Lithospheric flexure and the origin of the dichotomy boundary on Mars

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ABSTRACT

The crustal dichotomy between the ancient highlands of the Southern Hemisphere and the young-appearing northern lowlands is a defining feature of Mars. In the Eastern Hemisphere the dichotomy boundary is marked by a prominent scarp and extensional and compressional tectonic features. Topographic data across the boundary returned from the Mars Global Surveyor indicate lithospheric flexure of the southern highlands. The topography of the boundary can be fit by a universal lithospheric deflection profile that corresponds to an elastic thickness of ~31–36 km. Flexure of the southern highlands may be due to late Noachian–early Hesperian vertical loading of the northern lowlands. Fracturing and normal faulting along the boundary may be in response to bending stresses, while thrust faulting may result from a combination of stresses due to flexure, erosion, and global contraction.

Keywords: Mars, tectonics, flexure, dichotomy boundary, elastic thickness.

INTRODUCTION

The distinct geologic contrast between the ancient, heavily cratered Southern Hemisphere and the younger, relatively featureless Northern Hemisphere of Mars was determined by Viking Orbiter–based geologic mapping (Scott and Tanaka, 1986; Greeley and Guest, 1987). Mars Orbiter Laser Altimeter (MOLA) data from the Mars Global Surveyor (MGS) have revealed the dramatic difference in elevation between the two hemispheres, as much as 6 km in some areas (Frey et al., 1998; Smith et al., 1998, 1999, 2001; Zuber et al., 2000). In the Eastern Hemisphere, the dichotomy has a distinct boundary that is often marked by an erosional scarp (Fig. 1). Models for the origin of the crustal dichotomy involve either impact (Wilhelms and Squyres, 1984; Frey and Schultz, 1988; McGill, 1989) or internal processes (Wise et al., 1979; McGill and Dimitriou, 1990; Sleep, 1994; Zhong and Zuber, 2001; Zuber, 2001). An impact origin is not strongly supported by the poor correlation between estimates of crustal thickness and the dichotomy boundary in some areas, the noncircular outline of the northern lowlands, and the lack of other Utopia-scale circular zones of crustal thinning (Zuber et al., 2000; Zuber, 2001). Models invoking internal processes involve thinning of the northern lowlands crust by mantle convection (Wise et al., 1979; McGill and Dimitriou, 1990; Zhong and Zuber, 2001; Zuber, 2001) or plate recycling (Sleep, 1994, 2000). Subdued circular depressions in the northern lowlands, interpreted to be buried ancient impact basins, suggest that the basement of the northern plains is as old as that of the southern highlands (Frey et al., 2002). Thus, if the dichotomy resulted from lithospheric recycling, it must have occurred very early in the geologic history of Mars. An early, short-lived episode of plate recycling may have been re-

