THE EVOLUTION OF THARSIS: IMPLICATIONS OF GRAVITY, TOPOGRAPHY, AND TECTONICS:

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Introduction: Dominating the western hemisphere of Mars, the Tharsis rise is an elongate area centered on Syria Planum that ascends as much as 8 to 10 km above the datum. It is intensely fractured by long, narrow grabens that extend radially hundreds of kilometers beyond the rise and is ringed by mostly concentric wrinkle ridges that formed over 2,000 km from the center of the rise. Its size, involving a full hemisphere of Mars, gives it a central role in the thermo-tectonic evolution of the planet and has stimulated a number of studies attempting to determine the sequence of events responsible for this unique feature [1–5]. In this abstract I review the constraints that gravity and topography data place on the current structure of Tharsis, along with insights into its development derived from comparisons of detailed regional mapping of faulting with theoretical deformation models. Finally, a self-consistent model for the structure of Tharsis is proposed.

Gravity and Topography: The gravity and topography of Tharsis show a high degree of correlation, with a large proportion of the spectral power contained in the lowest harmonics (degrees 2–3). The apparent depth of compensation derived from the spectral admittance depends strongly on wavelength, ranging from over 1000 km at degree 2 to about 100 km for the shorter wavelengths [6]. Stated plainly, there is a large excess of gravity at long wavelengths relative to that which can be explained by simple compensation models. There are a limited number of ways to realistically accommodate this. One is isostatic compensation utilizing a density dipole, with a shallow positive anomaly overlying a deeper negative anomaly [4,7]. This model requires massive removal of crustal material and static support by a thick (~300–400 km), immobile layer of magmatically depleted mantle. Another approach is dynamic support by mantle convection [8]. This would imply a single immense plume that has not moved significantly with respect to the lithosphere since the Noachian. The third possibility is partial flexural support of the load [2]. In this case a modestly thicker crust is required with a >100 km thick lithosphere that is capable of supporting stresses of several hundred MPa.

Faulting: The timing and extent of faulting around Tharsis is both long lived and varied, involving both local/regional events and full hemispheric events [1,9–11]. For hemisphere-wide patterns relevant to the theoretical stress models, three distinct events have been recognized. In the upper Noachian, a radial system of grabens formed that marks the first unequivocal tectonic event in the formation of Tharsis. This fracture system, centered on Syria Planum [10] can be traced from near the center of the rise to beyond its flanks in exposed Noachian aged units. In the lower Hesperian, massive outpourings of fissure volcanics formed the surface now recognized as Lunae Planum and similarly aged plains surrounding Tharsis (the so-called ridged plains). Shortly after deposition of the plains, concentric wrinkle ridges formed [11] that are also centered in Syria Planum. By upper Hesperian times another enormous radial normal faulting event occurred, this time centered near Pavonis Mons [10]. This was followed by long-lived volcanism (throughout the Amazonian) to form the prominent central volcanoes of Tharsis and their aprons. One other faulting event has been related to stress models. A system of E–W trending normal faults formed in Claritas Fossae, an uplifted horst of Noachian aged terrain that is covered by all Hesperian and Amazonian units [5,9]. These faults are consistent with a Tharsis-concentric pattern, but this fracture system is only found in a limited area, so its regional significance is unclear.

Stress calculations: These two types of information, gravity/topography and surface strain, can be linked in a complementary fashion via theoretical stress modelling [2,4]. In broad terms, three distinct fault patterns can be generated at the surface of a spherical shell that supports a roughly circular, long-wavelength topographic high by static means. If the topography is due to uplift of the lithosphere, circumferentially oriented extensional features within the uplifted portion and radially oriented compressional features in the periphery are predicted. In contrast, a surface load that causes subsidence of the lithosphere predicts the opposite sense of faulting, with circumferential ridges within the load region and radial extensional faulting farther out. Isostatic support of topography generates a stress field that predicts radially oriented normal faulting in a region around the topographic center and circumferential ridge formation near its edges. In addition, the isostatic stresses are much smaller in magnitude than those for the flexural cases (~50 MPa vs. 200–400 MPa). Stresses due to convective support of topography are still under study, but the patterns are likely to be similar to those of the uplift case.

These results place some strong constraints on the evolution of Tharsis as reflected in its structural record. Only the uplift case (and, possibly, convective support) can form circumferentially oriented grabens. Such grabens have tentatively been identified only in the oldest (early Noachian) units in Claritas Fossae [5,9]. Thus this mechanism can be ruled out for all but perhaps the earliest stages of formation. Circumferentially oriented ridges near the edge of the rise are a feature of both the isostatic and subsidence cases, with the former extending the ridge zone outward and the latter extending it inward. Thus the distribution of ridges tends to marginally favor an isostatic regime. The most clear–cut distinction between these two cases, however, is in the respective regions of radial extensional faulting. Inner radial faulting is possible only in the isostatic case, whereas outer radial faulting can occur only in the subsidence case; the conditions under which these two patterns form are mutually exclusive. However stratigraphic mapping has shown that both inner and outer radial faulting have occurred contemporaneously over a considerable interval of Tharsis history [12]. Thus there is a fundamental contradiction between apparently robust model results and observation.

Proposed model: The stress models described above assume that the load is supported by a homogeneous elastic shell. But the actual rheology of the lithosphere is undoubtedly more complex [e.g., 12–14]. Laboratory and field measurements on Earth indicate that the strength of rocks in the shallow lithosphere is generally limited by frictional sliding on preexisting faults, giving a strength that increases with depth. At the higher temperatures characteristic of the lower portions of the lithosphere ductile creep becomes the strength–limiting factor, with the conductive thermal gradient causing a decrease in strength with depth. In addition, ultramafic minerals characteristic of mantle rocks have a considerably higher creep resistance than those minerals common in crustal rocks. Thus the lithosphere may have two strength maxima separated by a ductile layer in the lower crust. The existence and strength of this ductile layer will depend on the crustal thickness and thermal gradient, with larger values of either of these parameters making such a layer more pronounced.

The gravity observations described above, along with the difficulties inherent in creating a realistic isostatic structure, argue for flexural support of the Tharsis load. Additionally, most of the regional tectonic deformation, with the notable exception of the inner radial faulting, is consistent with subsidence of the lithosphere. We contend that the formation of the inner radial fault pattern is a natural consequence of the thickened crust and higher heat flow resulting from the extrusive and intrusive volcanic construction of the Tharsis rise.

If Tharsis is formed by construction, it acts as a flexural load on the elastic lithosphere. Far from Tharsis the lithosphere consists of both the crust and upper mantle. However, within Tharsis itself, the thickened crust and high heat flow will act to decouple the upper crust from the strong zone in the upper mantle. In this situation the upper mantle strong layer, which constitutes most of the lithosphere in either case, will deform as part of the global shell, transferring flexural stresses and displacements to the rest of the shell. The relatively thin, brittle upper crustal layer will deform not as part of the greater shell, but rather as a spherical cap with a lubricated lower surface and a peripheral boundary which is fixed to the global shell. Thus it will respond primarily to isostatic spreading forces and increases in its radius of curvature [15] induced by the subsidence of the lower lithosphere. Both processes induce circumferential extension within the cap, leading to radial faulting within the highland area. Outside this region of decoupled crust, faulting will be due to flexural stresses caused by the overall lithosphere subsidence. Radial compression is likely to be concentrated near the boundary of the two regions.

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