CONSTRAINTS ON THE EVOLUTION OF THE THARSIS REGION OF MARS.

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Introduction: The western hemisphere of Mars is dominated by topography associated with the Tharsis volcanic province. A range of models for the formation and/or evolution of this region have been proposed and include (1) dynamic support of topography by a large mantle plume [1,2], (2) regional uplift due to underplating of crustal material derived from the northern hemisphere [3], (3) uplift due to solely mantle anomalies - thermal and/or compositional [4], and including crustal thickening by intrusion [5], (4) flexural loading due to volcanic construction [6, 7]. Recent studies suggest that models invoking present-day dynamic support of the Tharsis rise are problematic due to the requirement of persistent plume structure for the 4 Ga history of Tharsis [7], and the indication that an upper mantle plume is responsible for less than 10% of the present-day geoid [8]. Support of the Tharsis rise purely by mantle thermal and compositional anomalies requires the maintenance of large lateral variations in density over billions of years. Clearly, none of the models alone can explain the complex history of the Tharsis region.

Mars Global Surveyor (MGS) gravity, topography, magnetic, and imaging data provide new constraints on models for Tharsis. Here we summarize the primary aspects of the tectonic history of the region, the present-day gravity and topography, and the magnetic field. We suggest a mechanism for the formation and evolution of the Tharsis province that satisfies these observations qualitatively. We present preliminary results on constraints on the thermal history of the crust provided by the magnetic field observations.

Tectonic History: *Observations*. Prior mapping of the Tharsis region has revealed at least four major episodes of predominantly radial large-scale extensional faulting [6, 9, 10, 11], and approximately concentric wrinkle ridges that are concentrated on the Hesperian units of eastern Tharsis (type locale: Lunae planum). Schultz and Tanaka [12] identified concentric contractional deformation of the coprates Rise and of cratered highland material (the South Tharsis ridge belt). This deformation is of a fundamentally different wavelength and amplitude than the Hesperian plains ridges, and deforms older (mid-late Noachian) units. In addition to the radial extensional deformation, concentric fractures in the oldest (early Noachian) units of Claritas Fossae [5] have been noted, and are evident in recent detailed mapping of this region [13]. Fractures concentric to Tharsis are indicative of uplift.

Inferences. The oldest observable deformation in the Tharsis region may be the concentric extensional fracturing in Claritas Fossae [4, 13]. If so, this was followed (quickly) by the large-scale contractional deformation of mid-late Noachian units [12]. By the early Hesperian the scale of contractional deformation had changed to produce wrinkle ridge terrain. Radial extensional faulting appears to have persisted throughout the construction of Tharsis, but was evidently concentrated during the Noachian [11].

Magnetics: *Observations*. MGS magnetic field data provide critical new constraints on the history of crustal evolution in the Tharsis region. For simplicity, we discuss here the altitude-normalized (200-km altitude) radial magnetic field anomalies of Purucker et al. [14]. Anomalies of more than 50 nT amplitude are observed above the 8-km-high early Noachian basement complex at Claritis fossae (unit Nb of Scott and Tanaka [15]). Similar magnitude anomalies are seen above the Nf units of Nectaris Fossae [15]. In contrast, no magnetic field anomalies are associated with the Noachian units (Nf) of Tempe Fossae and Ceraunius Fossae. Negligible anomalies are observed over Sinai Planum, Syria Planum, Solis Planum and western Valles Marineris. Anomalies at the eastern edge of the Terra Cimmeria region are associated with deformed Noachian terrain south-west (Nplr, Npl1) of Daedalia Planum. Significant, though lower amplitude, anomalies are observed at eastern Daedalia Planum which rises to elevations of about 4 km above the planetary mean. The volcanic surface units here are Amazonian in age. Finally, magnetic anomalies are observed over a small area on the lowermost western flanks of Olympus Mons. The surface units here are also Amazonian.

Inferences Some of the oldest and highest exposed Noachian terrain in the Tharsis region exhibits significant magnetic anomalies, indicating long-lived crustal magnetizations. The retention of significant magnetization at Claritas Fossae means that models for uplift/construction in that region must allow a significant depth extent of the magnetization source region to remain cool. Crust below the young Amazonian units of

Daedalia Planum is magnetized, but less strongly so, suggesting that burial of older basement units by volcanics has reduced, but not removed, the remnant magnetism. The basement below the Tharsis Montes is not magnetized. The fracture system associated with Tempe Fossae has been proposed to underlie the Tharsis Montes. Since Tempe Foaase exhibits no magnetic signature, it is possible that the crust beneath the Tharsis Montes was never magnetized, or that magnetization was removed by fracture-associated magmatism.