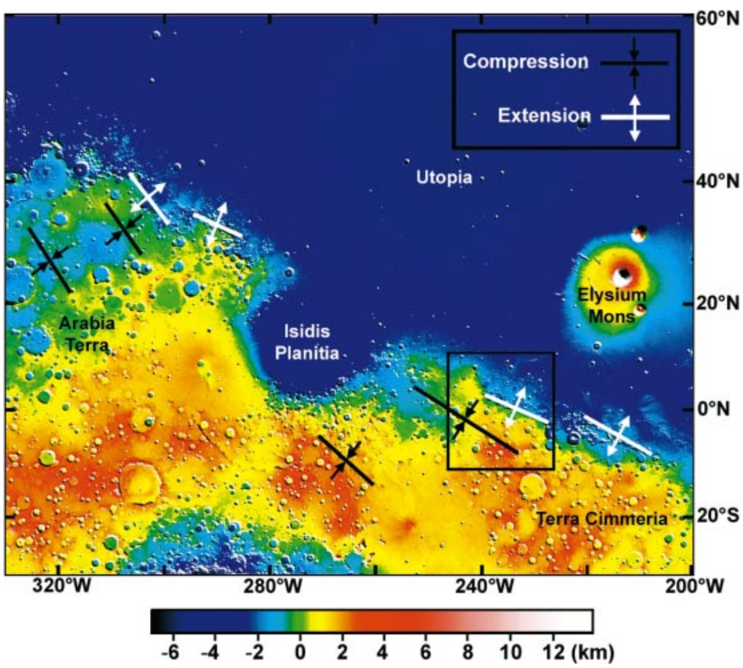

Figure 1. Generalized location of inferred extensional and compressional stresses along dichotomy boundary in Eastern Hemisphere. Inferred stresses are based on location of thrust faults (lobate scarps) and fractures and normal faults. Inferred stresses are overlaid on color-coded digital elevation model combined with shaded-relief map derived from Mars Orbital Laser Altimeter $^{1}/_{32}$ degree per pixel resolution gridded data. Black box is area in northern Terra Cimmeria shown in Figure 2.

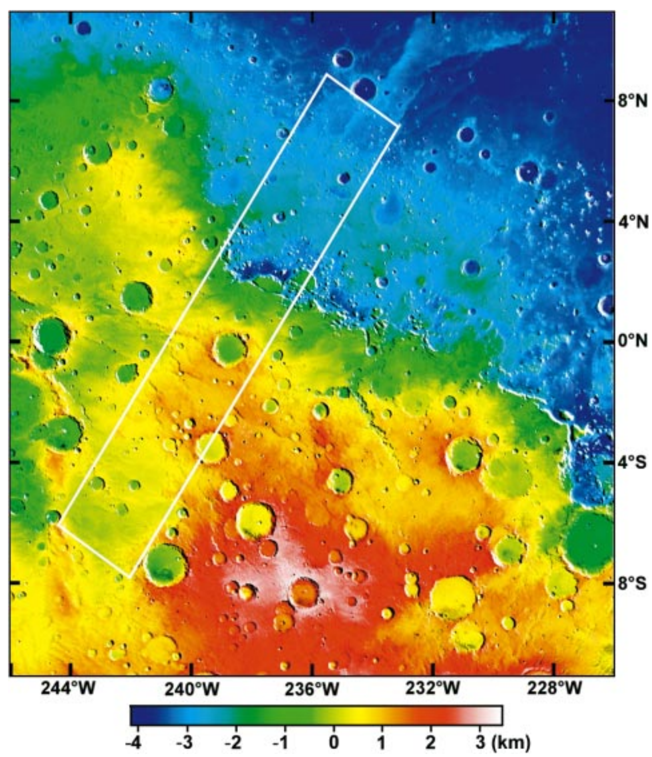

Figure 2. Digital elevation model (DEM) of dichotomy boundary in northern Terra Cimmeria. White box shows area in which topographic profiles across dichotomy boundary were analyzed (see Fig. 3). Color-coded DEM was derived from Mars Orbital Laser Altimeter $^{1}/_{32}$ degree per pixel resolution gridded data; DEM is overlaid on Mars Digital Image Mosaic.

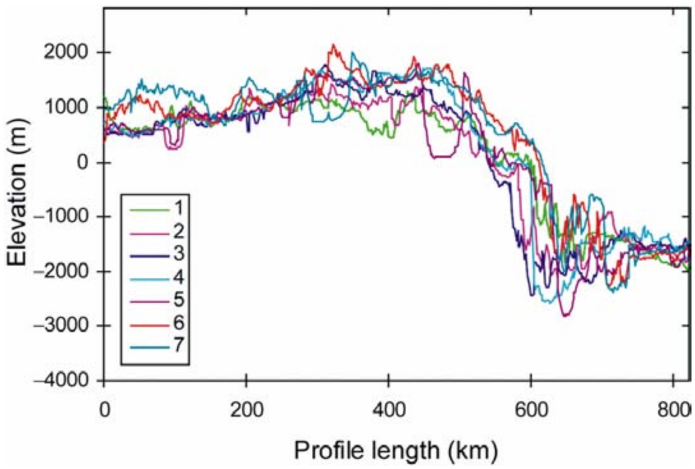

Figure 3. Topographic profiles across dichotomy boundary in northern Terra Cimmeria. Topographic profiles were derived from Mars Orbital Laser Altimeter $^1/_{32}$ degree per pixel resolution digital elevation model covering rectangular area shown in Figure 2. Profiles 1 and 7 are located on left and right side of rectangular area, respectively. Vertical exaggeration is ~75:1.

