THE OPENING OF THE VALLES MARINERIS CANYONS ON MARS: STRESS FOCUSING ALONG THE BURIED DICHOTOMY BOUNDARY BENEATH THARSIS.

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Introduction: Valles Marineris is the largest tectonic canyon in the solar system, with a length of ~2500 km, depths of up to 10 km, and widths in excess of 100 km. The location of this canyon on Tharsis, and its orientation radial to the center of the rise suggests Tharsis control of Valles Marineris tectonism. Tharsis loading dominated the tectonic history of Mars, accounting for the radial graben, circumferential wrinkle ridges, and strike-slip faults around the rise [1-4]. However, the reason for the growth of this canyon to its extreme size is unknown. Valles Marineris is an order of magnitude larger than all other Tharsis-radial graben.

Valles Marineris also represents a unique style of tectonism, without parallel in the solar system. Extensional tectonic environments generally develop into either narrow rifts (such as the East African rift on Earth, or the Thaumasia graben on Mars) or wide basin and range provinces (such as the southwestern US), depending on the strain rate and heat flux [5]. In contrast, Valles Marineris is a simple fault-bounded graben accomodating in excess of 10 km of extension.

A clue to the mechanism responsible for Valles Marineris tectonism comes from its location south of and roughly parallel to the sub-Tharsis dichotomy boundary [6], suggesting that the buried boundary may be controlling the tectonism on this part of the rise. Prior to Tharsis formation, the sub-Tharsis dichotomy boundary marked a narrow transition between thick highlands and thin lowlands crust, similar to that seen to the west of the rise [6]. The emplacement of the Tharsis lavas over a pre-existing step function in topography and crustal thickness would have resulted in an abrupt change in the thickness of the load and the flexural response of the lithosphere along the boundary, leading to narrowly focused bending stresses.

Modeling: Studies of loading and tectonism on Mars commonly employ inversions of the gravity and topography to solve for the membrane and flexural stresses in the lithosphere [2, 7]. However, because of its immense size, stresses predicted in the vicinity of the canyon based on the present day gravity and topography are greatly affected by the canyon itself. In order to understand the stresses responsible for the initiation of tectonism and the formation of the canyon, we must rather use forward modeling techniques.

Forward modeling requires a representation of the state of both the pre-Tharsis crust and the Tharsis load. *Andrews-Hanna et al.* [6] inverted the gravity and topography of Mars for the isostatic crustal roots and revealed a distinct transition in the root thickness beneath Tharsis that was interpreted as the sub-Tharsis
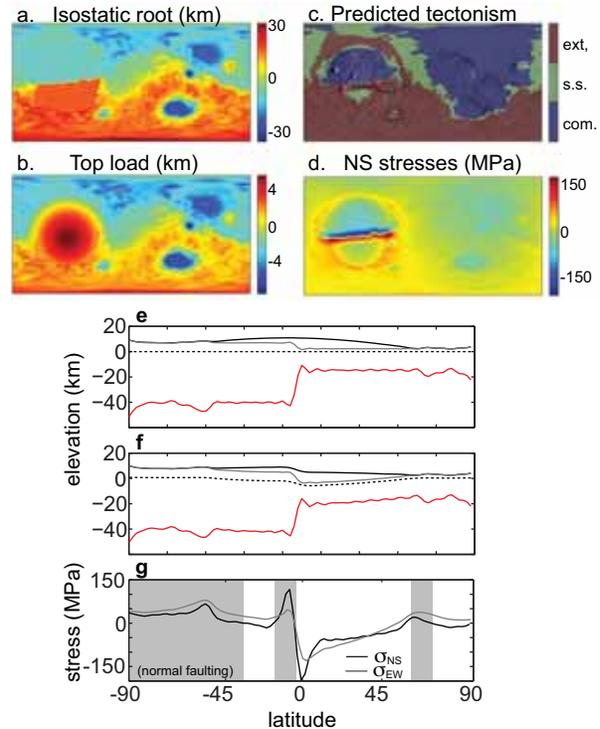

Figure 1. Thin shell model of Tharsis loading over the dichotomy boundary, showing (**a**) the isostatic crustal roots representing the pre-Tharsis crustal dichotomy, (**b**) the surface loads including the surface topography in isostatic balance with the roots of the dichotomy plus an additional "proto-Tharsis" load, (**c**) the predicted style of faulting, and (**d**) the predicted stress in the north-south direction (positive=tensile). Cross-sections are shown through the center of Tharsis before (**e**) and after (**f**) flexural adjustment, leading to large tensile stresses south of the boundary (**g**; gray = predicted normal faulting).

continuation of the dichotomy boundary. Shortwavelength variations in the pre-Tharsis isostatic roots were interpreted as resulting from spatial and temporal variations in the load density and lithospheric thickness during Tharsis formation. In representing the pre-Tharsis crust in our forward models, we note that the crustal thickness in each of the highlands and lowlands are remarkably uniform outside of Tharsis, the large impact basins, and Arabia Terra. Thus, it can be reasonably assumed that the original sub-Tharsis highlands crust had a thickness equal to that of the highlands outside of the rise, and similarly with the lowlands. We can also assume that the pre-Tharsis crust was largely isostatic, and invoke this as an initial condition prior to loading in our models.

