THE GEODYNAMICAL END GAME FOR MARS: SOUNDING RADAR CONSTRAINTS ON THE PRESENT THERMAL STATE.

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Introduction: On Mars, data from orbital radar sounders shows that the mass loads of Planum Boreum and Planum Australe deflect their underlying substrates only minimally, if at all. This condition requires either a very thick martian lithosphere or a nonequilibrium state for the viscous response of the mantle to the load. Either way, this result provides a bound on the thermal structure of the martian interior in the present epoch [1]. Here, we explore the radar observations that provide this geodynamical constraint, interpreting what the low degree of deflection means in terms of the planet's internal thermal state.

Radar Instruments: There are presently two radar sounders in martian orbit – MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding, on Mars Express) and SHARAD (Shallow Radar, on the Mars Reconnaissance Orbiter). In its subsurface sounding mode, MARSIS operates in 1-MHz bands centered on 1.8, 3, 4, and 5 MHz, while SHARAD operates in a single 10-MHz band centered on 20 MHz. The combination of frequencies and bandwidths means that MARSIS has superior depth penetration and SHARAD has superior depth resolution. SHARAD was designed later with the intention to complement MARSIS, and this has proven to be the case.

Planum Australe: MARSIS typically penetrates to the base of the South Polar Layered Deposits (SPLD) [2], which make up the bulk of Planum Australe; SHARAD only occasionally does so, while showing superior resolution of the layering [3]. Thus, MARSIS is the vehicle to look for substrate lithospheric flexural/membrane deformation in response to the SPLD load. Conveniently, a DEM for the substrate has been constructed by combining a MOLA DEM with MARSIS basal reflector depth estimates [2]. However, the SPLD are emplaced on the rugged, highly cratered topography of the southern highlands, so any flexural signal is likely to be obscured unless it has a large amplitude. The substrate elevations [2] do show a tendency to decrease towards the center of the SPLD, but at least some of this is due to old impact basins such as Prometheus. Figure 1 is a polynomial fit (degree 7) to MARSIS-determined substrate elevations (magenta dots). The flexural/membrane response to the load would be a relatively smooth surface because the elastic response acts as a low-pass-filter on the deflection. The smoother parts of the polynomial surface in the quadrant 90°-180°E (lower right) are loosely reminiscent of flexural/membrane deformation and span an elevation range of ~200-250 m. This range is a reasonable upper bound on the geodynamical deflection of the substrate, and in fact may be nothing more than topographic "noise." Response of an elastic shell to the SPLD load requires lithospheric thicknesses of 275-300 km to match these deflections [1].

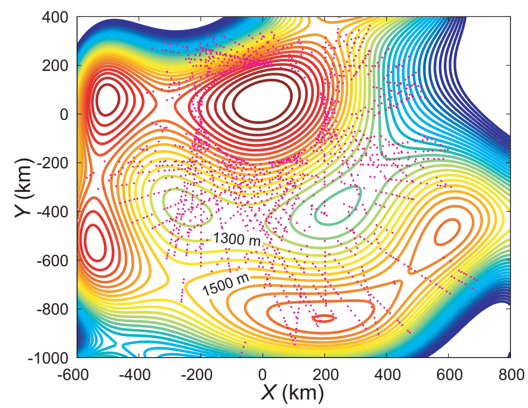

Figure 1. Degree-7 polynomial fit to SPLD substrate DEM determined from MARSIS and MOLA data [2]. Magenta dots are the locations of substrate determinations. Apparent gaps in along-track coverage are due to the lack of a discernible basal interface, and not to gaps in observations, and there is no data poleward of 87°S latitude. The map is a south-polar projection with $X = 0$ running from longitude 0° E (top) to 180° E (bottom) and $Y = 0$ running from 270° E (left) to 90° E (right). Contour interval is 50 m. Surface behavior outside of data coverage can be ignored.

Planum Boreum: The north polar plateau can be divided into two distinct units, the predominantly water-ice [1] North Polar Layered Deposits (NPLD) and the underlying ice-sand mixture of the Basal Unit (BU) [4]. MARSIS penetrates both units, while SHARAD only occasionally sees the basal reflector of BU and is susceptible to volume scattering within this unit. However, BU is absent beneath the Gemina Lingula portion of Planum Boreum [1, 5, 6]. Here SHARAD maps the contact of NPLD with an underlying unit, presumably the Vastitas Borealis formation (VBF) of the northern lowlands. Time-to-depth conversion of the radargrams using a value of 3 for the real part of the dielectric constant (ε') shows a remarkably flat contact (e.g., Figure 2). The uncertainty in zero deflection is 100 m, based on doubling the rms error of range resolution, small-scale boundary variations, and a 10% range in ε'. The last quantity dominates the error. To limit deflection of the substrate to 100 m or less requires an elastic thickness greater than 300 km.

