STRESS AND CRUSTAL THICKNESS THE THARSIS REGION OF MARS

W. Bruce Banerdt. Jet Propulsion Laboratory, Pasadena, CA. E-mail: bruce.banerdt@jpl.nasa.gov.

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 historical 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. For example, 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]? In addition, these models can help to identify regions of interest for seismic studies by indicating areas of likely high stress and anomalous crustal thickness.

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 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 (ρ_m–ρ_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 broad downward deflection (~12 km), upon which is superimposed additional flexure of ~10 km beneath its volcanoes. 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.

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 both larger-scale structure and local features 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.

It is clear from these calculations that the stress levels in the Tharsis region dwarf those over the rest of the planet. Stress magnitudes peak beneath the large volcanoes (stress differences of several thousand Mpa), as would be expected. However, stress concentrations (greater than 500 Mpa) are also predicted in the regions of Tempe Terra, Valles Marineris, Amazonis Planitia, and several regions in the northern plains. Thus, these areas might be expected to exhibit higher than average levels of seismicity, and should be considered when deciding landing sites for a seismic network.

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* **287**, 1788.

1. 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 (Banerdt et al., 1992; Tanaka et al., 1991). 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., Phillips et al., 1973)? Was it formed isostatically by magmatic intrusion (Sleep and Phillips, 1979; 1985)? Or is it a massive volcanic surface load (Solomon and Head, 1982)?

Previous modeling, using harmonic expansions of Viking-era topography and gravity up to degree 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 regional flexure beneath a surface load (Banerdt et al., 1982; 1992). But the quality of the data was adequate only to delineate the broad outlines of the structure in this complex region. For this study, we have extended the previous analyses using high-resolution topography (Smith et al., 1998; Figure 1) and gravity (Smith et al., 1999; Figure 2) from Mars Global Surveyor measurements.

2. Method

The basic method involves calculating the stress and strain at the surface of Mars for plausible geophysical models of the lithosphere, and comparing the results with observed tectonic structures (Banerdt et al., 1982; 1992). For this we use an analytic spherical deformation code (Banerdt, 1986) based on a derivation of elastic thin shell theory by Vlasov (1964). It utilizes topography and gravity (represented as a set of spherical harmonic coefficients) as boundary conditions, lateral gradient loads, and incorporates a full thin shell treatment with both bending and membrane stresses. It includes both top- and bottom-loading (Figure 3); 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.

3. Results: Deflection and Crustal Thickness

For these calculations, we assume a lithosphere thickness of 100 km, a mean crustal thickness of 50 km, and a density contrast (rm-rc) of 600 kg/m3. These values are based on preliminary results of gravity and topography spectral analyses (Zuber et al., in prep.) The rotational contributions have been removed from the gravity and topography coefficients (base on a value of I/MR2 of 0.361, Folkner et al., 1997).

The deflection of the lithosphere is shown in Figure 4. Moderate uplift (<10 km) is seen under Tempe Terra, Amazonis Planitia, and Valles Marineris and its outflow channels. The Tharsis plateau is characterized by a huge amount of downward deflection, upon which is superimposed additional flexure beneath its volcanoes. Argyre shows a slight amount of downwarping (relative to its surroundings), indicating a weak mascon.

The inferred crustal thickness is illustrated in Figure 5. 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 likely due to flexure, whereas the thin center is probably an artifact of assuming too low a density for the construct and its underlying crust. Note that Syria Planitia strongly shares these characteristics, while the signature of Olympus Mons is hardly noticeable.

4. Results: Stress and Strain

Stresses are shown in Figure 7 (extension) and Figure 8 (compression). The color levels denote the magnitude of the difference between the maximum and minimum principal stresses. The lines show the direction of the respective maximum or minimum principal stress in the horizontal plane. If no line is present, the respective principal stress is vertical, and no faulting of that character is expected.

It can be seen that in general, as seen in earlier studies with lower resolution, compressional stresses tend to be radial and extensional stresses circumferential to Tharsis. However, we can now see the effects of local features (such as the volcanoes) and subtle variations in the larger-scale structure, as the wavelengths change from the spherical to the planar response regime (Banerdt et al., 1992).

