ESTIMATING LITHOSPHERIC THERMAL GRADIENT ON MARS FROM ELASTIC LITHOSPHERE THICKNESS: NEW CONSTRAINTS ON HEAT FLOW AND MANTLE DYNAMICS. Sean C. Solomon, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, and James W. Head, Department of Geological Sciences, Brown University, Providence, RI 02912.

Introduction. The thickness of the elastic lithosphere on a planet is essentially a measure of the reciprocal of the vertical thermal gradient in the lithosphere, i.e., the depth to a temperature at which ductile behavior replaces brittle behavior at typical geological strain rates. Under flexure there is an elastic "core" of the lithosphere occupying the depth interval over which the bending stress is less than an envelope of "strength" versus depth defined by a frictional failure curve at shallow depths and a ductile flow law at greater depth [1,2]. The depth of the lower limit to "elastic" behavior is governed primarily by temperature and also by strain rate, composition, and load magnitude. Estimates of elastic lithosphere thickness derived from simple models of flexure have been quantitatively related to the average vertical thermal gradient of the lithosphere on the Earth [e.g., 3] and Moon [4], and similar concepts have been used to constrain the thickness of the elastic lithosphere on Venus [e.g., 5]. In this paper we apply these concepts to Mars.

Elastic Lithosphere Thickness. The thickness T_e of the elastic lithosphere of Mars has been estimated from the tectonic response to individual loads [6-8] and from the global response to the long-wavelength load of the Tharsis rise [9,10]. A summary of these results is given in Table 1. The values for T_e derived for individual loads are not consistent with a simple progressive increase with time in the thickness of the elastic lithosphere of Mars. The largest estimates of T_e, for instance, are for perhaps the oldest (Isidis mascon) and youngest (Olympus Mons) features considered [11]. Spatial variations in elastic lithosphere thickness must have been at least as important as temporal variations [7]. In particular, there appears to have been a dichotomy in lithosphere thickness that spanned a significant interval of time, with comparatively thin elastic lithosphere (T_e = 20 to 50 km) beneath the central regions of major volcanic provinces and substantially thicker elastic lithosphere (T_e in excess of 100 km) beneath regions more distant from volcanic province centers and appropriate for the planet as a whole.

Thermal Gradients. The values of T_e may be converted to the mean lithospheric thermal gradient, given a representative strain rate and a flow law for ductile deformation of material in the lower lithosphere. Formally, this is done by converting T_e to T_m, the depth to the rheological boundary marking the base of the mechanical lithosphere. This conversion is accomplished by constructing models of bending stress consistent with the strength envelope and finding for each model the equivalent elastic plate model having the same bending moment and curvature [3]. We take the representative strain rate for the flexural response to each local load to be the quotient of the maximum horizontal strain given by the elastic model and the growth time of the load, taken to be $10^{8\pm1}$ yr. A large uncertainty arises from the poorly known value for the thickness of the martian crust and the distinct flow laws for crustal and mantle material. The mean crustal thickness consistent with global topography and gravity must be at least 30 km [12], which corresponds to zero thickness beneath the Hellas basin. Viking line-of-sight (LOS) residuals over the Hellas basin and the 370-km-diameter crater Antoniadi are best fit if the topographic depressions are compensated at 120-130 km depth [13,14]. LOS data over Elysium Planitia and Olympus Mons can be fit with varying degrees of Airy isostatic compensation and crustal thicknesses of 30-150 km [8,15].

We assume that the large values of elastic lithosphere thickness determined from the local response to the Isidis mascon and Olympus Mons and from the global response to the Tharsis rise exceed the thickness of the martian crust. Because flexurally-induced curvature is modest for these loads, the depth T_m to the base of the mechanical lithosphere is approximately equal to T_e [3] and is determined by the ductile strength of the mantle, assumed to be limited by the creep strength of olivine [16]. The mimumum values of T_e for the Isidis mascon and Olympus Mons correspond, by this line of reasoning, to mean lithospheric thermal gradients of no greater than 5-6 K/km.

The values of T_e derived from the Tharsis Montes and Alba Patera are less than or comparable to the thickness of the crust. The mechanical lithosphere thickness T_m, which exceeds T_e for these loads [3], is likely governed by the strength of crustal material, taken to be limited by the creep strength of anorthosite [17]. The mean thermal gradients consistent with the values of T_m for these loads under this assumption are in the range 11-18 K/km (Table 1). The thermal gradient corresponding to the value T_e = 54 km determined for Elysium Mons [7] depends strongly on the thickness of the martian crust but generally falls between those for Olympus Mons and Isidis and those for the Tharsis Montes and Alba Patera.

Implications. While the heat flow and thermal structure of Mars are not known, we may compare these gradients with values derived from scaling arguments. If Mars loses heat at the same rate per mass as the Earth [18], then the mean heat flux would be about 30 mW/m^2-K. For a representative value of lithospheric thermal conductivity of 2-3 W/m-K, the mean lithospheric thermal gradient would be 10-15 K/km. The gradient implied by the global response to the Tharsis rise falls below this range by at least 30-50%. Two possible explanations are that the fractional heat loss contributed by secular global cooling is much lower on Mars than on Earth or that a higher fraction of radioactive heat sources on Mars are concentrated in the crust. The low ^{40}Ar abundance in the Martian atmosphere [19] provides an argument against the second possibility.

As noted above, the differences in lithospheric thermal gradients implied by the different values of T_e must be at least in part due to lateral variations in temperature within and beneath the lithosphere. These variations can be due to lithospheric reheating beneath the centers of major volcanic provinces, thermal differences remaining from major pre-volcanic events such as large impacts [20], or some combination of these two effects [21]. Essentially contemporaneous temperature differences of at least 400 K at 30 km depth at a late stage in the development of the Tharsis province are implied by the variation in gradients in Table 1. Such differences are too large to be solely the effect of large impacts of order 10^9 yr earlier [22]. They are, however, similar to the temperature variations associated with lithospheric reheating beneath hot spot volcanic centers on Earth [23]. The areas of anomalously high temperature gradients on Mars must be similarly affected by mantle dynamic processes, including convective upwelling and associated magmatism. These results thus provide new constraints on the spatial pattern of heat delivered by mantle upwelling beneath major volcanic provinces on Mars.

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Table 1. Estimates of elastic lithosphere thickness and lithospheric thermal gradient on Mars

Feature	Age of deformation	D, 10^{30} dyn cm	T_e, km	dT/dz, K/km
Arsia Mons	UA	0.5	18	18
Ascraeus Mons	UA	1.0	22	14
Pavonis Mons	UA	1.6	26	13
Alba Patera	LA	3.2	33	11
Elysium Mons	LA	14	54	7-13
Olympus Mons	UA	50 - 240	140 - 230	< 5
Isidis mascon	UN	>150	>120	< 6
Tharsis rise	MN - UA	>100	>100	< 7

Sources: D, T_e [6-10]; ages [11]; N = Noachian, H = Hesperian, A = Amazonian, L = lower, M = middle, U = upper.