Coronae on Venus and Mars: Implications for similar structures on Earth

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ABSTRACT

Complex volcano-tectonic structures, referred to as coronae, had not been described until the exploration of the surface of Venus. These large, generally circular structures are characterized by an elevated surface, concentric and radial fracture systems, and extensive volcanism. Thought to be unique to Venus, rare circular features on Mars bear a close resemblance to coronae. The most prominent corona-like feature on Mars is Alba Patera, a broad, low-relief, plateau-shaped volcano-tectonic center surrounded by an annulus of concentric fractures ~600 km in diameter. A geophysical model for the formation of Venusian coronae involving uplift due to an ascending mantle diapir followed by gravitationally driven relaxation is applied to Mars. The results indicate that Alba Patera could have formed by such a mechanism. The formation of coronae and corona-like features on Venus and Mars from mantle diapirs suggests that similar structures may have formed in Earth's lithosphere.

INTRODUCTION

Comparative studies made possible with data obtained from the various planetary missions over the past three decades have shown that many of the geologic processes that operate on Earth are common on the other terrestrial planets. Terrestrial analogs are of fundamental importance in the interpretation of planetary landforms, particularly ones of volcanic or tectonic origin (e.g., Wilson and Head, 1982; Watters, 1992). Such studies have also revealed features that are not familiar and thus not readily understood on the basis of terrestrial analogs. Some features are recognized not on the basis of Earth analogs, but analogs on other terrestrial planets. A family of structures referred to as coronae may be an example.

Coronae are common landforms on Venus. They are circular to ovoid features characterized by tectonism, volcanism, and unique morphologies. First observed using ground-based radar, they were described as crater- and basinlike features (Campbell et al., 1979). Images returned from the Soviet Venera 15 and 16 spacecraft revealed that coronae were volcano-tectonic features (Barsukov et al., 1984). Coronae were described as elliptical features with elevated interiors surrounded by concentric high-relief ridge systems (Barsukov et al., 1986). It was also noted that radially and concentrically oriented features are associated with many coronae; however, the resolution of the Venera images was not sufficient to distinguish them as either compressional or tensional in origin (Basilevsky et al., 1986).

The full range and complexity of coronae on Venus have been revealed in radar images returned by the Magellan spacecraft. Stofan et al. (1992) identified more than 360 coronae ranging in diameter from 60 to 1100 km. The distribution of the coronae on Venus is complex, demonstrating a preference to form at mean planetary radius, in a concentration near the equator at long 240°E, and in linear chains (Squyres et al., 1993).

Years before the first observations of coronae on Venus, a prominent ovoid structure was imaged on Mars in 1972 by the Mariner 9 spacecraft. Referred to then as the Arcadia ring, the feature was described as a fracture ring formed by fractures deflected around a circular structure, at the center of which were caldera-like pits (Carr, 1973). The most detailed view of this volcano-tectonic feature now known as Alba Patera was provided by the Viking orbiters. The similarity between Alba Patera and coronae on Venus was noted previously (see Cyr and Melosh, 1993; Watters et al., 1993). Although rare, other circular volcano-tectonic features are found on Mars.

This paper presents the results of a comparison between coronae on Venus and circular volcano-tectonic structures on Mars to determine if the features are analogous and have a common origin. The origin of Venusian coronae is thought to involve uplift of the lithosphere due to a rising mantle diapir and subsequent relaxation. We apply this model to Alba Patera in an effort to explain its origin and that of other corona-like structures on Mars. In addition, we discuss implications for the formation of corona-like structures in Earth's lithosphere.

OBSERVATIONS

Venus

The morphologic and topographic expressions of structures that are classed as coronae or related features are highly variable (see Stofan et al., 1992; Squyres et al., 1992). However, three generalized end members can be isolated on the basis of topography: domes, plateaus, and depressions. These are thought to reflect three stages in the formation of coronae (Stofan et al., 1992; Squyres et al., 1992; Janes et al., 1992).

Domes are generally irregular to Gaussian-shaped mounds dominated by well-developed radial fracture systems emanating from their centers. Although domes lack the concentric fractures that define coronae, they are thought to be related features (Squyres et al., 1992; Janes et al., 1992). Volcanism is also clearly associated with these domes.