The presence of remnant magnetization high on the Tharsis rise provides an important constraint on models for the evolution of this region: Tharsis – a region volumetrically rich in volcanism – must have been assembled in such a way that portions of the upper crust remained below the appropriate Curie temperature. Furthermore, part of the crustal volume comprising Tharsis, must have cooled through the Curie temperature while the global field was in existence

Thermal Demagnetization. We have investigated two 1-D end-member scenarios for thermal demagnetization of a magnetic source layer. We assume that the crust in the Tharsis region prior to the formation of Tharsis was uniformly magnetized, had a thickness of 40 – 50 km [16, 17], and a Curie temperature of 580°C (typical of magnetite). Emplacement of surface lava flows heats the underlying crust, and the maximum depth to the Curie isotherm scales linearly with the flow thickness [18]. For 1-km thick flows, only the upper few hundred meters of the underlying crust are raised above the Curie temperature. Thus volcanic extrusions after the cessation of a dynamo will only have a small demagnetization effect on the underlying crust, unless the magnetic carriers are strongly concentrated upwards.

In the second calculation we use the results of the nominal thermal model of Hauck and Phillips [17] to estimate the temperature gradient in the martian lithosphere at ~ 4 Ga. We assume the base of the magnetic source region (crust) is initially at the Curie temperature. Persistent intrusions and underplating of crustal material are permitted, such that the temperature at the base of the crust is held close to its melting temperature. This provides a crude upper limit on the vertical extent of demagnetization of the crust due to intrusions. In this case, the lower 50% of the crust is raised above the Curie temperature. In practice this model would correspond to a requirement of continuous intrusions over a 100 Myr period.

From these preliminary calculations it is clear that it is possible retain significant magnetization signatures during the construction of Tharsis. Further modeling is needed to better constrain the trade-offs between magnetization distribution, volcanic construction and the resulting crustal thermal anomalies.

Gravity and Topography: Recent studies [7, 16] indicate that the present-day gravity and topography are consistent with flexural loading of the lithosphere and crustal thickening at Tharsis. As mentioned, current dynamic support of Tharsis accounts for only a minor component of the geoid in that region [8]. Radial extensional fracturing is also consistent with models for flexural loading. An important conclusion of these models is that the Tharsis mass distribution has not changed significantly since the Noachian [7, 19, 20]. The response of the lithosphere to the Tharsis load globally deformed the planet and appears to have controlled the orientation of many of the Noachian valley networks [7].

Preliminary Synthesis: We suggest that during the Early Noachian thermal (and possibly compositional) buoyancy resulted in uplift of the ancient, partially magnetized crust in the Tharsis region and in deep intrusions. During the middle-late Noachian and subsequently, the Tharsis rise has been supported by crustal thickening that preserved magnetic anomalies in places and by membrane and bending stresses from loading. Thin post-Noachian lava flows did not completely remove upper crustal magnetization. This model makes qualitative predictions that are in agreement with the observed tectonic history, present-day gravity and topography, and the retention of strong magnetizations in regions of elevated ancient crust.

References: [1] Hartman, W. K. (1973), *JGR*, 78, 4096 [2] Carr, M. H. (1974) *JGR*, 79, 3943. [3] Wise, D. U. et al., (1979) *Icarus*, 38, 456. [4] Sleep, N. H. and R. J. Phillips, (1979) *GRL*, 6, 803. [5] Phillips, R. J. et al., (1990) *JGR*, 95, 5089. [6] Solomon, S. C. and J. W. Head, (1982), *JGR*, 87, 9755. [7] Phillips, R. J. et al. (2001) *Science*, 291, 2587, [8] Zhong, S. (2002) *JGR*, 107, 2001JE001589. [9] Plescia and Saunders (1979), LPS *X*, 986. [10] Scott and Tanaka (1980) *Proc. LPSC, 11th* 2403. [11] Anderson, R. L. et al. (2001), *JGR*, 106, 20,563. [12] Schultz and Tanaka (1994), *JGR*, 99,8371. [13] Dohm, J. M. et al., (1997), LPSC 28th, Abstract # 1642. [14] Purucker, M. et al. (2000), *GRL*, 27, 2449. [15] Scott, D. H. and K. L. Tanaka (1986) *U. S. Geol. Surv. Map I-1802-A*. [16] Zuber, M. T,. (2001), *Nature*, 412, 220. [17] Hauck, S. A. and R. J. Phillips, (2002), *JGR* 107, 2001JE001801. [18] Turcotte, D. and G. Schubert, (2002), *Geodynamics*. [19] Banerdt et al. (1992) *JGR*, 87, 9723. [20] Banerdt and Golombek, (2000), LPSC 31st, Abstract # 2038.