sponsible for the demise of the martian dynamo (Nimmo and Stevenson, 2000; Stevenson, 2001).

TECTONICS AND TOPOGRAPHY

Studies of the tectonic features in the Eastern Hemisphere suggest that deformational events involving extension and compression were related to the formation of the dichotomy boundary (McGill and Dimitriou, 1990; Watters, 1993, 2002; Watters and Robinson, 1999). In the highlands of northern Terra Cimmeria (0°N, 240°W) and northern Arabia Terra (40°N, 310°W), landforms described as lobate scarps are found ~100–500 km from the dichotomy boundary (Fig. 1). Lobate scarps are interpreted to be the surface expression of thrust faulting and are oriented roughly parallel to the dichotomy boundary (Watters, 1993, 2002; Watters and Robinson, 1999; Watters et al., 2000). Fracturing and faulting occur along the dichotomy boundary and in the adjacent lowlands (McGill and Dimitriou, 1990) (Fig. 1). Extensional and compressional deformation along the boundary appears to have occurred during the late Noachian to early Hesperian (McGill and Dimitriou, 1990; Watters and Robinson, 1999; Watters, 2002), suggesting that this deformation may have played a role in shaping the present-day dichotomy boundary in the Eastern Hemisphere.

The morphology of the dichotomy boundary in the Eastern Hemisphere varies, largely because of the extent of erosion. However, the boundary along much of its length is characterized by a scarp and rise morphology. This consists of a scarp where the slope reaches a maximum, a broad rise, and a gently sloping back rise. The regional slope of the back rise is generally away from the dichotomy boundary (Fig. 1). Extensional features are located on the slopes of the scarp and in the adjacent lowlands, whereas the thrust faults are usually located on the rise and back rise. One of the best-preserved areas of the dichotomy boundary occurs in northern Terra Cimmeria (Figs. 1 and 2). The scarp and rise morphology is most pronounced here, along a ~200 km segment of the boundary (Figs. 2 and 3). The topographic data indicate that the southern highlands are >3 km above the northern lowlands.

MODELING

The scarp and rise morphology of the dichotomy boundary in northern Terra Cimmeria is very similar to profiles across bent terrestrial elastic lithosphere. Lithospheric flexure can be modeled by an elastic plate overlying an incompressible fluid subjected to an end load

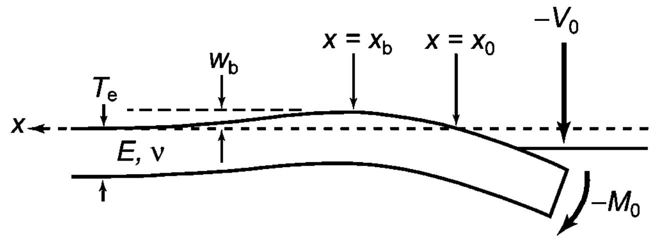

Figure 4. Illustration of flexure of elastic lithosphere subjected to semi-infinite load V_0 and bending moment M_0. Measurable parameters are height w_b and half-width $x_b - x_0$ of rise. Physical properties of elastic lithosphere are Young's modulus *E*, Poisson's ratio *v*, and thickness T_e.