Plateau-shaped coronae are broad topographic features with the greatest slopes on the outer rise. These structures may have prominent radial and concentric fracture systems. A good example of this type of corona is Selu (lat 43°S, long 6°E) (Fig. 1). Selu is 350 km in diameter and has a rolling interior that is >1 km above the surrounding terrain. Flanking the outer rise to the northwest is a shallow trough or moat. The outer concentric fracture system, encompassing more than half the structure, lies on top of and along the rise where slopes are the steepest, and appears to postdate most of

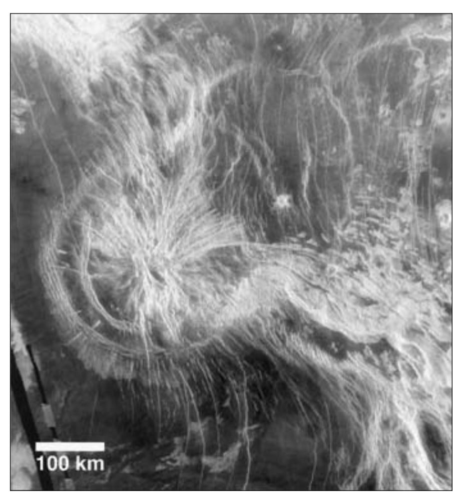

Figure 1. Magellan synthetic aperture radar (SAR) image mosaic of corona Selu on Venus. Selu is plateau-shaped corona (lat 43°S, long 6°E) characterized by concentric and radial fracture systems. Image mosaic is from C1-45S011.

the radial fractures (Squyres et al., 1992). On the interior of the structure is a less extensive inner concentric fracture system. Regional north-northeast– and north-northwest–trending fractures are clearly deflected toward the outer and inner concentric fracture trend (Fig. 1). Embayment of the fracture systems by lava flows suggests that volcanism occurred during all stages of Selu's formation (Squyres et al., 1992).

Coronae and related features that are characterized by topographic depressions can be subdivided into two types, elevated and simple depressions. Coronae distinguished by elevated depressions have interior basins that are usually above the level of the surrounding terrain. The basins are rimmed by topographic rises that may be ≥500 m in height. Moats with depths on the order of hundreds of metres encompass these features (see Squyres et al., 1992; Janes et al., 1992). Simple depressions are characterized by basins that are below the level of the surrounding terrain and have subdued rims (see Squyres et al., 1992). Both elevated and simple depressions exhibit concentric fractures on their rims.

Mars

Alba Patera and other corona-like structures are found in the Tharsis region, a province of intense volcanism and tectonism that dominates the western hemisphere of Mars. Alba Patera is a low-relief volcanic center surrounded by a well-developed fracture and graben system (Tanaka, 1990). Although generally interpreted to be a low-relief shield volcano (see Mouginis-Mark et al., 1988), Alba Patera is distinct from Martian shield volcanoes. Concentric fractures form an annulus ~100 km wide at a distance of ~200 km from the center of Alba (Fig. 2). Many of the north-trending fractures south of Alba Patera are part of a regional system that is deflected around and in some cases merges with the Alba concentric system. North of Alba Patera, the predominant orientation of the fractures is to the northeast. Another much less well developed set of concentric fractures is found to the southwest, ~250 km from the primary annulus (Fig. 2A). Volcanic material associated with Alba Patera extends 1600 km from the central caldera complex (Mouginis-Mark et al., 1988). The emplacement of these materials, thought to have occurred during the late Hesperian and early Amazonian epochs (estimated to be >1 Ga in age) (Tanaka, 1990), clearly predates the formation of the concentric fractures. The morphology of Alba Patera is not known with great certainty because of the lack of high-resolution topographic data. A digital terrain model (DTM) (U.S. Geological Survey, 1993) compiled by weighted interpolation of digitized 1:2 000 000-scale topographic maps with 1 km contour intervals (Wu et al., 1986), reveals Alba Patera to be a broad, roughly elliptically shaped rise ~700 km in diameter at the base that flattens to form a plateau ~2 km above the Tharsis rise (Fig. 3). The caldera complex is the most prominent feature on the plateau. A topographic rise is associated with the complex; however, because of limited stereo imaging, the DTM of this feature is not well constrained. The graben annuluses are on or near the flanks of the plateau (Fig. 2B).

