GLOBAL STRUCTURE OF THE MARTIAN DICHOTOMY: AN ELLIPTICAL IMPACT BASIN?

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Introduction: The topography and crustal thickness of Mars are dominated by the near-hemispheric dichotomy between the southern highlands and northern lowlands. The dichotomy boundary can be traced along an apparently irregular path around the planet, except where it is buried beneath the Tharsis volcanic rise [1]. The isostatic compensation of the dichotomy [2] and the ancient population of buried impact craters beneath the lowlands [3] suggest that the dichotomy is one of the most ancient features on the planet. Early workers suggested a giant impact origin for the dichotomy [4], but the attempted fit of a circular "Borealis basin" to the irregular dichotomy boundary proved unsatisfactory, leaving large regions of the lowlands unexplained [5]. Alternatively, an endogenic origin of the dichotomy has been proposed, calling on spherical harmonic degree-1 mantle convection [6,7] or degree-1 overturn of a buoyantly unstable cumulate mantle [8].

We use the gravity [9] and topography [10] of Mars to identify the location of the sub-Tharsis dichotomy boundary, taking advantage of the different modes of compensation for Tharsis and the dichotomy to distinguish between them. We find that the globally continuous dichotomy boundary is accurately fit by an ellipse measuring ~10,650 by 8,520 km, centered at 66˚N 209˚E. The elliptical nature of the crustal dichotomy is most simply explained by a giant impact origin, representing the largest such structure thus far identified in the solar system.

Methods: We investigate Mars' early crustal structure by inverting the gravity and topography fields under the assumption of crustal thickness-compensated flexure [11]. The model solutions are formulated in terms of a uniform crust, to which thickness perturbations are added at the top and bottom surfaces (the load and isostatic root, respectively), combined with flexural displacements to reproduce the observed gravity and topography. While the dichotomy outside Tharsis is largely isostatic [2] and thus dominated by the isostatic roots, the gravity anomalies [12] and tectonic features [11,13] associated with Tharsis suggest it is largely a flexurally supported load. Thus, Tharsis should dominate the loads and displacements in this region, while the isostatic roots should reflect the pre-Tharsis dichotomy, allowing us to isolate the dichotomy boundary beneath Tharsis (Figure 1).

Results: The modeled isostatic roots reveal the continuation of the dichotomy boundary beneath Tharsis (Figure 2b). Short-wavelength anomalies in the model crustal roots can result from either local density anomalies or the spatially- and temporally-variable lithosphere thickness during Tharsis construction. Thus, the roots are negative beneath younger portions of the rise that are likely composed of dense lava flows and supported by a thicker lithosphere (e.g., Olympus Mons), and positive beneath older portions that are largely isostatic today (e.g., Tempe Terra). Nevertheless, we are able to map the dichotomy boundary both beneath Tharsis and elsewhere (Figure 2b). The location of the sub-Tharsis dichotomy boundary is largely insensitive to the choice of lithosphere thickness. The sub-Tharsis dichotomy is continuous to the west with the observed boundary, and to the east with the break in slope north of Arabia Terra. While the northern edge of Arabia Terra is
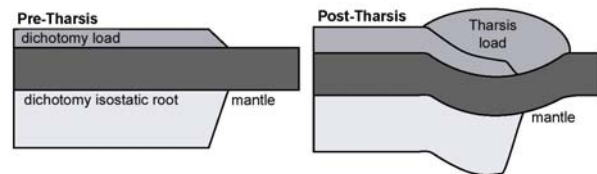

Figure 1. Schematic cross-sections of the crustal structure of the Tharsis region before (left) and after (right) Tharsis loading, showing the division of the crust into "loads" and "isostatic roots".
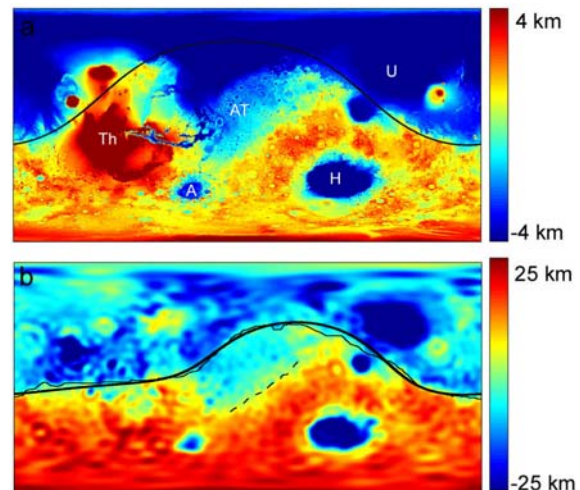

Figure 2. (a) Topography of Mars showing the location of the "Borealis Basin" as mapped by *Wilhelms and Squyres* [4]. (b) The modeled isostatic crustal root, showing the continuation of the dichotomy boundary beneath Tharsis. The globally continuous dichotomy boundary (thin line) is compared to the best-fit ellipse (bold line).

sharply defined and continuous with the dichotomy boundary on either side, the southern edge is less distinct and does not obviously connect with the boundary, leading us to suggest that Arabia Terra is a part of the highlands in which the crust has been substantially thinned by an unknown process.