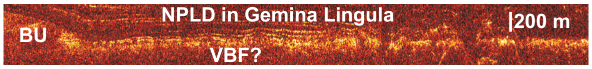

Figure 2. Portion of a SHARAD radargram over Gemina Lingula from orbit 5297, traversing Planum Boreum from ~85°N, 45°E (left) to ~79°N, 21°E (right) and showing the basal contact zone. Abscissa is distance along ground track, while the standard time (range) delay of the ordinate has been converted to depth, assuming the subsurface propagation medium has a real dielectric constant of 3.

A sufficiently low value of ε' in the time-to-depth conversion produces a basal surface that could rightly be interpreted as flexural/membrane deflection. Displayed in range-delay, the substrate boundary beneath Planum Boreum is strongly concave, but using an ε' around that of ice, ~3, transforms this boundary to a flat surface in depth, as mentioned above. If the actual effective ε' value is less than this value, then the substrate boundary truly is concave. Figure 3 suggests that beneath Gemina Lingula an ε' value less than ~2.6 would create a depression greater than 100 m, allowing elastic thicknesses less than the 300-km bound.

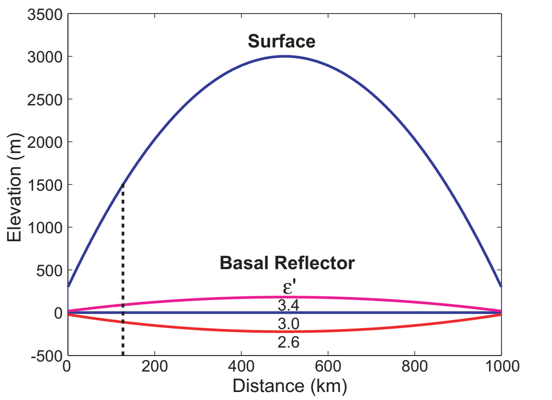

Figure 3. Consider a simple parabolic model (plus pedestal) of Planum Boreum, with a flat basal contact assigned an ε' value of 3. Perturbations of this contact with time-to-depth conversions using ε' values of 3.4 and 2.6 are shown. Vertical dashed line indicates ~100 m perturbations at a 1500 m surface elevation, typical of Gemina Lingula.

The leading candidates for lowering ε' within the polar deposits are CO_2 ice and CO_2 clathrate hydrate. Because the thermal conductivities of these materials are low (~0.5 W m^{-1} K^{-1}), the resulting high temperature gradients limit the stability fields of these phases in the NPLD and SPLD [7]. Further evidence that low thermal conductivity material is not present resides with the transparency of the NPLD and SPLD to radar waves, requiring very low temperatures throughout the volume [e.g., 8]. Using very generous upper bounds of the allowable CO_2 ice and CO_2 clathrate hydrate fractions [7] yields estimates of ε' of 2.75 and 2.93, respectively [9]. Thus, it appears unlikely that CO_2 can be invoked to argue for an ε' of 2.6 or lower in the NPLD.

Discussion: The Planum Boreum and Planum Australe results both suggest a lower bound of ~300 km on the present day elastic thickness of Mars. An alternative hypothesis is that the lithosphere is thinner, but its deflection has not reached mechanical equilibrium in response to the load. The response time is controlled by the viscosity of the upper mantle. A lower bound on mantle viscosity can be determined from a lower bound on the age of the NPLD of 10 Ma, which is established by linking two distinct periodicities of reflectors observed by SHARAD in the NPLD to periodic or chaotic climate forcing signals [1]. Employing viscoelastic modeling, the 10-Ma minimum age yields an upper mantle viscosity > 10^{25} Pa s. This value corresponds to absurdly low upper-mantle temperatures, compelling us to reject this hypothesis [1].

The 300-km estimate for elastic thickness is higher than any previous estimate by at least a factor of two [e.g., 10, 11]; however, it is an estimate for the present epoch, perhaps 2 Ga younger in load age than any other estimate (e.g., the Tharsis volcano loads). In fact, by using a Chondritic thermal model for Mars [12], it can be shown that the 300-km value is consistent with the parent isotope decay of heat sources, with a slightly sub-Chondritic heat flux at the poles and a slightly elevated heat flux at Tharsis [1].

Thus, the sounding radars have provided an important constraint on the geodynamical "end-game" – the present-day thermal conditions of the martian interior.

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