, 220$\pm$60 ppb Th, and 90$\pm$20 ppb U [1]. This implies a K/Th ratio of 5200$\pm$1800, comparable to other terrestrial planets.

The moment of inertia factor C/MR^2 was estimated to be 0.353, and the normalized mantle moment of inertia C_m/C was estimated to be 0.452. These values indicate the presence of a large iron core, and while previous estimates for the core size were close to 1800 km, new interior structure models require core sizes of 2000-2100 km [2]. Bulk sulfur contents required to satisfy these constraints are close to 10 % [2], and SO_2 could be the volatile driving pyroclastic volcanism [3]. Photogeological evidence suggests that volcanism was a globally extensive process even after 3.8 Gyr [4], and the northern plains were likely emplaced in a flood lava mode by high-temperature, low-viscosity lava. Elemental abundances of Mg, Al, and Ca indicate that surface rocks were derived from partial melts at high melt fractions between 20 and 30 % [5], indicating a composition intermediate between basalt and terrestrial komatiite.

Major constraints for thermal evolution models are the inferred small radial contraction of Mercury [6] and its magmatic history [4]. While previous models required a large bulk content of long-lived heat producing elements in the planetary interior to minimize planetary heat loss [7], recent models have shown that the presence of a thermally insulating regolith layer is sufficient to slow planetary cooling even for more volatile rich compositions [8].

Modeling: Using the above constraints, we have reinvestigated the coupled thermal and crustal evolution of Mercury. Thermo-chemical evolution models are calculated using the model by [8], which takes the presence of a thermally insulating regolith layer into account. We consider models with a core size of 2050 km, which significantly reduces the silicate fraction of the planet along with its inventory of heat producing elements. Furthermore, the mantle Rayleigh number is reduced by a factor of three with respect to models with a core radius of 1850 km. We tie the bulk concentration of heat producing ele-

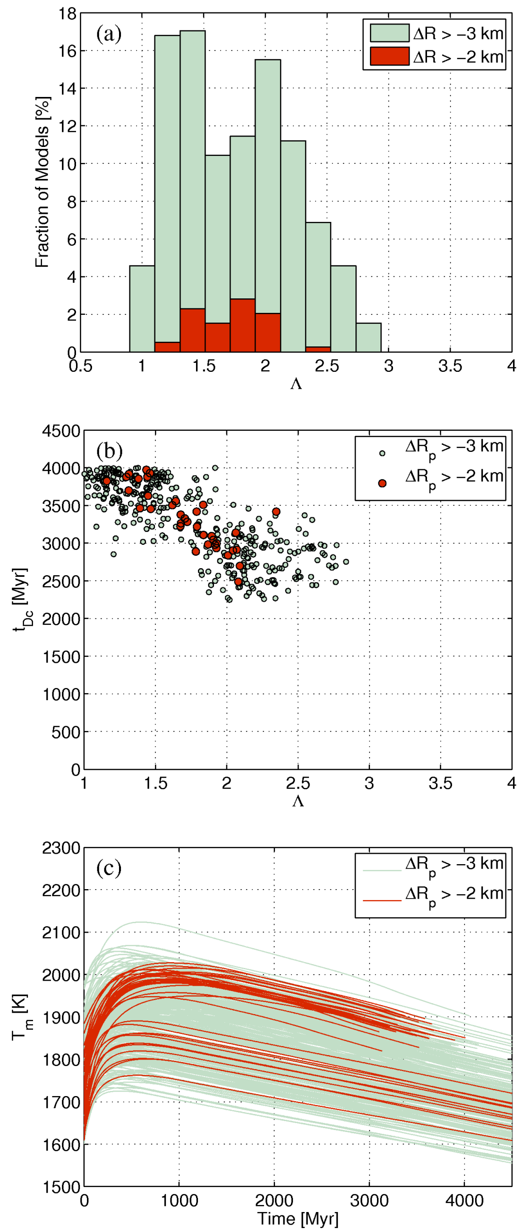

Figure 1: (a) Histogram of successful models as a function of crustal enrichment factor λ. (b) The cessation time for crustal production as a function of Λ for successful models. (c) Upper mantle temperature T_m as a function of time for successful models. Lines ending before 4500 Myr indicate the cessation of mantle convection.

ments through the enrichment factor Λ to their measured surface concentrations [1]. For the concentrations given above, an enrichment factor of one corresponds to a bulk uranium content of 90 ppb, while an enrichment factor of four would correspond to 22.5 ppb bulk uranium content.