The dichotomy boundary is now seen to follow an elliptical path around the planet, centered on 66˚N 209˚E, with long and short axes of 10,650 and 8,520 km, respectively (Figure 2b). The shape of the dichotomy is best seen in polar coordinates around the center of the ellipse (Figure 3). The elliptical shape of the dichotomy provides a new constraint on models of its formation. Giant impacts with low-angle trajectories are known to generate elliptical basins, including Hellas on Mars (ratio of major to minor axes, $a/b = 2414$ km$/1820$ km $= 1.33$) and South Pole-Aitken on the Moon ($a/b = 2125$ km$/1542$ km $= 1.38$). The similarity in shape to the much larger "Borealis basin" ($a/b=1.25$) suggests the possibility of a common origin. It remains to be determined whether endogenic processes can explain the observed elliptical dichotomy boundary. While the upwellings in degree-1 convection models range from irregular to quasi-circular in shape [7], there is no *a priori* reason why the observed elliptical pattern would be expected.

Another key observation regarding the nature of the dichotomy is the bimodal crustal thickness distribution between the lowlands and highlands [2]. The excavation of crust during a giant impact generates a bimodal crustal thickness distribution between the thin basin floor crust and its surroundings, as observed in Hellas. Degree-1 convection models have not explicitly calculated the effects on the crustal thickness distribution. However, the convection patterns are characterized by a centralized upwelling that expands laterally upon reaching the lithosphere [6,7], resulting in gradually decreasing thermal and mechanical effects away from the upwelling [6], and suggesting a similar pattern of crustal thickening or thinning.

One of the primary objections to an impact origin for the dichotomy is that the basin would be buried and erased by the voluminous melt generated by the impact [14,15]. However, recent hydrocode simulations of oblique dichotomy-forming impacts have found that the melt volume produced is much less than earlier estimates and is largely contained within the basin [16]. The impact ejecta in the simulations was found to be widely distributed across the surface of the planet [16], explaining the lack of an annulus of thickened crust surrounding the lowlands as typically observed around smaller lunar basins [17].

A giant impact origin for the crustal dichotomy would make the northern lowlands of Mars the largest observed impact scar in the solar system by a factor of ~4. This Borealis basin would span the gap between traditional basin-forming impacts and the catastrophic self-erasing giant impacts responsible for the formation of the Earth's Moon [18] and the possible stripping of the outer mantle of Mercury [19]. Such "mega-impacts" appear to have been common in the early history of the terrestrial planets during the waning stages of planetary accretion [20].
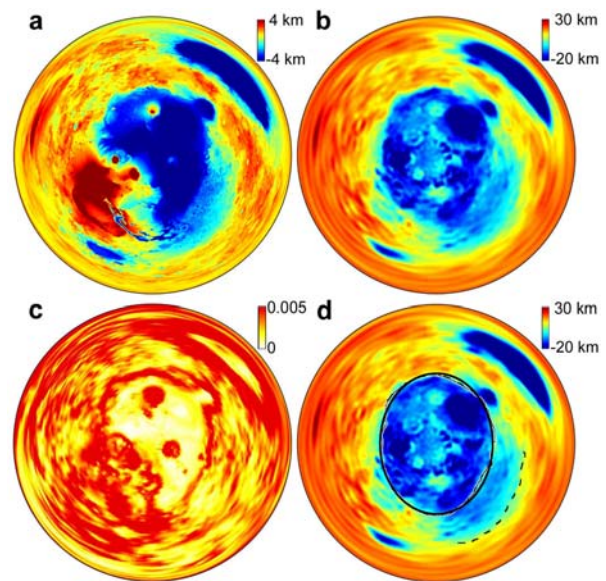

Figure 3. Projected views of the Martian lowlands in topography (**a**), isostatic crustal root thickness (**b,d**), and topographic gradient (**c**). The best-fit ellipse is shown in **d** compared with the outlines of the dichotomy boundary and the southern edge of Arabia Terra.

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