THE EARLY THERMAL AND MAGNETIC STATE OF TERRA CIMMERIA, SOUTHERN HIGHLANDS OF MARS.
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Introduction: The heavy cratered highlands are the oldest terrain on Mars, with basement dating from the early Noachian. Inversions of topography and gravity data indicate the existence of long wavelength crustal thickness variations [1]; these probably have survived throughout Martian history and therefore require ancient lower crust temperatures cold enough to prevent their relaxation until present day [1-3]. Furthermore, some regions of the highlands (principally in Terra Cimmeria and Terra Sirenum) display strong, likely remnant, magnetization [4, 5], requiring that temperatures at substantial depths in the crust have not exceeded the Curie temperature for the mineral(s) that carries the magnetization. On the other hand, crustal (and upper mantle) temperatures must have been warm enough to allow mechanically weak responses to loading in these regions, as inferred from gravity/topography admittances [6, 7].

Previous workers have calculated ancient heat flows for diverse places on Mars from the effective elastic thickness of the lithosphere [e.g., 1, 6, 8, 9]. Such studies used linear thermal gradients, which is equivalent to ignoring the existence of heat sources within the crust, and for that reason the obtained lower limits on heat flow values. Here we take into account crustal heat sources in the calculation of surface heat flows for Terra Cimmeria. Indeed, from geochemical arguments it has been proposed that a high percentage (maybe over 50%) of radioactive heat sources in Mars are located in the crust [10]; moreover, in the Earth, roughly half of the heat flow lost in continental areas originates from crustal heat sources.

Methodology: The temperature-depth profile in planetary crusts is a function of the intensity and distribution of crustal heat sources. The distribution and intensity of heat sources in the Martian crust is poorly constrained. For this reason, here we assume crustal heat sources homogeneously distributed in a radioactive element-rich layer (which is not necessarily equivalent to the whole crust) 25 or 50 km thick. The lower value is in accordance with the estimations of 20-30 km for the thickness of an LREE-enriched crust deduced from the geochemistry of martian meteorites [11], whereas the higher value corresponds to a typical value for the planetary mean crustal thickness deduced from topography and gravity [1].

Temperature at depth z within the crust is given by

$$T_z = T_s + \frac{Fz}{k}\left(1 - \frac{fz}{2b}\right), \qquad (1)$$

where f is the fraction of the surface heat flow originated from crustal heat sources, T_s is the surface temperature, F is the surface heat flow, k is the thermal conductivity of the crust (assumed as 2.5 W m^{-1} K^{-1}), and b is the thickness of the radioactive element-rich layer. On Earth, radiogenic sources are sparse beneath the upper radioactive element-rich layer, and so, for the b = 25 km case we use a constant heat flow of $F(1 - f)$ for depths between 25 and 50 km. Temperature profiles are calculate for two different values of the surface temperature: 220 K (roughly the present-day mean surface temperature) and 273 K (appropriate for a possibly warm and wet early Mars).

We compute surface heat flows following the methodology described in [12], which relates effective thickness of an elastic plate (T_e) to the mechanical thickness of an elastic-plastic plate (T_m) via a lithospheric strength envelope; the bending moments of the two types of plate must match. Additionally, the condition of zero net axial force is imposed. We calculated the brittle strength with the low-pressure Byerlee's rule for zero pore pressure and a crustal density of 2900 kg m^{-3}. The temperature-dependent ductile strength is calculated for the diabase flow law of [13], and is then linearized following [14]. The fiber stress is calculated from curvature using lithospheric constants as in [6]. The surface heat flow is calculated for each set of values of elastic thickness, plate curvature, T_s, f, and b, by simultaneously solving equation (1), the bending moment of the lithosphere, and the net axial force.

Estimates of elastic thickness for several regions on the southern highlands give values lower than 15 km [6], although they could also have been nearly Airy compensated at the loading time. These results are similar to the 12-15 km obtained for the elastic thickness in the regions located southward of 20º S latitude considered as a whole [7]. Here we use the elastic thickness for Terra Cimmeria, ≤12 km [6], in order to calculate lower limits to the surface heat flow, for the loading time, at these locations. For calculate ductile strength we used a slow strain rate of 10^{-19} s^{-1}. We are only capable of estimate lower limits to the surface heat flows, due to that elastic thickness here used are upper limits, and for that reason faster strain rates (which give higher heat flows) are not used here.

Surface heat flows and crustal temperatures: Surface heat flows calculated for Terra Cimmeria are shown in Fig. 1. Surface heat flow increases with the proportion of heat sources within the crust. Also, heat flows are higher for the case with 25-km-thick radioactive element-rich layer, and for the case with lower surface temperature.

Heat flow results can be used to calculate temperatures within the crust. Fig. 2 shows crustal geotherms for T_s = 220 K and f = 0 (linear thermal gradient), 0.5 and 1. Results for T_s = 273 K are similar. It can be seen that geotherms are clearly divergent, due to the specific values for b and f, in the lower part of the crust. (For the case with b = 25 km and f = 1 the temperature is constant below the radioactive element-rich layer, which is as unrealistic as a strictly linear thermal gradient). It is clear that an increase in f causes a drastic decrease in lowermost crust temperatures, which is more evident for the b = 25 case. These low temperatures seem cold enough to permit long wavelength highlands crustal thickness variations to be stable against relaxation (when compared with models in [2, 3]), especially given that subsequent cooling will further reduce the temperatures.

Depth of magnetization: At the time of magnetization, the temperature at the base of the strongly magnetized layer should be equal or lesser than the appropriate Curie temperature. Given similarly ancient inferred ages of crustal magnetization and topography formation for the cratered highlands, the results described here are likely to be relevant for the depth to the Curie temperature when magnetization was acquired.