V_0 and a bending moment M_0 (Fig. 4) (Turcotte, 1979; Turcotte and Schubert, 1982). The deflection *w* as a function of *x* is governed by

$$D(d^4w/dx^4) + \Delta\rho g w = 0, \tag{1}$$

where *D* is the flexure rigidity, $\Delta\rho$ is the difference in density between the material overlying the lithosphere and the mantle, and *g* is the acceleration due to gravity. The solution defines a universal flexure profile that is valid for any two-dimensional elastic

$$w = \sqrt{2}e^{\pi/4}\exp\left[-\left(\frac{x - x_0}{\alpha}\right)\right]\sin\left[\left(\frac{x - x_0}{\alpha}\right)\right]w_b. \tag{2}$$

flexure of a semi-infinite lithosphere under an end load (Turcotte and Schubert, 1982). Parameters that can be directly measured from topographic profiles are the height of the forebulge or rise w_b and the half-width of the rise $x_b - x_0$ (Fig. 4). The flexural parameter α is related to the half-width of the rise by $x_b - x_0 = \alpha(\pi/4)$ (Turcotte and Schubert, 1982). A good fit to the topography of the dichotomy boundary in northern Terra Cimmeria is obtained for $x_b - x_0 = 120$ km and $w_b = 600$ m (Fig. 5). Although the universal flexure profile fits the mean profile across the dichotomy very well, the fit to individual profiles varies the greatest in the area of the scarp, reflecting varying degrees of erosion.

The thickness of the elastic lithosphere T_e is related to α and the flexural rigidity by

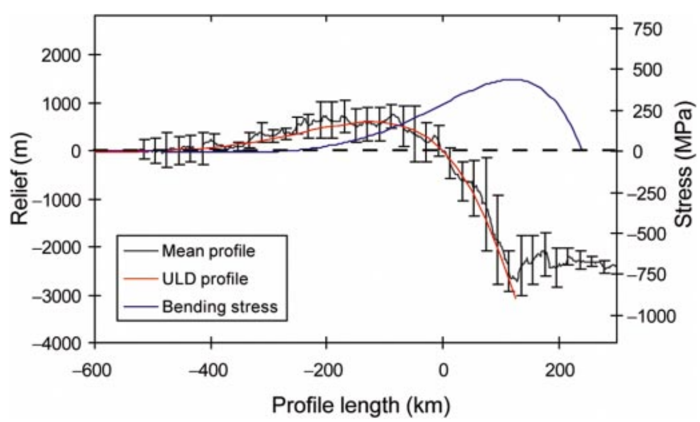

Figure 5. Topographic profile across dichotomy boundary in northern Terra Cimmeria compared to universal lithospheric deflection (ULD) profile and predicted bending stresses. Topographic profile (black curve) is mean of 7 profiles shown in Figure 3 with ±1 standard deviation error bars. ULD profile (red curve) was obtained by using equation 2 (see text) with $x_b - x_0 = 120$ km and $w_b = 600$ m. Bending stresses due to flexure (blue curve) are extensional (positive) at top of lithosphere and reach maximum near base of dichotomy boundary scarp. Vertical exaggeration is ~75:1.

$$T_e = \left[\frac{12(1 - \nu^2)\alpha^4(\rho_m - \rho_r)g}{4E}\right]^{1/3}, \tag{3}$$

where ρ_m and ρ_r are the density of the mantle and overlying material, respectively, ν is Poisson's ratio, and E is Young's modulus. The nature, thickness, and mean density of the overlying material are not well determined. It was once thought to consist of a thick megabreccia, but Mars Orbiter Camera (MOC) images have revealed evidence of widespread layering in the upper crust to a depth of several kilometers (Malin et al., 1998). The origin of the layered material is thought to be either volcanic or sedimentary, or a mix of the two (Malin et al., 1998). Assuming that the mean density of the highland layered material ρ_r ranges from 2600 kg·m^{-3} to 2900 kg·m^{-3} (density range from sediments to basalts), the density of the martian mantle is assumed to be $\rho_m = 3400$ kg·m^{-3}, the martian lithosphere has $E = 100$ GPa and $\nu = 0.25$, and $g_{Mars} = 3.72$ m·s^{-2}, the thickness of the elastic lithosphere at the time of loading was ~31–36 km. This range is in good agreement with independently derived estimates of T_e for the martian highlands in Terra Cimmeria of ~20 km using MGS gravity and topography (Zuber et al., 2000). The range is also consistent with the results of forward modeling of Amenthes Rupes, the largest lobate scarp in the highlands near the dichotomy boundary, which suggests that the thrust fault extends to a depth of 25–30 km, cutting the entire elastic and seismogenic lithosphere (Schultz and Watters, 2001). However, if the average density of the layered materials is significantly less, T_e near the dichotomy could be much greater, as suggested by Nimmo (2002). In the extreme case, setting ρ_r to zero results in an elastic thickness of 58 km.

