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On the spatial variability of the Martian Elastic Lithosphere Thickness: Evidence for Mantle Plumes?

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Introduction

The way in which the lithosphere responds to tectonic stresses gives important clues to its thermal state. Lithospheric strength is usually expressed in terms of its effective elastic thickness T_e and T_e has been estimated for different regions on Mars using gravity / topography admittance studies [1,2] and forward modelling of tectonic features. Recent estimates of the present day elastic thickness indicate that T_e is larger than 300 km at the North Pole today [3], a value well above the estimates for the Tharsis volcanoes, which also exhibit an Amazonian loading age. It has been speculated [3,4] that this discrepancy may be caused by recent volcanic activity driven by mantle plumes, but other models for the generation of partial melt underneath Tharsis do exist [5]. Here we investigate how lateral variations of crustal thickness and the distribution of heat producing elements on the surface influence the Martian elastic lithosphere thickness. Model results will then be compared to the available elastic thickness data.

Modelling

We have calculated the present day T_e on Mars using the strength envelope formalism for the two layer system comprised of crust and mantle. The thermal structure of the lithosphere is calculated by constructing lithospheric temperature profiles corresponding to purely conductive heat transport and prescribing a constant mantle heat flow derived from thermal evolution models [6]. Mantle heat flow is kept globally constant and lithospheric temperature profiles take into account the local crustal thickness [7] as well as the local concentration of heat producing elements in the crust [8]. For the crust and mantle, wet diabase and wet olivine rheologies are assumed, respectively.

Results

The calculated present day elastic lithosphere thickness T_e is shown in Fig. 1 for a model assuming a chondritic concentration of heat producing elements and exhibits a large degree of spatial variability. T_e ranges form 70 km near Arsia Mons to more than 200 km in the Hellas Basin. This large variation is mainly driven by the large crustal thickness differences and regions of reduced T_e coincide with those of elevated crustal heat flow. Furthermore, due to the large crustal thickness in the Tharsis region, an incompetent crustal layer is present in regions with crustal thicknesses in excess of 95 km. This results in an abrupt drop of T_e at Arsia Mons. The resulting distribution of T_e is trimodal (Fig. 2), with the lowest values around 75 km corresponding to regions with a crustal detachment layer. The southern highlands exhibit T_e ~160 km, while the northern lowlands have T_e ~ 180 km.

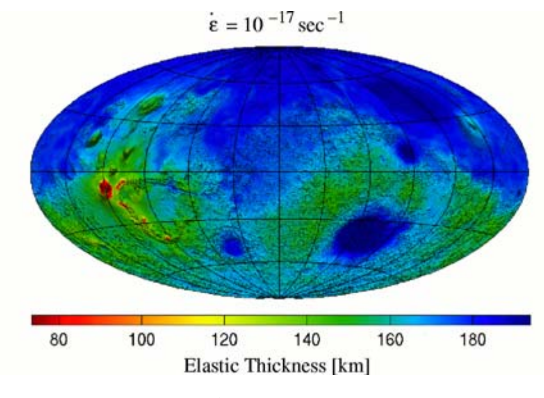

Figure 1: Map of today's elastic lithosphere thickness on Mars. A chondritic concentration of heat producing elements was assumed.

The strain rate used in the calculation was chosen to be 10^{-17} s^{-1}, appropriate for processes associated with the speed of mantle convection. However, loading at the polar caps is probably driven by the

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Martian obliquity cycles and deformation rates of the order of 10^{-14} s^{-1} are more appropriate there [3]. This results in a T_e increase of 20%.

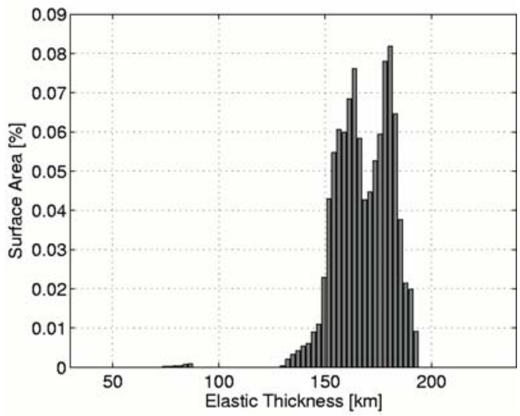

Figure 2: Histogram of the distribution of T_e on the surface of Mars as derived from Fig. 2.

Results for specific features are summarized in Table 1, where the first column of modelled T_e values corresponds to a thermal evolution model assuming chondritic concentrations of heat producing elements and a loading age of the Tharsis Montes of 1 Gyr b.p. The second column corresponds to a model in which the bulk content of heat producing elements has been reduced by 35% and loading ages of 3 Gyr b.p. were assumed. For the calculation of the elastic thicknesses at the poles and volcanoes strain rates of 10^{-14} and 10^{-17} s^{-1} have been assumed, respectively.

Feature	Age	T_e [km] est.	T_e [km] mod.	
NP	Rec	>300	226,	303
SP	Rec	>275	202,	274
OM	A	93 ± 40	93,	81
AsM	A	105 ± 40	77,	70
PM	A	50 -100	65,	58
ArM	A	20 - 35	58,	50

Table 1: Loading age (Rec: recent, A: Amazonian) as well as estimated and modelled T_e for the North (NP) and South Pole (SP), Olympus (OM), Ascraeus (AsM), Pavonis (PM) and Arsia Mons (ArM).

Although elastic thicknesses at the Tharsis Montes are satisfactorily reproduced for the chondritic model, this model fails to reproduce the extremely large elastic thicknesses observed at the Poles. In contrast, the subchondritic model reaches T_e > 300 km there. However, in this case deformation at the volcanoes needs to represent old loading ages of 3 Gyr b.p., i.e., loading in the early Amazonian epoch.

Discussion

Although the models presented here result in a large degree of spatial variability of T_e, these variations by themselves are insufficient to explain the observations if a spatially homogeneous mantle heat flow and a chondritic concentration of heat producing elements is assumed. Only if the bulk content of heat producing elements is reduced by 35% can the assumption of a spatially homogeneous mantle heat flow be maintained. However, this seems to be incompatible with geochemical evidence derived from the analysis of the SNC meteorites and the persistence of Martian volcanism to the recent past.

Therefore, other effects need to be considered. These include a spatially variable mantle heat flow and for the model presented here, a local reduction of the mantle heat flow from 13.5 to 9 mW m^{-2} would be sufficient to explain the large T_e observed at the Martian poles. This suggests that a moderately strong mantle plume is present underneath Tharsis and/or a cold down-welling is situated beneath the poles. In order to affect the elastic lithosphere properties, plumes and down-wellings need to be stable for hundreds of millions of years as the associated temperature anomalies only slowly diffuse into the stagnant lid.

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