The identity of the main magnetization carrier is unknown. This could be pyrrhotite, magnetite or hematite, and we perform calculations for these three minerals, assuming Curie temperatures of 600 K, 850 K and 950 K respectively, using heat flows in Fig. 1. The Curie depth for pyrrhotite is nearly constant, and it is ~20 km in all the cases. Otherwise, Curie depth for both magnetite and hematite increases with the proportion of crustal heat sources and with surface temperature, with minimum depths of ~35 and ~40 km respectively. For magnetite, Curie depth is deeper than the 50-km-level (roughly represent the crust base) for *f* values higher than ~0.6-0.9. For hematite, Curie depth more than 50-km-deep requires *f* values higher than ~0.4-0.6. Results for b = 25 km are shown in Fig. 3.

Analysis of highlands demagnetization by impact cratering suggest that magnetization extends to at least 30-40 km depth [15]. Also, analysis of the Martian magnetic spectrum [16] suggests magnetic sources up to ~50 km deep. Moreover, it has been suggested [17] that the absence of magnetic signature associated with the martian topographic dichotomy boundary indicates that the magnetic sources are mostly located in the lower part of the crust. These results are inconsistent with our Curie depths for pyrrhotite, but are widely consistent with our results for magnetite and hematite.

Conclusions: Our results show the importance of taking into account the presence of crustal heat sources in calculating heat flows and crustal temperatures. The presence of ~50% (or even more), of heat sources located within the martian crust is consistent with geochemical analysis and permit reconciliation of the low elastic thickness deduced for Terra Cimmeria with both unrelaxed crustal thickness variations and magnetic sources probably placed deep in the lower crust, two lines of evidence suggesting relatively cold temperatures in the early lower crust.

References: [1] M.T. Zuber et al., *Science 287*, 1788, 2000. [2] F. Nimmo and D.J. Stevenson, *JGR 106*, 5085, 2001. [3] E.M. Parmentier and M.T. Zuber, *LPS 33*, 1737, 2002. [4] M.H. Acuña et al., *Science 284*, 790, 1999. [5] J.E.P. Connerney et al., *Science 284*, 794, 1999. [6] P.J. McGovern et al., *JGR 107*(E12), 2002. [7] D. McKenzie et al., *EPSL 195*, 1, 2002. [8] S.C. Solomon and J.W. Head, *JGR 95*, 11,073, 1990. [9] S. Anderson and R.E. Grimm, *JGR 103*, 11,113, 1998. [10] S.M. McLennan, *GRL 28*, 4019, 2001. [11] M.D. Norman, *LPS* 33, 1175, 2002. [12] M.K. McNutt, *JGR 89*, 11,180, 1984. [13] Y. Caristan, *JGR 87*, 6781, 1982. [14] D.C. McAdoo et al., *Tectonophysics 116*, 209, 1985. [15] F. Nimmo and M.S. Gilmore, *JGR, 106*, 12,315, 2001. [16] C.V. Voorhies et al., *JGR 107*(E6), 2002. [17] J. Arkani-Hamed, *JGR 107*(E5), 2002.

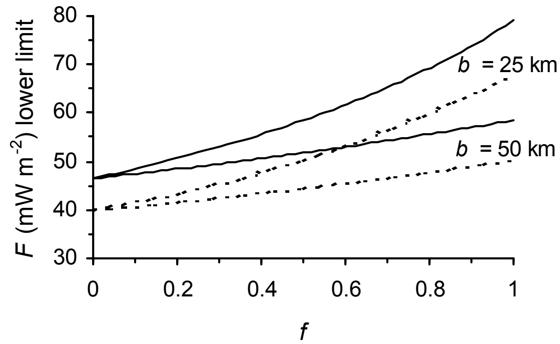

Figure 1. Lower limits to the surface heat flow estimated for Terra Cimmeria in terms of *f*. Solid and dotted curves indicate surface temperatures of 220 K and 273 K, respectively.

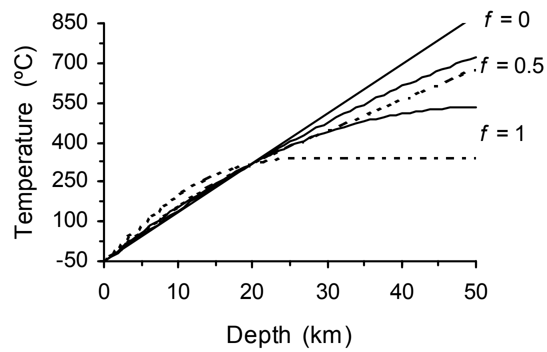

Figure 2. Crustal geotherms for T_s = 220 K. Solid and dotted curves indicate radioactive element-rich layer thickness b of 25 km and 50 km respectively. The f = 0 case corresponds to a linear thermal gradient for both radioactive layer thicknesses.

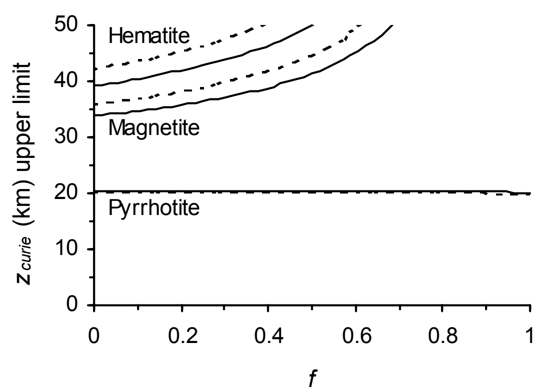

Figure 3. Curie depths for pyrrhotite, magnetite and hematite in terms of *f*, calculated for b = 25 km. Solid and dotted curves indicate surface temperatures of 220 K and 273 K respectively (for the pyrrhotite case the curves are coincident).