Supporting Online Material for

Mars North Polar Deposits: Stratigraphy, Age, and Geodynamical Response


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Published 15 May 2008 on Science Express
DOI: 10.1126/science.1157546

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Materials and methods

1. SHARAD and MARSIS Descriptions

SHARAD (SHAllow RADar) (S1) is a sounding radar provided by the Italian Space Agency to the Mars Reconnaissance Orbiter, which is operated for NASA by Caltech’s Jet Propulsion Laboratory. SHARAD has a 20-MHz center frequency and a 10-MHz bandwidth, yielding a two-way range resolution of 15 m divided by the square root of the real part of the permittivity of the propagation medium. The radar transmits a 10-W, 85-μs chirped (linear FM) pulse from a 10-m dipole antenna at a pulse repetition frequency of 700 Hz. The nominal spatial resolution at the surface is 3-6 km and processing can narrow this to 0.3-1 km in the along-track direction. Coherent integration is performed on-board and synthetic-aperture processing is performed on the ground. The along-track processed data frames of radar power are assembled into “radargrams” with abscissa and ordinate axes of spacecraft distance along track and range time delay, respectively. The time coordinate can be converted to depth by predicting or detecting the surface position in each frame and assigning a subsurface wave speed below that point.

MARSIS (S2) (Mars Advanced Radar for Subsurface and Ionospheric Sounding), a joint Italian-US experiment on the European Space Agency’s Mars Express orbiter, is similar to SHARAD in principle, but operates for subsurface sounding between 1.3 and 5.5 MHz in four 1-MHz bands radiating from a 40-m dipole antenna. Much of the data processing for MARSIS is done onboard the spacecraft.

2. Uncertainty in Estimating Zero Lithospheric Deflection Beneath the NPLD

How certain is the estimate of zero deflection beneath the NPLD at Gemina Lingula? The inherent range resolution of SHARAD in subsurface ice is ~10 m. A reasonable range for the real part of the permittivity of dusty ice in the NPLD is 2.85 to 3.15, which leads to a basal depth uncertainty for the NPLD of ~40 m. Small-scale boundary variations lead to an uncertainty of ~30 m. Assuming these errors are independent, the root mean square error is 50 m, and we adopt a conservative 100-m value for the uncertainty in zero flexure. Stated another way, for the time-to-depth conversion to yield a depression beneath Gemina Lingula greater than 100 m, and thereby allowing an elastic thickness less than the 300-km bound, the integrated permittivity of the NPLD would have to be less than ~2.6, which is highly unlikely. Values of permittivity much greater than 3 yield a convex surface, i.e., an upward deflection.
3. Mantle Rheology and the Elastic-Plastic Lithosphere

For calculating elastic-plastic moments, a mantle rheology, a strain rate, and a thermal profile, *inter alia*, must be defined. Of minerals likely to be abundant in the martian mantle, olivine is the weakest and thus controls the overall flow. For the mantle portion of elastic-plastic bending moment calculations, we used olivine flow laws for dislocation and diffusion creep, with wet and dry rheologies (S3); in all cases dislocation creep was the weaker of the two mechanisms. The strain rate was taken as $1 \times 10^{-14} \text{ s}^{-1}$, which is the reciprocal of the characteristic loading age if the NPLD accreted over the last $\sim 5$ m.y. We matched the elastic moment to the elastic-plastic moment at the maximum flexural curvature of the 300-km elastic solution. The temperature profile adopted was obtained from a simple conduction model (S4) with a mantle heat flux and the concentration of crustal heat sources decreasing downward with an $e$-folding depth of 30 km. The assumed surface temperature was 155 K, typical of polar regions, and the assumed thermal conductivity was 4 W m$^{-1}$ K$^{-1}$. The resulting crust and mantle heat fluxes of 8 and 17 mW m$^{-2}$ closely match present-day values from a chondritic parameterized convection thermal model (S5). Heat fluxes were scaled from these values to test models other than chondritic. This is an approximation sufficient for this application, as Mars’ heat flow should presently be dominated by the balance of its heat production and secular cooling.