DISCUSSION AND CONCLUSIONS

There are several possible origins for the apparent flexure along the dichotomy boundary. On Earth, lithospheric flexure is common at ocean trenches, and significant flexure of the elastic lithosphere occurs prior to subduction (Turcotte, 1979; Turcotte and Schubert, 1982). This setting is an unlikely analogue to the martian dichotomy boundary, because flexure is observed in the highlands and there is no topographic evidence of a trench. Topographically, the dichotomy boundary in the Eastern Hemisphere has a greater resemblance to a terrestrial passive margin than to a convergent margin (see Frey et al., 1998). Sleep (1994) was the first to propose that the dichotomy boundary in northern Terra Cimmeria might be a relict passive margin. Flexure of the lithosphere at passive continental margins occurs as a result of vertical loading due to subsidence of the cooling oceanic lithosphere and loading resulting from the accumulation of sediments on the oceanic lithosphere and the continental margin (Turcotte et al., 1977; Turcotte, 1979).

Evidence of buried ridged plains volcanic material in the northern lowlands has been found in MOLA topographic data (Zuber, 2001; Head et al., 2002). The buried unit appears to be early Hesperian in age (ca. 3.5 Ga) and is similar to ridged plains volcanic units in the southern highlands (Head et al., 2002). The thickness of the ridged plains volcanic material in the northern lowlands is estimated to be as much as several kilometers (Head et al., 2002). The emplacement of kilometers of basalt-like volcanic material in the northern lowlands would be expected to have generated a significant vertical load. In addition, the Utopia basin may have been filled with significantly more volcanic material, if one assumes that it was once as deep as the comparably sized Hellas basin (Zuber et al., 2000). MGS-based gravity models indicate large positive free-air anomalies associated with the Utopia basin (Zuber et al., 2000; Yuan et al., 2002). Recent modeling also indicates significant linear positive Bouguer anomalies in the northern lowlands paralleling portions of the dichotomy boundary (G.A. Neumann, 2002, personal commun.). One interpretation for the positive anomalies is that they result from thick (in excess of several kilometers) accumulations of volcanic material along the dichotomy boundary and in the Utopia basin (see Zuber et al., 2000).

Flexure of the southern highlands may also have resulted from subsidence of the northern lowlands. If the northern lowlands crust was thinned by mantle convection (McGill and Dimitriou, 1990; Zhong and Zuber, 2001; Zuber, 2001), the replacement of crust by mantle material would result in a vertical load and subsidence. Loading due to crustal thinning may have been complemented by volcanic loading. Because ridged plains in the northern lowlands do not extend into the adjacent highlands, the dichotomy must have already existed or was in the process of forming at the time of ridged plains volcanism. Thus, flexure of the southern highlands may be due to vertical loading from the accumulation of a thick volcanic sequence, subsidence of the northern lowlands from crustal thinning, or a combination of both.

