LOCALIZED THARSIS LOADING ON MARS: TESTING THE MEMBRANE SURFACE HYPOTHESIS.

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Introduction: Restricting the topographic load on Mars to the Tharsis region alone results in a warping of the planetary surface outside of Tharsis as a thin spherical lithospheric membrane [1]. This is a spherical analogy to flexural deformation in response to an isolated volcanic load on a flat lithospheric plate. Using MGS topography and gravity data [2,3], and localizing the Tharsis load by its zero elevation contour, we showed that the long wavelength shape of Mars can be explained by the pole-to-pole slope, regional Tharsis topography, and the deformation of the rest of the planet in response to the Tharsis load [4]. Here we revisit the hypothesis that the long-wavelength surface outside of Tharsis is, essentially, a deformed membrane.

Previous Model: The Phillips *et al.* 2001 model [4] was successful in that it accounted, qualitatively, for the negative ring in the gravity perturbation [4, Figs. 1 & 2] and in the geoid surrounding Tharsis [5, Plate 1], as well as the broad gravity/geoid high over Arabia Terra [4, Fig 2]. Further, it also explained the topographic moat ("Tharsis trough") surrounding much of Tharsis, as well as the high-standing terrain of Arabia ("Arabia bulge") and its extension into the northern lowlands surrounding the Utopia basin [4, Fig. 3]. Finally, the model was able to account for the azimuths of a significant fraction of late-Noachian valley networks [4, Fig. 4].

The model also had shortcomings. It did not attempt to satisfy the amplitude of the gravity field over Tharsis or elsewhere, and compensation of Tharsis was implemented in a simple fashion by calibrating the model to match approximately the amplitude of long-wavelength topography outside Tharsis.

A More Rigorous Approach: We have reformulated the localized loading model of a thin elastic lithospheric shell so that it satisfies the observed geoid everywhere on the planet and the observed topography just in the Tharsis region. Outside of Tharsis, the topography is set to zero, so that surface relief is due solely to membrane deformation. A crustal perturbation is introduced to allow the geoid boundary condition to be satisfied everywhere, and over Tharsis the amount and style of compensation is controlled by the parameters of the model (elastic thickness, T_e, Young's modulus, E, and Poisson's ratio, ν, of the elastic shell; mean crustal thickness, T_c, crustal density, ρ_c, and mantle density, ρ_m). The model parameters also control the nature of the membrane deformation outside of Tharsis, and thus how well the model is able to reproduce the long-wavelength topography there.

The solution originates in the elastic thin-shell formulation of *Banerdt* [6], except that the vertical and horizontal loads, and the model geoid (surface and Moho), are different inside of Tharsis (Domain 1, D1) and outside of Tharsis (Domain 2, D2). This requires localizing the geoids in D1 and D2, and the topography in D1 (it is zero in D2). The localization scheme follows *Simons et al.* [7], except that shapes of the localizing functions in D1 and D2 are defined by the boundary that separates these two regions. Spectrally, this produces a coupling among the spherical harmonic coefficients for deformation, W_{lm}, so the solution is obtained by matrix inversion once other unknowns are substituted out by employing the boundary conditions. The simultaneous, complex equations are given by:

$$
{}_0p_{lm} = {}_3p_l W_{lm} - {}_1p_l \sum_{l_1=0}^{l_{1\max}} \sum_{m_1=-l_1}^{l_1} W_{l_1 m_1} f\left(l,m,l_1,m_1,1\right) - {}_2p_l \sum_{l_1=0}^{l_{1\max}} \sum_{m_1=-l_1}^{l_1} W_{l_1 m_1} f\left(l,m,l_1,m_1,2\right) \qquad l = 0,1,\ldots,l_{\max}
$$

where the coefficient ${}_0p_{lm}$ contains localized representations of observed topography and geoid quantities, plus model parameters. The other coefficients, ${}_ip_{lm}$ (i = 1,2,3), include just model parameters. The functions $f(\ldots,1)$ and $f(\ldots,2)$ are localizing operators for D1 and D2, respectively. Decomposing this set into its real and imaginary parts, and expressing the negative m spectrum in terms of the positive m spectrum yields a set of $(l_{1\max}+1)^2$ simultaneous equations with $l_{\max}$ = $l_{1\max}$. The triangle inequality [7] then demands that the localizing functions must be expanded to exactly twice the degree, $l_{\max}$, of the solution.

The boundary definition between D1 and D2 is, in effect, a model parameter. For the results below, the D1 localizing function boundary (zero outside of it) was defined by the 1-km contour on Tharsis, with a cosine taper to 3 km, and a value of unity for higher elevations. The D2 localizing function is simply the one's complement on the sphere of the D1 function.