4. Non-equilibrium Solutions for Load Response

The SHARAD-derived lower-bound NPLD age of 1 Ma can be used to test the load response of layered viscosity structures derived via creep laws from thermal models with chondritic heat sources. Such thermal models for present-day Mars contain a thick stagnant lid (S6) overlying a convecting interior. In principle, the polar loads could be supported in the “cool” stagnant lid, SL, with a hot convecting mantle beneath. However, there is a large linear temperature gradient across a stagnant lid, and the fraction of the lid with high viscosity values that would inhibit lithospheric deflection in response to a polar load is confined to the lid’s upper portion. The question is whether or not the high viscosity region is thick enough to have a major influence on the deflection magnitude as a function of time. We search for viscosity structures that produce at 1 Ma no more than $\sim 100$ m of deflection beneath the NPLD at Gemina Lingula in response to the Planum Boreum load.
We examined two thermal models as they behave during the present epoch. One model (S5), with chondritic heat sources, has an upper mantle convecting temperature ($T_{um}$) of ~1500 K and an SL thickness of 270 km. The elastic thickness, $T_e$, for this model is ~150 km, which leaves a ~120-km-thick lower, viscous portion of the SL. The temperature range in the SL is ~920-1500 K, and the corresponding range in viscosity, $\eta$, is $\sim$3$\times$10$^{22}$-3$\times$10$^{19}$ Pa s (olivine, wet, dislocation creep). Such a viscosity distribution in a viscoelastic model will evolve to elastic equilibrium fairly rapidly. The viscoelastic spherical shell model (S7) adopted for this thermal model has $T_e$ = 150 km, with, very conservatively, $\eta$ = 10$^{24}$ Pa s in the remainder of the lid, here taken as the depth range 150-300 km; the convecting mantle below is assigned $\eta$ = 10$^{21}$ Pa s. The deflection at 1 m.y. for this model is 300 m for the characteristic wavelength (spherical harmonic degree $l$ = 9) of Planum Boreum (Fig. S5, Model 1). This is three times the deflection constraint.

A second thermal model (S8) has a thicker stagnant lid than the first (S5) and thus may be more appropriate for transient support of the polar loads. This model has heat sources that are close to chondritic heat production in the current era. The SL thickness is 500 km, $T_{um}$ = 1900 K, and the viscosity range in the viscous part of the lid is $\sim$4$\times$10$^{25}$-4$\times$10$^{18}$ Pa s. If we assign a single viscosity of $\eta$ = 10$^{24}$ Pa s to the stagnant lid (below $T_e$ = 150 km), then ~140 m of deflection occurs at 1 Ma (Fig. S5, Model 2). This value is somewhat close to the SHARAD-derived deflection limit of 100 m, but this model is unrealistic because of the strong temperature (and thus viscosity) gradient across the SL. We ran two additional models with divisions of the stagnant lid, beneath the elastic layer, into discrete viscosity layers (see Fig. S5 caption for descriptions). A two-layer model yields a deflection of 220 m at 1 Ma (Model 3), and a more realistic model with 7 layers has a deflection of 310 m (Model 4). We also ran the latter model with a dry rheology, and the deflection at 1 Ma decreases to 270 m (Model 4-dry).

In summary, realistic thermal models for Mars with chondritic heat sources translate to viscosity stratifications that in response to the Planum Boreum load produce too much deflection at 1 Ma. Thus, it is likely that the martian mantle is sub-chondritic.
Supporting figures

Fig. S1. Radargram in range-delay (time) format, acquired by the MARSIS sounding radar on orbit 3738 of the Mars Express orbiter. Frequency band is 4.5-5.5 MHz. Reflector at the bottom of Basal Unit (BU) is evident and extends beneath Olympia Planum. Because MARSIS has one-tenth the bandwidth of SHARAD, its range resolution is ten times coarser and the reflectors internal to the North Polar Layered Deposits (NPLD) are not as well resolved. However, the lower frequency of MARSIS allows deeper penetration than SHARAD, providing superior detection of deeper features.

![Radargram in range-delay (time) format](image)