Two other circular structures are found in the Tempe Terra region (Scott, 1982), ~1500 km east of Alba Patera. The annulus of fractures surrounding these features defines structures that are ~250 km in diameter (Fig. 4A). These structures are also associated with volcanic centers. One of the graben sets encircles a volcanic dome and a caldera-like depression (Fig. 4A) (see Scott, 1982). As in the case of Alba Patera, northeast-trending grabens are deflected and often merge with the concentric grabens. The topographic expression of these structures, like Alba Patera, is not well defined. The available data suggest that they are low-relief (maximum elevation ~500 m above the surrounding plains), circular to elliptically shaped plateaus, with the most prominent concentric grabens found near their flanks (Fig. 4B). The northernmost of the two structures appears to have a slight central depression that is not associated with the formation of a caldera complex.

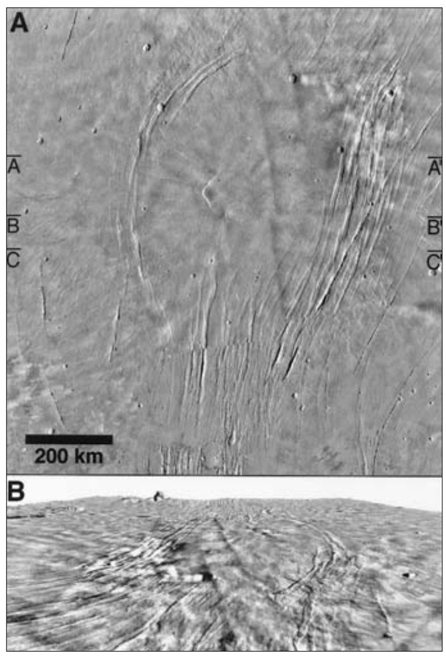

Figure 2. A: Viking Orbiter image mosaic of Alba Patera on Mars. Alba (lat 40°N, long 110°W) is broad plateau-shaped feature with prominent concentric fracture system and central caldera complex. Image mosaic is from Mars mosaicked digital image model. B: Three-dimensional perspective view of Alba Patera generated with 3× vertical exaggeration using digital terrain model for Mars. Volcano Uranius Tholus is visible in background.

ORIGIN OF CORONAE

One of the best working models for the origin of coronae involves the ascent of a mantle diapir (Stofan et al., 1991, 1992; Squyres et al., 1992; Janes et al., 1992). Mantle flow above the rising diapir results in uplift of the lithosphere and the development of a topographic dome. Once the diapir impinges on the base of the lithosphere, it spreads out radially, eventually resulting in the uplift of a circular plateau. Radial fractures that develop as a result of uplift may serve as conduits for rising magma supplied by the diapir. As the flattened diapir cools, relaxation of the uplift forms concentric faulting.

The topography and tectonic features associated with coronae on Venus have been modeled (Janes et al., 1992; Janes and Squyres, 1993) using the diapir model developed by Janes and Melosh (1988). The lithosphere is treated as a spherical elastic shell and the mantle as a viscous spherical layer with constant thickness and rheological properties. The mantle is bounded at the bottom by a rigid core and at the top by the elastic lithosphere, and the diapir is treated as a density anomaly within the mantle. The model utilizes a support parameter (q), which is the ratio of buoyant to elastic re-

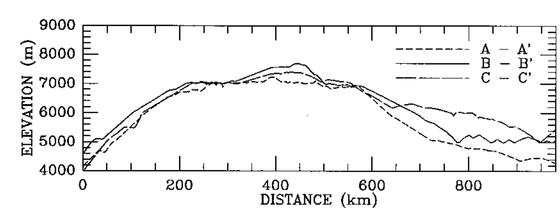

Figure 3. Elevation profiles across Alba Patera. Elevation profiles extend east-west; their locations are shown in Figure 2A. Uncertainty in absolute elevation (elevation above or below Mars datum) north and south of ±30° latitude is estimated at ±1.5 km (U.S. Geological Survey, 1991). Relative vertical accuracy is estimated to be better than ±500 m, on the basis of shadow measurements (see Wu and Doyle, 1990). Digital terrain model of central caldera complex is not well constrained and thus may not accurately reflect dimensions or morphology of this feature. Vertical exaggeration is ~60×.

