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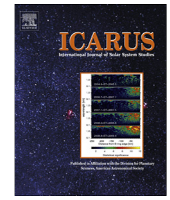

Is Earth-based scaling a valid procedure for calculating heat flows for Mars?

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ABSTRACT

Heat flow is a very important parameter for constraining the thermal evolution of a planetary body. Several procedures for calculating heat flows for Mars from geophysical or geological proxies have been used, which are valid for the time when the structures used as indicators were formed. The more common procedures are based on estimates of lithospheric strength (the effective elastic thickness of the lithosphere or the depth to the brittle–ductile transition). On the other hand, several works by Kargel and co-workers have estimated martian heat flows from scaling the present-day terrestrial heat flow to Mars, but the so-obtained values are much higher than those deduced from lithospheric strength. In order to explain the discrepancy, a recent paper by Rodriguez et al. (Rodriguez, J.A.P., Kargel, J.S., Tanaka, K.L., Crown, D.A., Berman, D.C., Fairén, A.G., Baker, V.R., Furfaro, R., Candelaria, P., Sasaki, S. [2011]. Icarus 213, 150–194) criticized the heat flow calculations for ancient Mars presented by Ruiz et al. (Ruiz, J., Williams, J.-P., Dohm, J.M., Fernández, C., López, V. [2009]. Icarus 207, 631–637) and other studies calculating ancient martian heat flows from lithospheric strength estimates, and casted doubts on the validity of the results obtained by these works. Here however we demonstrate that the discrepancy is due to computational and conceptual errors made by Kargel and co-workers, and we conclude that the scaling from terrestrial heat flow values is not a valid procedure for estimating reliable heat flows for Mars.

1. Introduction

Numerous studies have attempted to calculate paleo heat flows for several regions and times of Mars through a diversity of approximations. The most commonly used procedure (e.g., Solomon and Head, 1990; McGovern et al., 2004; Grott et al., 2005; Ruiz et al., 2006a,b, 2011; Kronberg et al., 2007; Grott and Wieczorek, 2012) is the conversion of estimates of the effective elastic thickness of the lithosphere (usually denoted as T_e) to heat flows by comparing with an equivalent strength envelope, which depends on the temperature profile. Another methodology consists of deducing the heat flow from the depth to the brittle–ductile transition (BDT) associate with large thrust faults (Schultz and Watters, 2001; Grott et al., 2007; Ruiz et al., 2008, 2009). Both kinds of calculations are, therefore, based on estimates of lithospheric strength. Alternatively, some works have modeled the heat flow necessary to cause melting in chaotic areas (Schumacher and Zegers, 2011), relaxation of crater topography (Karimi et al., 2012), or even the heat flow consistent with melting pressures and degrees of partial melting proposed from the estimated geochemistries of volcanic provinces (Baratoux et al., 2011). These paleo heat flow estimations were derived by using different sets of parameters, and comparisons are not always easy, but the obtained values are usually comparable, at least when the effect of different assumptions are taken into account.

Thermal history models also provide calculations of the average surface heat flow of Mars as a function of time (e.g., Hauck and Phillips, 2002; Grott and Breuer, 2010). In general, thermal history models predict surface heat flows somewhat higher than those obtained from geophysical or geological proxies (which could have implications on our knowledge of the thermal evolution of Mars; see Ruiz et al., 2011), but the estimated values are comparable to those derived from lithospheric strength.

On the other hand, several works by Kargel and co-workers (Kargel, 2004; Kargel et al., 2006; Rodriguez et al., 2011; hereafter collectively referred as Kargel and co-workers) have used heat flows of 30 and 120 mW m^{-2}, respectively, for the present-day and for 2.6 Ga (the latter is considered by these authors to be rep-

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resentative of the Late Hesperian or Early Amazonian epochs). These heat flow values are based on scaling the present-day terrestrial heat flow to Mars, and are much higher than those obtained from both geophysical/geological proxies and thermal history models. Indeed, lithospheric strength-based calculations usually obtain heat flows of at most 20 mW m^{-2} and 30–40 mW m^{-2}, respectively, for present-day and Late Hesperian/Early Amazonian times (McGovern et al., 2004; Ruiz et al., 2011).

In relation to this discrepancy (mostly with works based on the BDT depth), Rodriguez et al. (2011) wrote (see their page 147): "From a cosmochemical viewpoint, we doubt that heat flow could be as low as the 'tectonic' based estimates, as they would imply a composition that is highly depleted, relative to Earth, in both refractory lithophile (U and Th) and volatile–lithophile elements (K); this combination and the inferred degree of depletion generally does not occur for silicate bodies in the Solar System, and it points out a fundamental error in the reasoning based on the tectonic estimates." More specifically, Rodriguez et al. (2011) consider the heat flow results in Ruiz et al. (2009) to be low, and they claim that it is a consequence of assuming low potassium, thorium, and uranium abundances for Mars. These authors also claim that Ruiz et al. (2006b, 2008, 2009) did not take into account the release of heat stored in Mars from past radioactive heat generation and global differentiation.

