TECTONICS OF THE THARSIS REGION OF MARS: INSIGHTS FROM MGS TOPOGRAPHY AND GRAVITY.

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Introduction: The origin, evolution and internal structure of the Tharsis plateau, which dominates the western hemisphere of Mars, has been intensely studied with Viking and Mariner data. However, this fascinating region is still not well understood [1,2]. The topography, gravity, and the stress state implied by the well-developed system of tectonic structures associated with Tharsis can be used to test various models for the support of this vast province. Is Tharsis a huge uplifted dome [e.g., 3]? Was it formed isostatically by magmatic intrusion [4,5]? Or is it a massive volcanic surface load [6]?

Previous modeling, using harmonic expansions of Viking-era topography and gravity up to degree and order 8, suggested that faulting on or close to the topographic rise was broadly consistent with isostatic support, whereas more distant faulting could be associated with a regional flexural response to a surface load [1,7]. However, the quality of the data was adequate only to delineate the broadest aspects of the structure in this complex region. For this study, we have extended the previous analyses using MGS topography [8] and gravity [9] to degree and order 50.

Method: The basic method involves calculating the vertical deflection and internal density variations required to satisfy the gravity and topography for plausible geophysical models of the lithosphere. From these, the state of stress and strain are derived and compared with observed tectonic structures [1,7]. We use an analytic spherical deformation code [10] based on a derivation of elastic thin shell theory by Vlasov [11]. It utilizes topography and gravity (represented as a set of spherical harmonic coefficients) as boundary conditions, and incorporates a full thin shell treatment with horizontal gradient loads and both bending and membrane stresses. It includes both top- and bottom-loading; lithospheric deflection and a laterally varying crustal thickness (applied at the bottom of the crust) are dependent variables which are determined through the system of shell equations by the two boundary conditions. Once the deflection is known, stress and strain are determined uniquely by the displacement field. Thus the full spatial variation of the deflection, crustal thickness, stress and strain (magnitude and direction) are calculated in a self-consistent manner.

For these calculations, we assume a lithosphere thickness of 100 km, a mean crustal thickness of 50 km, a topography density of 2900 kg/m^3, and a density contrast ($\rho_m - \rho_c$) of 600 kg/m^3. These values are consistent with global gravity and topography analyses [12].

Results: Deflection and Crustal Thickness: The Tharsis plateau is characterized by downward deflection (~12 km), upon which is superimposed additional flexure of ~10 km beneath its volcanoes (Fig. 1). Uplift (<10 km) is seen under Tempe Terra, Amazonis Planitia, and Valles Marineris and its outflow channels. Argyre shows a slight amount of downwarping (relative to its surroundings), indicating a weak mascon.

Variations in crustal thickness are due to the topographic relief and deflection, plus an additional variation at the Moho. Our results agree well with those calculated from the Bouguer anomaly [12]. Tharsis shows up to 40 km of thickening, with Alba, Sirenum, and Tempe exhibiting lesser amounts. The thinnest crust (30 km) is found beneath Argyre, Acidalia Planitia, and the Olympus Mons aureole; Valles Marineris also exhibits ~20 km of thinning relative to its surroundings. All the major volcanoes, with the exception of Alba, have a thinned center surrounded by a thickened ring. The ring is primarily due to flexure, whereas the apparently thin center is almost certainly an artifact of assuming too low a density for the construct and its underlying crust. Syria Planum and the Olympus aureole also share these characteristics.

Results: Stress and Strain: In general, as seen in earlier studies with lower resolution [1,7], compressional stresses tend to be radial and extensional stresses circumferential to Tharsis. However, we can now see the effects of regional features, such as the Coprates ridge and Tempe Terra, and subtle variations in the larger-scale structure as well local features (such as the volcanoes), as the wavelengths change from the spherical to the planar response regime [1].

With the topography and gravity fields available prior to MGS, it appeared that it was necessary to invoke two distinct modes of support for Tharsis in order to explain both the radial structures on the elevated flanks (which were attributed to isostatic stresses) and those outside Tharsis proper (which were consistent with flexure). We can now see that both sets of faults (with the exception of those on top of the rise and those near Alba; see below) can be explained in a unified fashion by flexure alone, with the faulting within Tharsis proper caused by regional deformation that could not be resolved by the Viking-era data sets.

Elastic strain is a more directly useful quantity to compare with observed tectonics than stress, as it is a measure of the potentially observable fault displacement. The correlation between computed strain and the major structures in the western hemisphere is striking, both in terms of the directions and in the geographic distribution (Fig. 2). For extension, the major grabens and rifts of Memnonia, Sirenum, Thaumasia, and southern Claritas Fossae, Valles Marineris, and Tempe

Terra coincide with calculated strain concentrations. Note that these areas are also generally associated with local uplift. Only the structures associated with Alba Patera, and local structures around the Tharsis Montes and Syria Planum are not correlated. For compression, the major wrinkle ridge belts in Lunae Planum, Solis Planum, Sirenum, and Acidalia are also associated with predicted strain concentrations.

The magnitude of the calculated extensional strain (0.2–0.4%) agrees within about a factor of two with the integrated circumferential strains estimated from measurements of fault slip (e.g., see summary in [13]). Estimates of the extension across the heavily faulted regions of Alba [14], Tempe [13], Thaumasia [15] and Sirenum [16] have been combined with new estimates across Valles Marineris based on more detailed mapping and modeling of the structure as a rift [17]. Even given the large uncertainty in the estimates of extension, which mostly derive from the possible variation in normal fault dip, results suggest about 60±45 km total hoop extension (or ~0.4% strain at a radius of 2500 km) now expressed at the surface (not accounting for buried structures) [13]. For compression, our calculations of 0.2–0.3% in Lunae Planum also agree well with estimates of shortening derived from wrinkle ridge measurements in this area [18].