storing forces in the lithosphere. This is defined as

$$q = \rho_m g_1 R_1/\mu,$$

where ρ_m is the density of the mantle, g_1 is the gravitational acceleration at the base of the lithosphere, R_l is the planetary radius at the base of the lithosphere, and μ is the shear modulus of the lithosphere (Janes and Melosh, 1990). If we assume that the lithosphere has a μ of 30 GPa, typical for basalt (Turcotte and Schubert, 1982), q has a value of 4.70 for Venus. The topography and radial faults associated with Selu can be accounted for by using an elliptically shaped diapir with a density contrast of 40 kg/m^3 in contact with a 4-km-thick lithosphere (Janes et al., 1992). The other topographic and tectonic elements associated with Selu and other coronae—concentric fractures, a raised rim, and an annular moat—can be accounted for by viscous relaxation of the uplift (Stofan et al., 1991; Janes et al., 1992).

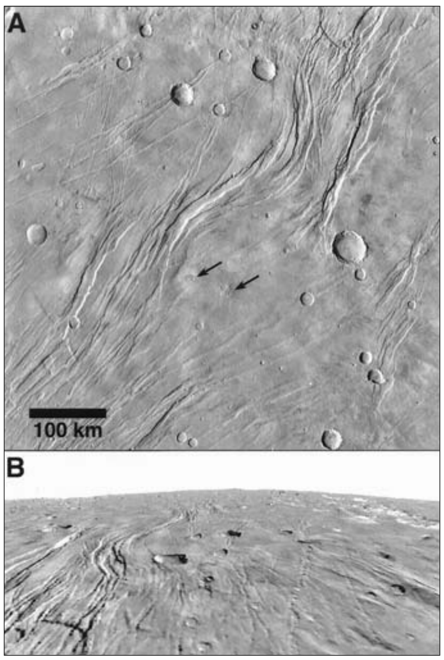

Figure 4. A: Viking Orbiter image mosaic of circular structures in Tempe Terra, Mars. Like Alba Patera, these structures are elevated volcanic centers surrounded by annulus of fractures. Arrows indicate location of volcanic dome and caldera-like depression. Image mosaic is from mosaicked digital image model. B: Three-dimensional perspective view of Tempe Terra structure generated with 3× vertical exaggeration digital terrain model for Mars.

On Mars, a similar mechanism can be envisioned for the origin of Alba Patera and the other corona-like structures. The value of the support parameter for Mars is 1.11, reflecting the lower mean density, gravity, and radius relative to Venus (Janes and Melosh, 1990). The topography of Alba Patera is most akin to a plateau-shaped corona. Modeling a flattened diapir as a series of point masses arrayed in an oblate ellipsoid having its semimajor axes parallel to the surface can produce somewhat plateau-like topography (Fig. 5). The diapir has a central thickness of 20 km and a radius of 224 km, equivalent in volume to a sphere 100 km in radius. It is in contact with the base of a 20-km-thick elastic lithosphere and has a density contrast with the surrounding mantle of 725 kg/m^3, i.e., ~20% less than the presumed 3300 kg/m^3 density of the mantle. The major constraint on model parameters is the plateau-like shape of Alba. Thicker lithospheres and less flattened diapirs produce an uplift that is broader, lower, and more domical than plateau shaped, because the lithosphere is less able to follow the contours of the diapir, or the diapir producing the uplift is itself more spherical. Thinner lithospheres produce topography that is even more plateau-like than Alba. Estimates of the thickness of the elastic lithosphere beneath the Tharsis Montes volcanoes, based on the radial distance of associated circumferential grabens, range from 20 to 50 km (Comer et al., 1985), and the preferred values are at ~20 km (McGovern and Solomon, 1993). If the elastic lithosphere was closer to the upper range of the estimated thickness when Alba formed, then significant thinning by the ascending diapir is suggested.

