RELAXATION OF CRUSTAL THICKNESS VARIATIONS ON MARS: IMPLICATIONS FOR THERMAL EVOLUTION.

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Introduction: Analysis of gravity and topography data for Mars provide estimates of crust thickness showing a long wavelength lateral variation present even beneath the old, heavily cratered terrain [1]. Isotopic analysis of SNC meteorites document an early differentiation on Mars [2] that likely produced the crust beneath the ancient heavily cratered terrain. Therefore, it appears that this crustal thickness variation may have survived throughout the geologic evolution of Mars. Other features such as large basins, like Hellas, and the crustal dichotomy are associated with shorter wavelength crustal thickness variations that have not relaxed. In this study we explore the constraints that the survival of long wavelength crustal thickness variations would have on the thermal evolution of Mars.

Relaxation of crustal thickness variations: Variations in the thickness of a low density crust result from topography both at the surface and at the crust-mantle boundary. Thermally activated creep in the crust and mantle will allow this topography and its corresponding crustal thickness variation to relax over time. A number of earlier studies [e.g. 5] show that topography at the surface and at the crust mantle boundary evolve on two distinct time scales involving two different forms of deformation. Following relatively rapid vertical, column-wise isostasy, horizontal crustal flow is required to reduce an initially nonuniform crust to constant thickness. This flow is driven by horizontal pressure gradients that result from isostatically compensated crustal thickness variations. Since thermally activated creep of crustal rock is strongly temperature-dependent, most of the flow must occur near the base of the crust where the temperature is high. In the model that we formulated, crustal flow is approximated as locally horizontal viscous flow with a viscosity that varies with temperature or depth in the crust. Temperature T within the crust, determined by conductive transfer of heat to the surface,

$$T = T_s + F_{cm}(D-z)/k + H(D^2 - z^2)/2k$$

depends on the depth z below the surface, the surface temperature T_s, the heat flux at the crust-mantle boundary F_{cm}, the rate of radiogenic heating H, the thermal conductivity k, and the thickness of the crust D. Thermally activated creep is described by a viscosity μ

$$\mu = \mu_0 \exp\left[\frac{Q}{RT_0}\left(\frac{T_0}{T} - 1\right)\right]$$

where μ_0 and T_0 are reference values and Q is the activation energy. With a strongly temperature dependent crustal viscosity ($Q \approx 500$ kJ/mol) and mantle rock with a higher viscosity, flow is restricted to a thin hot layer near the base of the crust. Detailed calculations show that, to a good approximation, this can be described as flow in a layer with a viscosity equal to that at the base of the crust and a thickness h determined by the height above the base at which the viscosity increases by about a factor of ten

$$h = 2.3\left(\frac{kT_{cm}}{F_{cm}}\right)\left(\frac{RT_{cm}}{Q}\right).$$

The relaxation rate for crustal variation of wavelength λ is then

$$r = \frac{\rho_c g}{12\mu_0}\left(\frac{\rho_m - \rho_c}{\rho_m}\right)\left(\frac{2\pi}{\lambda}\right)^2 h^3 \exp\left[\frac{Q}{RT_0}\left(\frac{T_0}{T_{cm}} - 1\right)\right]$$

with λ in the following results set equal to the circumference of the planet. The amplitude $A(t)$ of crustal thickness variation at time t is

$$A(t) = A(0)\exp\left(-\int_0^t r\,dt\right).$$

Values of r depend strongly on μ_0 and T_0 values. These could be evaluated from laboratory flow laws [6] or, alternatively, by noting that the occurrence of earthquakes requires that elastic stresses in oceanic crust be preserved for at least several Myr at temperatures below 700°C.

Thermal evolution models: $T_{cm}(t)$ and $F_{cm}(t)$ are calculated from a thermal evolution model. Temperatures in a cool conductive lid are calculated using a finite difference method with a heat flux at the base of the lid derived from relationships for volumetric heating [7] and transient cooling [8] due to thermal convection in a fluid with strongly temperature dependent viscosity. Recent models for Mars formulated on this basis include [7,8,9]. The models assume a mantle viscosity with an activation energy of 500 kJ/mol and a value of 10^{20} Pa-s at a reference temperature of 1400°C. The models do not include any possible effects of chemical stratification [10] except for crust with 50 km average thickness; a value of the thermally defined conductive lid less than the crustal thickness is set to this value.

Results: We vary two parameters in the cooling model. 1) Two values of the initial temperature for solid state convective cooling correspond to a) the average solidus temperature of the Martian mantle [11] ≈2000°C and b) a lower value of 1500°C that presumes melt transport, not considered in the model, may have lowered the temperature. 2) The fraction of bulk chondritic radioactive heating partitioned into the crust depends on incompatible element partitioning during melting and the fraction of the mantle that melted to generate the crust. Results for two cases are shown in Figure 1.

These results show that rapid relaxation will occur early in the evolution particularly for high T_i when secular cooling contributes significantly to the heat flux and temperature at the crust-mantle boundary. Figure 1 also compares T_{cm} for transient cooling and steady state models. In the steady state model with heat transfer through the crust only due to mantle heat production, T_{cm} is much lower and relaxation is much slower (dashed heavy line in b). In constrast to previously reported results [12], it thus appears important to account for secular cooling of the mantle, as may also be require to explain the presence of an internally generated magnetic field early in the history of Mars [13,14].

For a crustal thickness variation to persist over the evolution of Mars, the time-averaged value of r must be less than about 10^{-17}sec^{-1}. This appears to be possible only if T_i is significantly less than the mantle solidus and if an appropriate fraction of heat production is partitioned into the crust. It is interesting to speculate that compositional stratification resulting from early differentiation [10] may have suppressed solid state convective heat transfer. This may allow conductive cooling to significant reduce temperatures at the base of the crust allowing crustal thickness variations to be preserved for a longer time.

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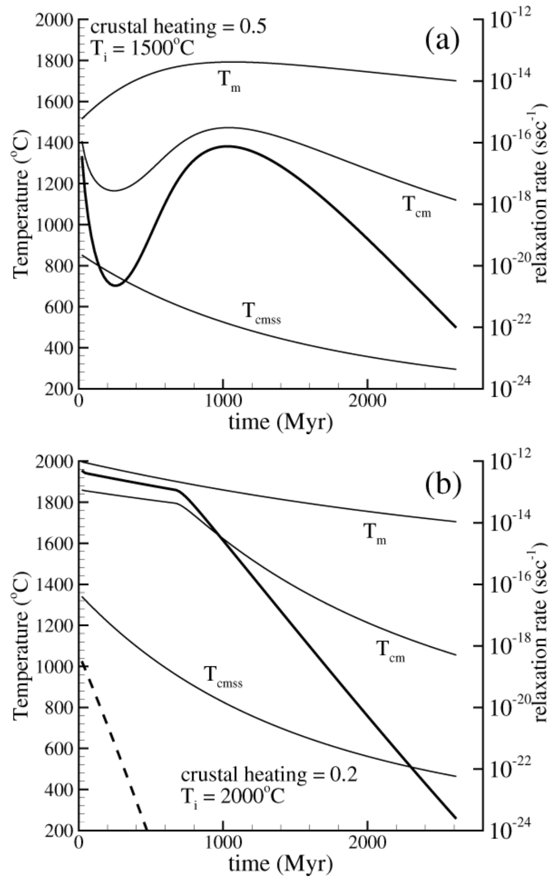

Figure 1. Relaxation rate r (heavy line), mantle potential temperature T_m, crust-mantle temperature T_{cm}, and steady state crust-mantle temperature T_{cmss} as a function of time for two different initial temperatures T_i and crustal heating rates.