Discussion: Most tectonic structures in the western hemisphere of Mars are consistent with a state of flexural support for Tharsis. Therefore it is not necessary to invoke an additional regime of purely isostatic support in Tharsis' history [1,2,7]. Our results indicate that Tharsis was formed primarily by volcanic construction (possibly including both extrusive volcanism and intrusion into the upper crust) accommodated by lithospheric flexure. As the observed faulting is consistent with the strain field predicted by *current* gravity and topography, we conclude that the character of Tharsis has not changed significantly since these structures were formed. Mapping indicates that these faults date from the Noachian, implying that Tharsis has existed in its current form for over 3 Ga.

The northern lobe of Tharsis, around Alba Patera, has been recognized as a geophysical province distinct from the southern rise [8]. The faulting extending from Ceraunius Fossae north and north-east through Tantalus and Alba Fossae is not well described by this model. Either these structures formed under different conditions than we see today, or the assumptions of this model (e.g., depth of compensation, mode of support) are not appropriate for this region. The pattern is indicative of relative uplift of the Alba rise, analogous to Tempe Terra. With the current gravity this would require support from within the mantle, rather than the crustal compensation assumed for the rest of Tharsis. Alternatively, the structures could have formed during an episode of thermal uplift which has since subsided.

References: [1] Banerdt et al. (1992) *Mars*, 249-297; [2] Tanaka et al. (1991) *JGR* **96**, 15617-15633; [3] Phillips et al. (1973) *JGR* **78**, 4815-4820; [4] Sleep & Phillips (1979) *GRL* **6**, 803-806; [5] Sleep & Phillips (1985) *JGR* **90**, 4469-4489; [6] Solomon & Head (1982) *JGR* **87**, 9755-9774; [7] Banerdt et al. (1982) *JGR* **87**, 9723-9733; [8] Smith et al. (1999) *Science* **284**, 1495-1503; [9] Smith et al. (1999) *Science* **286**, 94-97; [10] Banerdt (1986) *JGR* **91**, 403-419, [11] Vlasov (1964) *General Theory of Shells*; [12] Zuber et al. (2000) *Science*, in press; [13] Golombek et al. (1996) *JGR* **101**, 26119-26130; [14] Plescia (1991) *JGR* **96**, 18883-18895; [15] Golombek et al. (1997) *LPSC XXVIII*, 431-432; [16] M.P. Golombek et al. (1994) *LPSC XXV*, 443-444; [17] Schultz (1995) *PSS* **43**, 1561-1566; [18] Plescia (1991) *GRL* **18**, 913-916; [19] Scott & Tanaka (1986) *USGS Map I-1802-A*.

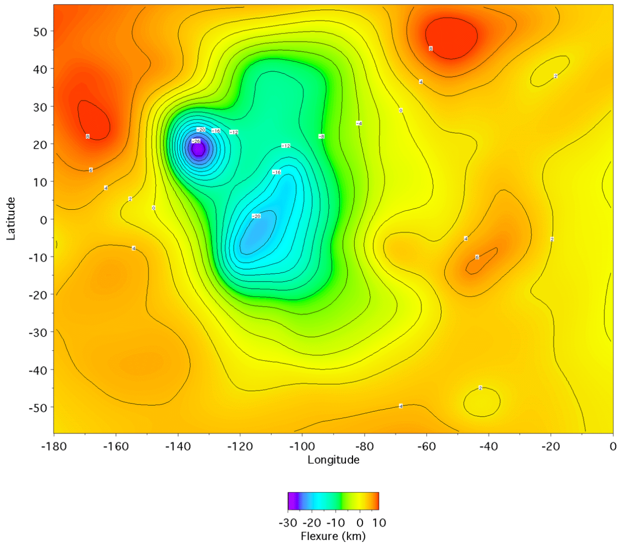

Figure 1. Modeled vertical displacement in Mars' western hemisphere (positive is up). Contour interval is 1 kilometer.

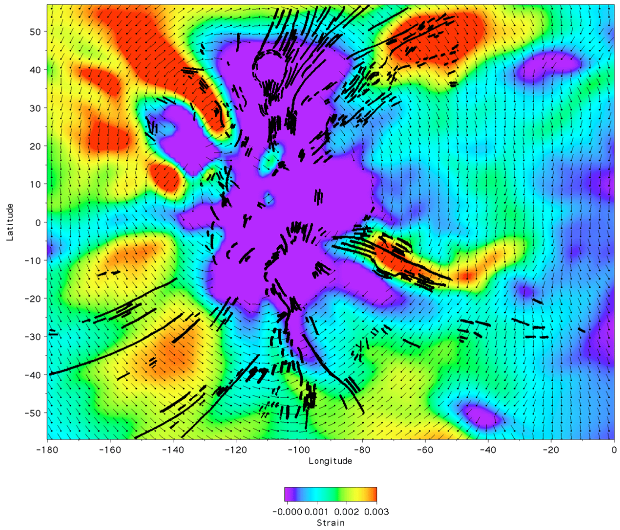

Figure 2. Extensional strain, magnitude and direction; superimposed are extensional structures mapped by Scott and Tanaka [19].