A more useful quantity to compare with observed tectonics is the elastic strain, as this is a measure of the potential fault displacement. The calculated strains are shown in Figures 9 (extension) and 10 (compression), with the appropriate faults from Figure 6 superimposed for comparison. The correlation is striking, both in terms of the directions and in the geographic distribution. For extension, the major grabens and rifts in Memnonia, Sirenum, Thaumasia, southern Claritas, Valles Marineris, Tempe, and Mareotis are associated 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, although some outlying ridges occuring outside the expected regions. In addition, the magnitude of the calculated strains agree within about a factor of two with the integrated fault strains mapped by Plescia (1991ab), Schultz (1995), Chadwick and Lucchitta (1993), Golombek et al. (1995, 1997), and Harrington et al. (1998).

5. Conclusions

1. The majority of tectonic structures (both extensional and compressional) in the western hemisphere of Mars are consistent with a current state of flexural support for Tharsis. Therefore it is not necessary to invoke an additional regime of isostatic support.

2. As the observed faulting is consistent with the strain field predicted by *current* gravity and topography, the character of Tharsis has probably not changed significantly since these structures were formed.

3. Northern Tharis, around Alba Patera, is not well described by this model. Either it formed under different conditions than we see today, or the assumptions of this model (e.g., depth of compensation) are not appropriate for this region.

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Figure 1. Topography of the western hemisphere of Mars from MGS MOLA measurements (Smith et al., 1998). This representation includes harmonics through degree and order 50 (truncated from a 720-degree field), derived from over 200 million measurements obtained during the first six months of mapping. The five major volcanoes of Tharsis are clearly resolved, as are the Argyre basin and Valles Marineris.

Figure 2. Mars' geoid, for the same region shown in Figure 1, from the MGS gravity experiment (Smith et al., 1999; GSFC gravity model mgm0978d). Again, this representation is complete through degree and order 50 and is a subset of a degree 70 field. The geoid (rather than gravity) representation tends to smooth smaller features, but Olympus Mons and the three Tharsis Montes are still clearly resolved. The signatures of Alba Patera, Valles Marineris, and Argyre are discernable, but are much more subdued.

Figure 3. Lithospheric model used in elastic shell calculations. The lithosphere is assumed to have a globally constant thickness. The crustal thickness can vary in three ways. First, the addition of topography obviously adds to the initial thickness. Second, flexure of the lithosphere causes a depression (or dome) that is filled (or removed). Finally, an additional thickening (or thinning) is applied to the base of the crust in order to simultaneously satisfy the observed gravity and mechanical equilibrium.

Figure 4. Lithospheric deflection for the western hemisphere. Positive (red) values denote upward displacement, negative (blue) values denote downward displplcement; the contour interval is 2 km.

Figure 5. Crustal thickness required by gravity and topography. The mean thickness is 50 km, contours are every 10 km. The thickest crust (>80 km) is beneath Tharsis and the "Scorpion Tail". The thinnest crust (<30 km) is found under Argyre, Acidalia, and the Olympus Mons aureole.

Figure 6. Location map showing various features discussed below. Black lines denote tectonic structures mapped by Scott and Tanaka (1986). Extensional features are named in blue, volcanic and impact features are red, and place names are green. The dichotomy boundary is shown schematically.

Figure 7. Extensional stresses, showing the magnitude of the maximum stress difference and the direction of the maximum (greatest tensional) stress in the plane of the surface.

Figure 8. Compressional stresses, showing the magnitude of the maximum stress difference and the direction of the minimum (greatest compressional) stress in the plane of the surface.

Figure 9. Extensional strains, showing the magnitude and direction of the largest extensional strain (if any) in the plane of the surface. Extensional structures from Scott and Tanaka (1986) are included for comparison.

Figure 10. Compressional strains, showing the magnitude and direction of the largest compressional strain (if any) in the plane of

the surface. Compressional structures from Scott and Tanaka (1986) are included for comparison.

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