Thin-shell models. We first consider a thin-shell spherical harmonic forward model of the flexural and membrane response to Tharsis loading over a preexisting crustal dichotomy, modified from the method of *Banerdt* [7]. This approach has the advantage of its simplicity and computational efficiency, though the stresses are calculated only within the uniform thin shell lithosphere, and are not reliable within the load itself. We model the elastic response to the addition of an axisymmetric "proto-Tharsis" load over an initial isostatic pre-Tharsis dichotomy.

The thin-shell model predicts north-south extension in a narrow band south of the sub-Tharsis dichotomy boundary (Figure 1). These focused tensile stresses greatly exceed the stresses in other portions of the rise. Profiles of the resulting topography and stresses show the concave-downwards curvature of the lithosphere immediately south of the sub-Tharsis boundary, and the large tensile bending stresses that result. The large compressional stresses predicted north of the boundary would be buried beneath a thicker load, and thus may not result in surface tectonism.

Finite element. We now use the finite-element code TEKTON [8] in a 2D cartesian geometry to represent the elastic response to the emplacement of a volcanic load over a pre-existing isostatically compensated crustal dichotomy. The finite-element model more accurately represents the flexural stresses within the load that dominate in the vicinity of the dichotomy boundary, but neglects the long-wavelength membrane stresses that result from the spherical shape of the planet. The lowlands crust is underlain by mantle lithosphere down to the depth of the highlands crust-mantle interface. We assume a Young's modulus of 90 GPa,

Poisson's ratio of 0.15, crustal density of 2700 kg/m^3, and mantle density of 3300 kg/m^3.

The finite-element model predicts strongly tensile stresses on the highlands side of the boundary, in agreement with the thin-shell models (Figure 2 b,c). However, the stresses on the lowlands side of the boundary are now only weakly compressional at the surface. The stresses along the dichotomy boundary are again much greater in magnitude than the stresses elsewhere in the region, due to the short wavelength and large magnitude of the change in the load thickness along the boundary. MOLA topographic profiles through Tharsis and Valles Marineris show that the canyons lie just south of a slope separating southern Tharsis from northern Tharsis, in agreement with the predicted topography and stresses in these models.

Conclusions. These results demonstrate that Tharsis loading over the preexisting dichotomy boundary would have generated a narrow belt of large-magnitude extensional stresses just south of the boundary, coincident with the present-day location of the Valles Marineris canyons. The unique mode of extensional tectonism represented by the Valles Marineris megagraben is thus likely a result of stress focusing along the buried sub-Tharsis dichotomy boundary, explaining the origin, large size, and location of the canyons.

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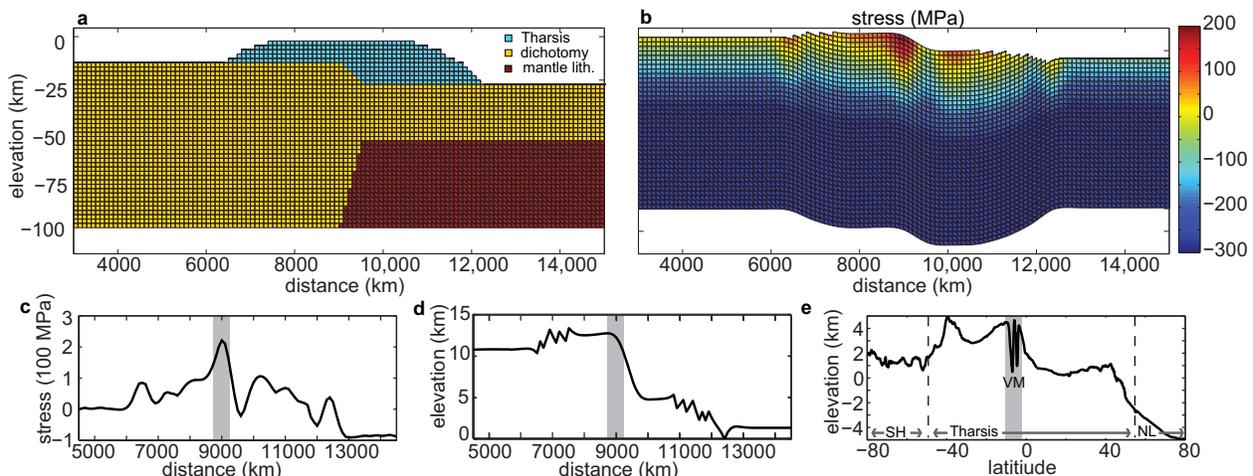

Figure 2. Finite-element model of Tharsis loading over the dichotomy boundary. Pre-flexure model geometry (**a**) assumes an initially isostatically compensated dichotomy crust, upon which is superimposed an additional load representing Tharsis. The resulting deformation and stresses are shown in (**b**) (positive=tensile). Models predict strong tensile stresses south of the sub-Tharsis dichotomy (**c**). Profiles of the model topography (**d**) compare well with mean topographic profiles through Tharsis between 270° and 280° E longitude (**e**). Locations of the southern highlands (SH), northern lowlands (NL) and Valles Marineris (VM) labeled in **e**.