During initial uplift by a spherical diapir rising through the mantle, stresses produced at the surface will cause radially oriented extensional fracturing on Venus (Stofan et al., 1991; Janes et al., 1992; Janes and Squyres, 1993) and Mars. In the case of Venus, as the diapir flattens against the base of the lithosphere, the stress state is modified and additional radial fracture systems are predicted. Stresses produced by the uplift of Alba are different (Fig. 6). In the center of the uplift, the hoop stress is the most extensional and the vertical stress is the least extensional, leading to the expectation of continued radial fracturing in this area. However, between about 160 and 250 km from the center, the radial stress becomes the most extensional. This is the area where the lithosphere is bending to produce the convex shoulder of the plateau. Here the stress state predicts the formation of concentric grabens. A similar but reversed condition holds at the base of the uplift, where the lithosphere is bending concavely and where the radial stress is the most compressional and the vertical stress the least compressional, which should produce concentric compressional features. The absence of com-

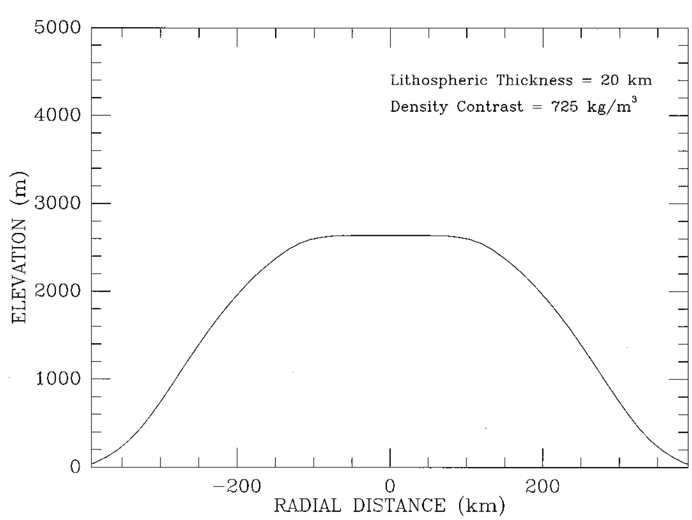

Figure 5. Model elevation profile resulting from uplift due to rising mantle diapir. Model parameters are provided in text. Vertical exaggeration is ~120×.

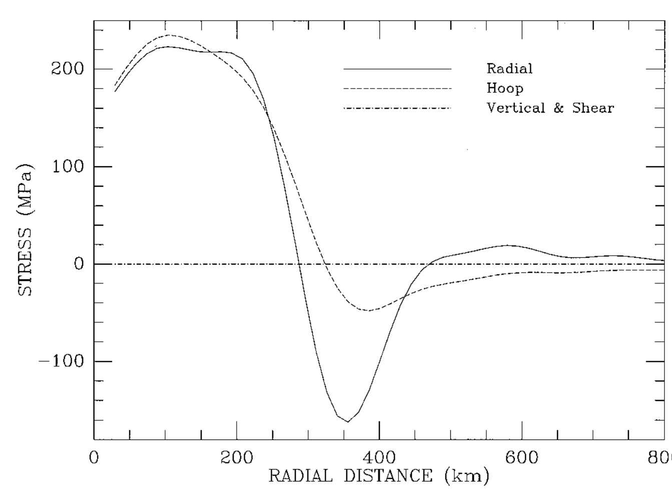

Figure 6. Surface stresses due to flattened diapir in contact with base of 20 km lithosphere. Diapir is 20 km thick, 224 km wide, and 500 kg/m^3 less dense than mantle.

pressional features may reflect the fact that the lithosphere is stronger in compression than in tension. Evidence of radial fractures formed during the initial uplift phase and as the diapir flattened may be completely obscured by lava flows.