Heat flow is an important parameter in the understanding of the thermal evolution of a planetary body, and specifically for Mars. For that reason, we consider it necessary to clarify the point of the discrepancy between the values obtained from geophysical/geological proxies and those proposed by Kargel and co-workers. In this work, we therefore assess: (1) the criticism of Rodriguez et al. (2011) to the calculation of heat flows from lithospheric strength (and specifically those performed by Ruiz et al. (2006b, 2008, 2009), hereafter collectively referred to as Ruiz and co-workers); (2) the derivation of the heat flow values proposed by Kargel and co-workers; and (3) the general validity of scaling Earth's heat flows for the calculation of average martian heat flows for a given time.

We show that the criticisms of Rodriguez et al. (2011) are invalid, that the scaled heat flow of 120 mW m^{-2} proposed by Kargel and co-workers for 2.6 Ga is an erroneous value, and that the scaling from terrestrial values is not a valid procedure to estimate heat flows for Mars. Thus, the discrepancy noted by Rodriguez et al. (2011) is a consequence of computational and conceptual errors made by Kargel and co-workers.

2. The role of heat-producing elements abundances in the calculation of heat flows from lithosphere strength

Recently Rodriguez et al. (2011) noted a strong discrepancy between heat flows calculated from lithospheric strength (referred by these authors as tectonic-based estimates) and the values derived by Kargel and co-workers. These authors consider that lithospheric strength-based heat flow calculations for Mars imply a highly depleted composition in U, Th, and K relative to Earth, which would indicate a fundamental error in the lithospheric strength-based heat flow estimates.

More specifically, Rodriguez et al. (2011) consider that the heat flow calculations presented in Ruiz et al. (2009) used low potassium, thorium and uranium abundances for Mars. For example, by using the crustal potassium mean abundance referred in Ruiz et al. (2009), which is 3300 ppm (value coming from Taylor et al. (2006)), and a crustal density and thickness of 2900 kg m^{-3} and 80 km respectively, Rodriguez et al. (2011) obtain potassium abundances less than 172 ppm for bulk Mars, a value lower than their prevision based on assuming the same abundances as for the average Earth, and they indicate that similar results are obtained for thorium and uranium. These authors also wrote (p. 147): "For their [Ruiz et al. (2009)] preferred model where the radiogenic elements are mainly concentrated at those abundances in the upper quarter of the crust, and the mantle supplies a roughly similar or slightly less abundant of heat, the inferred bulk-Mars abundances of heat-producing elements is even far less, with greater depletions of K, U, and Th than indicated above." Moreover, Rodriguez et al. (2011) also claim that Ruiz et al. (2006b, 2008, 2009) did not take into account the release of heat stored in Mars from past radioactive heat generation and global differentiation.

However, the criticisms of Rodriguez et al. (2011) arise from a misunderstanding of the work of Ruiz and co-workers. For example, the paper by Ruiz et al. (2009) performed an upper limit calculation of the surface heat flow at the Warrego rise (valid for the time when the thrust faults were formed: the Noachian Period and not the Hesperian) by assuming heat-producing elements (HPE) homogeneously distributed in the crust. This paper showed that, for the Warrego rise, a crust with homogeneously distributed HPE is not consistent with the local BDT depth, and therefore a stratified crust is favored for this region, but does not propose any particular preferred model, and there is no mention to a model with the HPE concentrated in the upper quarter of the crust. Thus, Rodriguez et al. (2011) are errant in attributing this preference to the work by Ruiz et al. (2009).

The work by Ruiz et al. (2009) used HPE abundances derived from Mars Odyssey Gamma Ray Spectrometer (GRS) measurement (Taylor et al., 2006); we realize that such estimates may be improved with future missions and/or studies. The actual HPE abundances would be somewhat increased by renormalizing considering the volatile content in order to obtain a composition more representative of crustal rocks and not surface contamination (Hahn et al., 2011), but this increase, about ten percent, does not alter the conclusions of Ruiz et al. (2009). Ruiz et al. (2009) performed a regional study, and the high crustal thicknesses in the Warrego rise are not representative for martian averages. Furthermore, we do not assume that all the HPE (including potassium) are in the crust, and our approach is independent of HPE abundances in the mantle. Thus, the calculation by Rodriguez et al. of potassium abundances in bulk Mars from "our" assumptions is not valid.

In the calculations by Ruiz et al. (2006b, 2008, 2009) a contribution to the surface heat flow is due to radioactive heating in the crust whereas the remainder reaches the crust from the mantle, but there is no assumption on the origin(s) of the mantle heat, and it could certainly include "fossil heat": the criticism of Rodriguez et al. related to the lack of use of stored heat flow is simply not applicable. Moreover, Ruiz et al. (2009) used their results for surface heat flow, along with the condition of non-negative heat flow (or of mantle heat flow being a given fraction of the surface heat flow), in order to obtain upper limits to the thickness of a homogeneous crust (which were compared with crustal thickness models for Warrego rise), but no calculation of mantle heat flow was presented.

Thus, it is clear that the discrepancy between the heat flow derived by Kargel and co-workers and those obtained from lithospheric strength are not related to assumptions on HPE abundances in the latter. In the next section, we therefore re-evaluate the estimation of martian heat flows proposed by Kargel and co-workers.

3. Scaling of radioactive heat generation and heat flows from present-day Earth to ancient Mars

The heat flows proposed for Mars by Kargel and co-workers were explicitly "mass- and surface area-scaled from Earth's mod-