Fig S2. DN values for a single frame extracted from radargram 5297 in its original range-time-delay format. Pixel spacing is 0.0375 μs (about 3.2 m). Packet and inter-packet regions are evident (see also Fig. 3 in the main text).
**Fig. S3.** Laboratory results for the variation of the real part of the permittivity ($\varepsilon'$) and the loss tangent ($\tan \delta$) as functions of water-ice contamination (in mass %) by basaltic dust. Results are for the SHARAD center frequency of 20 MHz and were obtained at -73 °C (200 K). The measurements were obtained for distilled water ice mixed with varying amounts of basaltic dust containing 14% iron oxides. The basalt powder was produced from the tephra of the Inferno Cone at Craters of the Moon National Monument (Idaho, USA) and is thought to have mineralogical, petrophysical, and electrical properties similar to those of the martian surface ($S9$). Tephra was reduced to a 50-μm powder that was then mixed with different amounts of water and frozen spontaneously using liquid nitrogen loops to ensure sample homogeneity. Measurements were performed using the Agilent E4991A impedance analyzer and two low temperature dielectric cells in an environmental chamber with controlled temperatures and pressures that simulated martian surface conditions. Results suggest that $\varepsilon'$ increases exponentially with the inclusion of basaltic dust; it ranges from ~3 for pure ice, to 3.72 for a 50% dust-contaminated mixture, then to ~5.25 for desiccated, compacted basalt powder. The loss tangent ranges from 0.003 for pure ice, to 0.05 for a 50% dust-contaminated mixture, to 0.06 for pure basaltic dust. The loss tangent of pure ice at colder temperatures (appropriate for Mars polar regions) can be lower than 0.001. The measurement accuracy is 3% and 11%, respectively, for the real part of the permittivity and the loss tangent. From the plot, it can be inferred that the observed transparency of the NPLD to SHARAD radar waves precludes an integrated dust fraction greater than about 10%.
**Fig. S4.** Deflection contours for a 300-km thick spherical-shell elastic lithosphere responding to a spherical-harmonic degree 90 representation of the Planum Boreum load. Deflection variation across Gemina Lingula is ~100 m, which matches the uncertainty in the SHARAD-observed zero substrate deflection. Deflections for 100- and 200-km elastic shells are ~400 m and ~200 m, respectively. Model parameters are: load density, 1100 kg m\(^{-3}\); crustal density, 2900 kg m\(^{-3}\); mantle density, 3500 kg m\(^{-3}\); Young’s modulus, 100 GPa; Poisson’s Ratio, 0.25. Lower values of Young’s modulus would require thicker lithospheres to achieve the same deflection. Background image is a Mars Orbiter Laser Altimeter (MOLA) Digital Elevation Model. Contour interval is 50 m.
Fig. S5. Deflection as a function of time after load is emplaced on a viscoelastic Mars, based on the formulation of (7). Arrow marks constraint of ≤ 100 m of deflection at 10^6 years. Load is spherical harmonic degree \( l = 9 \), corresponding to the Planum Boreum scale, with an amplitude of 2000 m. Results are shown for viscosity, \( \eta \), stratification based on present-day temperatures from parameterized convection thermal models with stagnant lids and convecting interiors. Unless otherwise noted, all temperature-viscosity conversions were based on wet olivine dislocation creep (3). Model 1, based on (5): \( T_e = 150 \) km (\( \eta = 10^{30} \) Pa s); rest of stagnant lid (SL), 150-300 km, has \( \eta = 10^{24} \) Pa s; and convecting mantle has \( \eta = 10^{21} \) Pa s. Models 2-4 from (8): all have \( T_e = 150 \) km (\( \eta = 10^{30} \) Pa s) and SL thickness = 500 km. Model 2 viscosities: \( 10^{24} \) Pa s for 150-500 km, \( 10^{20} \) Pa s for convecting mantle. Model 3 viscosities: \( 10^{25} \) Pa s for 150-350 km, \( 10^{20} \) Pa s for 350-500 km, \( 10^{20} \) Pa s for convecting mantle. Model 4 viscosities: \( 10^{27} \) Pa s for 150-175 km, \( 10^{26} \) Pa s for 175-200 km, \( 10^{25} \) Pa s for 200-225 km, \( 10^{24} \) Pa s for 225-250 km, \( 10^{23} \) Pa s for 250-275 km, \( 10^{22} \) Pa s for 275-325 km, \( 10^{20} \) Pa s for 325-500 km, \( 10^{20} \) Pa s for convecting mantle. Model 4-dry is the same as Model 4 except that dry olivine (dislocation creep) was used (3). For all models: Thickness/radius parameters are: crustal thickness = 35 km, upper-mantle/lower-mantle boundary radius = 2400 km, core radius = 1700 km. Densities: crust = 2900 kg m\(^{-3}\), upper mantle = 3500 kg m\(^{-3}\), lower mantle = 3600 kg m\(^{-3}\), Core = 6600 kg m\(^{-3}\), Young’s modulus = 100 GPa, Poisson’s ratio = 0.25.
Supporting references