The topography raised by diapiric uplift will eventually subside due to gravitational relaxation as dynamic support dissipates with cooling of the diapir. We model this relaxation using the viscoelastic finite element code TECTON (Melosh and Raefsky, 1980). The grid we employ is axisymmetric and extends 2381 km horizontally and 508 km in depth; the uplifted topography is represented as a series of elements atop the grid. The model crust is 52 km thick and has a density of 3000 kg/m^3 and a non-Newtonian diabase viscosity (Caristan, 1982), whereas the mantle is assigned a density of 3300 kg/m^3 and follows an olivine flow law (Goetze, 1978). Both the crust and mantle have a Young's modulus of 6×10^{10} Pa and Poisson's ratio of 0.25 (Turcotte and Schubert, 1982). The temperature is 250 K at the surface and follows an error function profile with a near-surface gradient of 9 K/km (Banerdt et al., 1992) to a mantle temperature of 1600 K (Schubert et al., 1992). These parameters result in a crust and mantle dominated by elastic behavior in their upper parts and by viscous behavior in their lower parts (Banerdt et al., 1992). This is modeled by setting the initial stress state to be hydrostatic in the viscous parts and lithostatic in the elastic parts, and by applying buoyant restoring forces at the elastic-viscous boundaries (D. M. Janes and S. W. Squyres, unpublished).

Viscoelastic gravitational relaxation produces a lower and somewhat flatter profile (Fig. 7) than that raised initially by the diapir. In addition, a broad, shallow annular depression forms around the base of the uplift as the lithosphere flexes under the load. Relaxation can occur very rapidly, so that the actual relaxation rate will be controlled by the cooling rate of the diapir. The final topography is maintained by isostasy and by flexural stresses in the lithosphere. There is good agreement between the predicted topography obtained by relaxation of the uplift and the present topography of Alba Patera (Fig. 8). Relaxation of the topography derived from our uplift model does not result in the formation of an annular rim such as those associated with coronae on Venus, due mainly to the gently domical rather than flat-topped shape of the uplift.

Stresses that develop after 1 m.y. are determined for a constant depth of 1 km below the surface of the average plains level (Fig. 9). Under the uplifted topography, stresses are compressional; the hoop stress is the largest and the vertical stress is the smallest. This stress state is exactly the opposite of that during uplift by the diapir and would be expected to produce radially oriented thrust faulting, or some closure of the previously opened radial grabens. Beyond the ~400 km extent of the uplift, in the area of downward flexure of the lithosphere, the radial stress is extensional and the vertical stress is compressional. Such a stress state might lead to the formation of concentrically oriented extensional fractures on the flanks of the shallow depression around Alba (radial distance of ~350 to 500 km). However, the differential stress (radial−vertical) is relatively low, less than 30 MPa, and is probably insufficient to produce large-scale faulting in the absence of additional regional stresses. As described previously, the formation of the Alba concentric fracture system appears to have influenced the orientation of regional fractures (see Cyr and Melosh, 1993). Thus radial stresses resulting from uplift and relaxation may have been enhanced by regional tensional stresses.

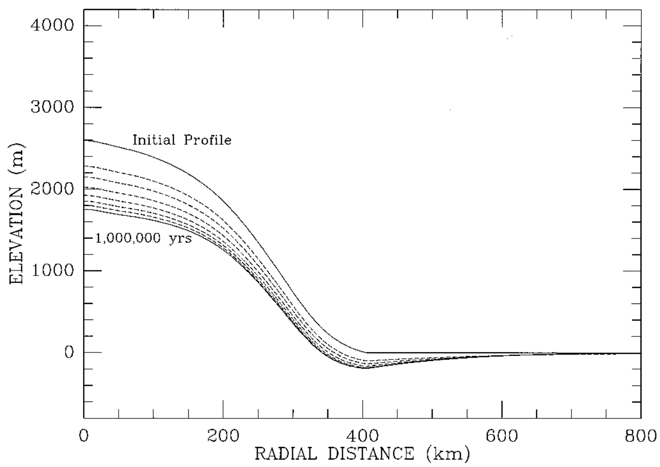

Figure 7. Model elevation profiles through time resulting from gravity-driven relaxation of plateau load shown in Figure 5 (upper solid line). Model parameters are provided in text. Profiles are shown for times 1, 10, 100, 1000, 10 000, 100 000 yr (dashed lines), and 1 000 000 yr (lower solid line). Vertical exaggeration is ~60×.

