MARS IS NOT DEAD: MANTLE CONVECTION CONTROLS THE OBSERVED LATERAL VARIATIONS IN LITHOSPHERIC THICKNESS ON PRESENT-DAY MARS

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Introduction Because the transition from elastic to viscous behavior in silicate materials is controlled by temperature [1], measurements of the thickness of a planet's elastic lithosphere (T_E) provide important constraints on the thermal structure and evolution of the lithosphere. For Mars, surface geophysical measurements have not yet been made, so estimates of T_E have been made using orbital observations of gravity anomalies, topography, and tectonic structure [2-4]. These results show that the lithosphere has thickened with time, as expected for a cooling planet [5]. T_E values for the Amazonian, the most recent geologic epoch on Mars, are typically around 100 km. An important limitation is that most of these measurements, particularly for geologic units that formed in the second half of martian history, have been made near large volcanos or extensional faulting. In either case, these measurements are likely to be in regions of upwelling mantle convection and higher than average heat flow.

Phillips et al. [6] recently reported observations of the internal stratigraphy in the north polar layered deposits made with the SHARAD sounding radar on Mars Reconnaissance Orbiter. Based on the limited (< 100 meters) deflection of the ice-rock interface at the base of the layered deposits, they inferred that T_E in this region is at least 300 km for deposits that are less than 5 million years old. This T_E value is dramatically larger than any prior estimate of elastic lithosphere thickness on Mars and places important constraints on the planet's thermal evolution. They suggested three possible explanations for their results: (1) the bulk silicate composition of Mars contains less radioactive elements than previously believed, corresponding to just 70-80% of chondritic abundances ("chondritic abundances" in Phillips et al. [6] means the Wänke and Dreibus [7] abundance model, hereafter WD94). (2) The measured deflection is not an equilibrium elastic configuration but rather a transient visco-elastic response to recent loading of the polar cap. Successful models of this type also require a sub-chondritic abundance of radioactive elements in the martian crust and mantle. (3) There are significant spatial variations in elastic thickness and heat flow on present-day Mars.

In this work, we show that it is unlikely that Mars has significantly sub-chondritic abundances of U, Th, and K. On the other hand, strong spatial variations in heat flow occur naturally in convecting systems, and we show that our existing models of mantle plume magmatism on Mars [8] provide a simple explanation for the Phillips et al. [6] polar flexure observations.

Radioactive Abundances Various geochemical models have been proposed for Mars. These models have been derived to explain the mass and moment of inertia of Mars, and various elemental and isotope abundance ratios of the martian meteorites. The WD94 composition model [7] corresponds to a radioactive heating rate of 4.1 pW/kg. Other proposed Mars composition models [9-11] correspond to heating rates of 6.0 to 6.2 pW/kg. In all cases, these heating rates are expressed for the primitive mantle composition, prior to extraction of radioactivity into the crust. For comparison, the Earth's primitive mantle composition [12] corresponds to a heating rate of 5.2 pW/kg and the silicate portion of the CI carbonaceous chondrite composition [13] has a heating rate of 6.6 pW/kg. These results show that WD94 has the lowest radioactive heating rate of any Mars model and is also lower than the much better constrained Earth value. These models were constructed from a broad range of meteorite precursors, ranging from oxidized and volatile rich (CI) to reduced and refractory (enstatite EH chondrites), and using a variety of geochemical constraints. This indicates that a Mars composition containing just 70-80% of the WD94 radioactivity is well outside the range of our current geochemical knowledge, although it can not be rigorously disproved. We therefore consider it preferable to look for a different explanation for the Phillips et al. [6] polar flexure observations.