Parameters most strongly influencing model results are the initial upper mantle temperature T_m, the mantle viscosity η, the initial temperature jump across the core-mantle boundary ΔT, the crustal thermal conductivity k_c, the regolith thickness D_{reg}, the volume change upon mantle differentiation $\delta V/V$, and the enrichment factor of radiogenic elements in the crust as compared to the primordial mantle Λ. We have run more than thirty thousand Monte-Carlo simulations varying these parameters between 1600-2000 K, 10^{19}-10^{21} Pa s, 0-300 K, 1.5-4 W m^{-1} K^{-1}, 0-5 km, 1-5%, and 1-4, respectively, and rejected all models which show radial contraction in excess of 3 km. In addition, models resulting in crustal thicknesses of less than 20 km or models continuing to produce crust to the present day have been disregarded. These constraints are satisfied by only a few percent of the calculated models.

Results: Fig. 1 shows the results of the calculations for 393 successful models, where models which show a radial contraction of less than 3 km are shown in green, while models satisfying the tighter constraint of a total contraction less than 2 km are shown in red. A histogram giving the fraction of models for a given enrichment factor is shown in Fig. 1a, and only models with $\Lambda < 3$ satisfy the constraints posed by the global contraction and crustal evolution. These low values of the enrichment factor are consistent with melts derived at high melt fractions and a komatiitic composition [5].

The time of cessation of global crustal production t_{Dc} is given in Fig. 1b as a function of the crustal enrichment factor, where we have ruled out models with present day volcanic activity. Λ and t_{Dc} are negatively correlated as expected, because larger crustal enrichment factors result in more efficient planetary cooling and an earlier cessation of global crustal production. Crustal growth continues up to at least 2.5 Gyr, consistent with the reported young ages for some volcanic planes on Mercury [4]. Successful models have average crustal thicknesses between 20 and 80 km.

Typical temperature profiles for successful models are shown in Fig. 1c, where the upper mantle temperature T_m is shown as a function of time. Although average mantle temperatures differ by up to 300 K, all models have similar cooling histories with secular cooling rates around 50 K Gyr^{-1}. Therefore, mantle temperatures are not strongly constrained by thermal evolution models, and warm as well as cold models are equally plausible [2]. Lines ending before 4500 Myr indicate the cessation of mantle convection, at which point the upper mantle temperature T_m is no longer defined. Therefore, sluggishly convecting models as well as purely conductive models are consistent with the constraints posed by Mercury's global contraction and magmatic history. Mantle viscosity, crustal thermal conductivity, regolith thickness, and the volume change upon mantle differentiation are not constrained by our models.

If sulfur is the light element in Mercury's core, sulfur contents above 6% are needed to prevent large scale core freezing, which would result in significant radial contraction in excess of the observed values. However, if silicon instead of sulfur would be the light core constituent, core freezing would not result in significant amounts of radial contraction, because silicon partitions almost equally between solid and liquid phases on the iron rich side of the eutectic [9]. In this case, core temperatures in excess of 1860 K would be required to sustain a liquid outer core [10], and such high temperatures are reached by only a few models investigated here.

Conclusions: Thermo-chemical evolution models for Mercury using observed abundances of heat producing elements and large core sizes are consistent with the small radial contraction and magmatic evolution of the planet if small crustal enrichment factors between 1 and 3 are assumed. This finding is consistent with a komatiitic composition for the crust, which is likely derived from source regions with high melt fractions [5].

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