JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. B7, PAGES 11,073–11,083, JULY 10, 1990

Heterogeneities in the Thickness of the Elastic Lithosphere of Mars: Constraints on Heat Flow and Internal Dynamics

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Derived values of the thickness of the effective elastic lithosphere on Mars are converted to estimates of lithospheric thermal gradients and surface heat flow by finding the thickness of the elastic-plastic plate having the same bending moment and curvature, subject to assumed strain rates and temperature-dependent flow laws for crustal and mantle material. Local thermal gradients and heat flow values so estimated were 10–14 K km^{-1} and 25–35 mW m^{-2}, respectively, at the time of formation of flexurally induced graben surrounding the Tharsis Montes and Alba Patera, while gradients and heat flow values of less than 5–6 K km^{-1} and 17–24 mW m^{-2}, respectively, characterized the lithosphere beneath the Isidis mascon and Olympus Mons at the time of emplacement of these loads. On the basis of the mean global thickness of the elastic lithosphere inferred to support the Tharsis rise and estimates of mantle heat production obtained from SNC meteorites, it is suggested that the present average global heat flux on Mars is in the range 15–25 mW m^{-2}. Approximately 3–5% of this heat flux during the Amazonian epoch has been contributed by excess conducted heat in the central regions of major volcanic provinces. Most likely, this excess heat flux has been delivered to the base of the lithosphere by mantle plumes. The fractional mantle heat transport contributed by plumes during the last 2 b.y. on Mars is therefore similar to that at present on Earth.

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 [*Goetze and Evans*, 1979; *Brace and Kohlstedt*, 1980]. At the shallowest depths, lithospheric bending leads to faulting to a depth that is dependent on the load, the flexural rigidity, and the failure law. 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 vertically averaged thermal gradient of the lithosphere on the Earth [e.g., *Caldwell and Turcotte*, 1979; *McNutt*, 1984; *McAdoo et al.*, 1985; *Willett et al.*, 1985; *Kusznir and Karner*, 1985] and Moon [*Solomon*, 1985], and similar concepts have been used to constrain the thickness of the elastic lithosphere on Venus [e.g., *Solomon and Head*, 1984]. In this paper we apply these concepts to Mars.

We begin with a review of estimates of the effective thickness of the Martian elastic lithosphere. We then convert these thickness values to estimates of lithospheric thermal gradients and heat flow by means of temperature-dependent strength envelopes. On the basis of the locations and geological epochs appropriate to each estimate of thermal gradient, we relate the results to global heat flux, interior thermal evolution, lithospheric reheating mechanisms, and the evolution of major volcanic provinces on Mars.

Paper number 90JB00541.
0148-0227/90/90JB-00541$05.00

ELASTIC LITHOSPHERE THICKNESS

The thickness T_e of the elastic lithosphere of Mars has been estimated from the tectonic response to individual loads [*Thurber and Toksöz*, 1978; *Comer et al.*, 1985; *Janle and Jannsen*, 1986] and from the global response to the long-wavelength load of the Tharsis rise [*Willemann and Turcotte*, 1982; *Banerdt et al.*, 1982; *Sleep and Phillips*, 1985]. A summary of these results is given in Table 1. It is important to distinguish the elastic lithosphere from the thermal or compositional lithosphere inferable from Pratt isostatic compensation models [e.g., *Sleep and Phillips*, 1979] or from the heights of volcanic constructs [*Vogt*, 1974; *Carr*, 1976]. The base of the elastic or mechanical lithosphere is governed by the temperature at which ductile strength becomes less than some threshold value at geological strain rates [*Goetze and Evans*, 1979; *Brace and Kohlstedt*, 1980].

The radial distances of graben circumferential to the major volcanoes Ascraeus Mons, Pavonis Mons, Arsia Mons, Alba Patera, and Elysium Mons (Figure 1) indicate best fitting values for flexural rigidity D of 10^{23}–10^{24} N m at the times of graben formation [*Comer et al.*, 1985]. These thicknesses are equivalent (for values of the lithospheric Young's modulus and Poisson's ratio of E = 100 GPa and ν = 0.25, respectively) to T_e in the range 20–50 km. In addition to best fitting values, *Comer et al.* [1985] obtained lower and upper bounds to T_e from formal error analysis as