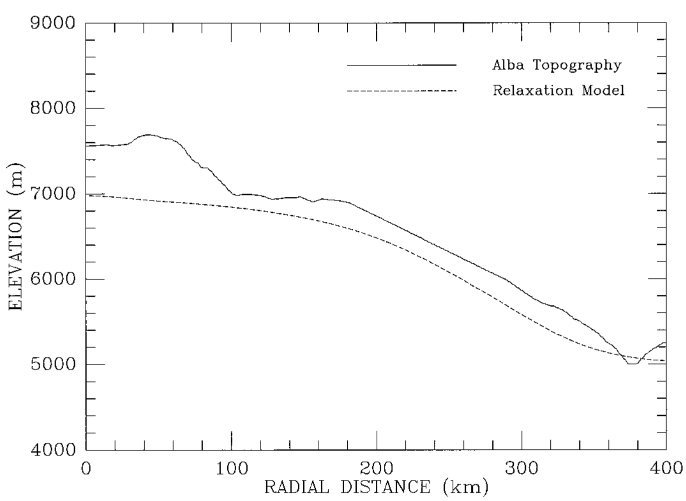

Figure 8. Elevation profile across eastern side of Alba Patera (solid line) (Fig. 3, B–B') with relaxation model profile at time 1 000 000 yr (dashed line) superposed. Vertical exaggeration is ~60×.

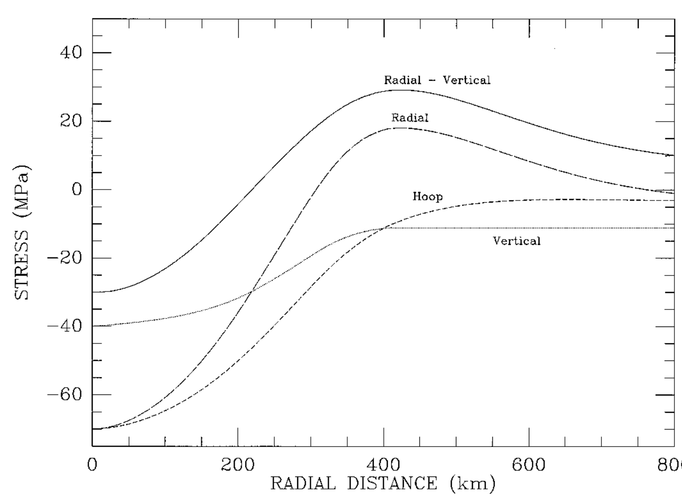

Figure 9. Surface stresses due to relaxation of initial uplift at time 1 000 000 yr.

DISCUSSION

The presence of coronae and corona-like structures on Venus and Mars suggests that mantle diapirism has played an important role in the volcanic and tectonic history of these planets. If this is the case, has mantle diapirism played a similar role on Earth? Janes and Squyres (1993) showed that radially fractured domes on the scale of those observed on Venus could form in thin oceanic lithosphere on Earth if mantle diapirism operates similarly on the two planets. They concluded that continental lithospheres are much less likely to exhibit the influence of mantle diapirs because of their greater thickness. The formation of coronae and corona-like structures on Venus and Mars in lithosphere that may have been as thick as 20 km suggests that these structures may have formed in Earth's oceanic lithosphere. The thickness of oceanic lithosphere increases with age and will approach a thickness of 20 km in ~27 m.y. (Turcotte and Schubert, 1982). The average age of oceanic lithosphere is 60 Ma; only a small part is older than 200 Ma (see Condie, 1982). Thus, coronae would be expected to form in young, relatively thin oceanic lithosphere. To date, only one feature in oceanic lithosphere has been described that is analogous to a radially fractured dome (see Christofferson and Hamil, 1978), and nothing analogous to coronae have been observed. It must be noted, however, that >95% of Earth's sea floor has not been imaged at resolutions comparable to those obtained by Magellan for Venus (Janes and Squyres, 1993) or by the Viking orbiters for Mars. Coronae and related structures may also be obscured by deep-sea sediments. Furthermore, corona-like structures older than 200 Ma would not be preserved. If coronae are not found, it would suggest that either mantle diapirism on Venus and Mars is fundamentally different than it is on Earth, or that corona-forming diapirism has not operated on Earth for the past 200 m.y.

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