The tectonic features along the dichotomy boundary reflect both extension and compression. Significant bending stresses are associated with lithospheric flexure. The maximum bending stress occurs at the top and bottom of the elastic plate and is given by $\sigma_{max} = 6M/T_e^2$, where M is the bending moment (Turcotte et al., 1978). For $T_e = 32$ km, the greatest bending stress is ~430 MPa, and it occurs ~200 km east of the maximum elevation of the rise, near the base of the dichotomy boundary scarp (Fig. 5). This stress is well in excess of the tensile strength of the near-surface rocks, and fracturing and normal faulting would be expected along the dichotomy boundary. The bending stresses at the bottom of the elastic lithosphere are compressional. The strength of the elastic lithosphere, however, is much greater in compression, and it is unlikely that the bending stresses are large enough to initiate faulting near the base of the seismogenic lithosphere. The surface bending stresses become compressional ~350 km from the base of the scarp, reaching a maximum at a distance of ~500 km. The maximum stress, however, is only ~20 MPa (Fig. 5). Other compressional stresses must have been superimposed on compressional bending stresses to cause the observed features.

Significant lithospheric stresses will result from thinning of northern lowlands crust through mantle convection. Loss of crustal material through surface erosion generates a negative vertical load, resulting in extensional stresses where material is removed and compressional stresses in the adjacent lithosphere (Stein et al., 1979; Zoback and Zoback, 1980). The removal of material from the bottom of the crust generates a positive vertical load and the sign of the surface stresses is reversed. This suggests that thinning of the northern lowlands crust will result in surface stresses that are compressional in the lowlands and extensional in the highlands. These stresses are significant and are inconsistent with the observed tectonic features along the dichotomy boundary. It is clear that although volcanic loading or crustal thinning of the northern lowlands can account for flexure of the highlands, neither model predicts the observed compressional features.

Erosion facilitated by flexure-induced extension of the highlands may have contributed to stresses along the dichotomy boundary. It has been estimated that eroded material along the highland margin may have formed a wedge several hundred kilometers wide and as much as 2–4 km high (Tanaka et al., 2001). The estimated maximum compressional stress in the highlands due to erosion along the dichotomy boundary, approximated by a rectangular finite-width load 3 km high and 200 km wide, is ~125–140 MPa for $T_e = 31$–36 km. This stress, however, is probably an upper limit because the amount of erosion in the study area was not great enough to remove the topographic expression of flexure. Another possible source of compressional stress is global contraction. The global-scale occurrence of late Noachian and early Hesperian compressional tectonic features on Mars suggests that the global stress state during that period was compressional (Tanaka et al., 1991; Watters, 1993). Volcanic resurfacing on Mars peaked during the early Hesperian (Greeley and Schneid, 1991), corresponding to a peak in compressional deformation (Watters, 1993). Widespread volcanism during the late Noachian and early Hesperian followed by rapid cooling of the interior may have resulted in global contraction and significant compressional stress in the highlands. Thus, the thrust faults in the highlands along the dichotomy boundary may be due to a combination of stresses resulting from flexure, erosion, and global contraction.

In conclusion, modeling the elastic flexure of a semi-infinite lithosphere under a vertical load results in a good fit to the topography of the dichotomy boundary in northern Terra Cimmeria. A semi-infinite or cracked lithosphere (Turcotte, 1979) is consistent with the formation of the crustal dichotomy by either crustal thinning from mantle convection or plate recycling. If the crustal dichotomy formed through lithospheric recycling during the earliest Noachian, the ancient dichotomy boundary may have been analogous to a terrestrial passive margin. Subsequent impacts and mass wasting, however, would be expected to have reduced the original boundary to a gradational, gently sloping surface. Flooding of the northern lowlands and the margin of the southern highlands by volcanic material during the late Noachian and early Hesperian resulted in a vertical load. In this case, preflexure topography makes estimates of T_e less reliable. If the crustal dichotomy formed through removal of the northern lowlands crust by mantle convection, the replacement of crust by mantle material resulted in a vertical load. In this case, estimates of T_e are less ambiguous. Independent of how the crustal dichotomy formed, vertical loading of the northern lowlands resulted in flexure of the highlands lithosphere and the present dichotomy boundary.

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