Results: One way to interrogate the model space is to find combinations of parameters that produce spatial values, $w(\theta, \varphi)$, of model deformation that match, approximately, the long-wavelength amplitude of the Arabia bulge (~3 km, as referenced to the 2nddegree hydrostatic shape, less the pole-to-pole slope coefficient, J_1). The 3-km value is for a spherical harmonic expansion to degree l = 10 – the spectral range in which the rest of the planet responds to the Tharsis load [4]. Our initial forays into the solution space show that the results are most sensitive to mean crustal thickness, T_c, amongst the model parameters. The most fundamental property of the solution is that there are two distinct domains, one dominated by Tharsis loading and one dominated by crustal perturbation loading outside of Tharsis. This is seen clearly in a plot of model Arabia topographic amplitudes vs. mean crustal thickness (Figure 1). The two domains are separated by a solution singularity at $T_c \approx 50$ km, where the determinant of the solution matrix switches signs. At large values of T_c, the solution is close to the ~3-km amplitude for which the model was tuned. Significant departures from this value occur at T_c less than ~80 km. The large T_c regime produces solutions similar to the 2001 model, which was not constrained by the gravity field, had no crustal perturbations, and had Tharsis loading as the sole source of antipodal deformation.

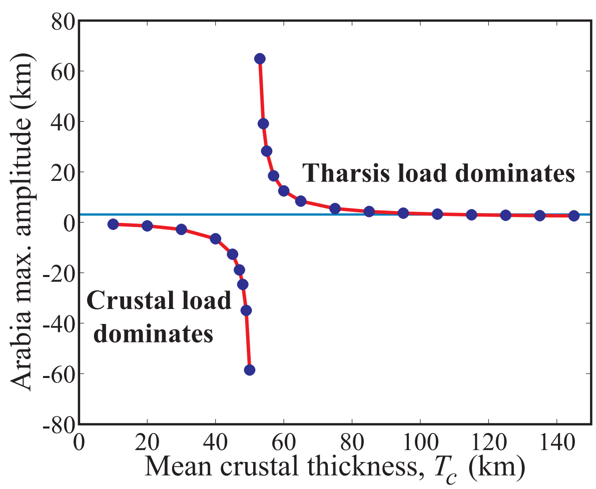

Figure 1. Plot of the maximum amplitude of model deformation in Arabia versus mean crustal thickness, T_c. Model parameters are: T_e = 75 km, $E = 5\times10^{12}$ Pa, $\nu = 0.25$, ρ_c = 2900 kg m^{-3}, ρ_m = 3500 kg m^{-3}. Singularity in solution occurs at $T_c \approx 50$ km. Horizontal line indicates the observed amplitude of the Arabia bulge.

At mean crustal values shortward of ~50 km, the solutions produce results essentially opposite to the 2001 model. That is, the solutions are characterized by an anti-bulge (negative relief) and an anti-trough (positive relief). Examination of the results shows that the positive geoid over Arabia is satisfied by a strong upward displacement of the Moho by crustal perturbations, and analogous results hold for the anti-trough. In this regime, crustal perturbation loading dominates over Tharsis loading in deforming the planet, as such perturbations have a stronger contribution to the geoid because of thinner average crust.

Figure 2 shows the mapped solution for T_c = 95 km, with actual topography in D1. A bulge of ~3 km appears over Arabia, and a trough surrounds Tharsis. Close inspection of the map reveals that the model trough extends into the eastern region of the Tharsis province, in the Lunae Planum region. As this locale is actually on the lower flanks of the rise, it indicates that the domain boundary should have extended to a lower elevation and thus needs redefinition.

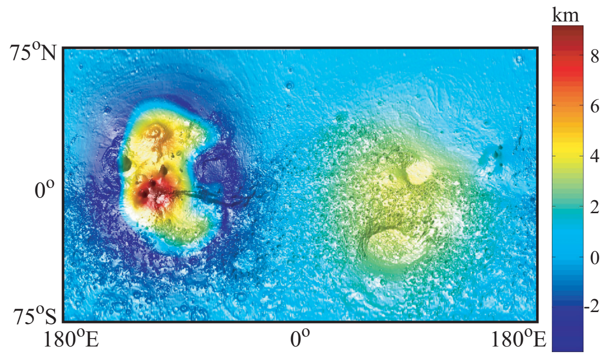

Figure 2. Model surface of Mars (l_{max} = 10). The surface in D1 (Tharsis) is actual topography (as described above). In D2, it is the model solution, $w(\theta, \varphi)$, for the parameters given in Figure 1, with T_c = 95 km.

Discussion: A new class of solutions for loading planetary lithospheric shells results from localizing the observed topography and gravity fields. Competition between interior and exterior loads leads to distinct solution domains. Extensive exploration of the model parameter space is required, as is a careful quantitative assessment, in a plethora of locales, of model versus topographic amplitudes. Further, the stress distribution from this model may be different from earlier solutions based on global loading of the topography [8].

This new model provides an integrated basis for exploring membrane deformation due to Tharsis, including considerations of the spatial extent of the load, the accompanying crustal structure, bounds on geophysical parameters (e.g., Figure 1), and relationships of solutions to valley network azimuths [4].

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