Mantle Convection Models As an alternative to sub-chondritic radioactive element abundances, we show here that the observed range of elastic thickness variations is the natural result of spatially variable heat flow in a convecting martian mantle. We analyze lithospheric thickness in a suite of models that were calculated in spherical axisymmetric geometry to simulate mantle plumes and include an Arrhenius temperature-dependent viscosity and partitioning of radioactivity between crust and mantle. The models satisfy a variety of observational constraints, including magma production rate, mean melt fraction, surface heat flux over the upwelling plume, and core heat flux [8]. A representative example is shown in Figure 1, which includes the thick, cold thermal boundary layer (blue) that is characteristic of stagnant lid convection. It is visually obvious that the lid thickness varies by about a factor of two from the upwelling to the downwelling. For example, on Earth, 600 °C is usually the maximum temperature at which the lithosphere exhibits elastic behavior [1]. The temperature field in Figure 1 reaches 600 °C at 120 km beneath the upwelling and at 240 km beneath the downwelling. The mantle heat flux varies by a factor of 2.2 from the upwelling to the downwelling.

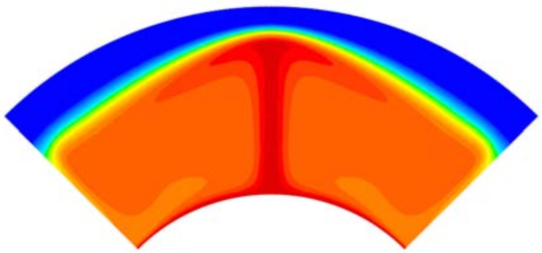

Figure 1: A representative temperature field, for a volume-averaged Rayleigh number of $6.1{\cdot}10^6$.

We quantify the thickness of the lithosphere using the standard yield strength envelope approach [14], in which the strength at any location is determined by the weaker of the brittle strength and the viscous strength. The brittle strength is controlled by frictional sliding, which depends on pressure but is independent of composition [15, 16]. The viscous strength is modeled using wet diabase for the crust and wet olivine for the mantle [17, 18].

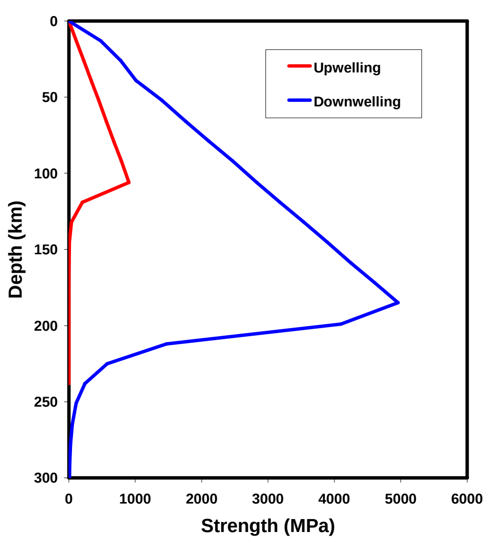

Figure 2: Lithospheric strength as a function of depth above the upwelling plume (red) and above the downwelling (blue).

Figure 2 shows the lithosphere's strength as a function of depth for the thermal field in Figure 1. The red line shows results calculated in extension over the upwelling plume, where the elastic lithosphere is 130 km thick. The blue line shows results calculated in compression over the downwelling, where the elastic lithosphere is 270 km thick. These results assume a reference strain rate of $3{\cdot}10^{-18}$ sec^{-1}, in the middle of the range usually assumed for Mars [2]. They also assume that the lithosphere behaves elastically when the strength difference exceeds 50 MPa [1]. Factor of 2 changes in the Rayleigh number change the lithosphere thickness over the downwelling by about 30 km. Factor of 3 changes in either the strain-rate or the elastic strength limit change the lithospheric thickness over the downwelling by about 20 km. The lithosphere varies in thickness by about a factor of about 2 from upwelling to downwelling except at low Ra.

These results show that stagnant lid mantle convection provides a natural explanation for the large lateral variations in lithospheric thickness that have been inferred for Amazonian-age units on Mars from orbital gravity, topography, and ground-penetrating radar observations. These models also explain the ~300 km lithosphere thickness inferred beneath the present-day north polar cap if the volume-averaged mantle Rayleigh number (which is a measure of convective vigor) is of order $5{\cdot}10^6$. This Ra range is consistent with mantle plume models that explain magma production in present-day Tharsis [8]. Thus, recent measurements of the flexural behavior of the north polar cap [6] are entirely consistent with a martian interior with moderately vigorous mantle convection.

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