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FORTUNA TESSERA, VENUS: EVIDENCE OF HORIZONTAL CONVERGENCE AND CRUSTAL THICKENING

R.W. Vorder Bruegge and J.W. Head

Department of Geological Sciences, Brown University, Providence, RI

Abstract. Structural and tectonic patterns mapped in Fortuna Tessera are interpreted to reflect a change in the style and intensity of deformation from east to west, beginning with simple tessera terrain at relatively low topographic elevations in the east and progressing through increasingly complex deformation patterns and higher topography to Maxwell Montes in the west. These morphologic and topographic patterns are consistent with east-to-west convergence and compression and the increasing elevations are interpreted to be due to crustal thickening processes associated with the convergent deformational environment. Using an Airy isostatic model, crustal thicknesses of approximately 35 km for the initial tessera terrain, and crustal thicknesses of over 100 km for the Maxwell Montes region are predicted. Detailed mapping with Magellan data will permit the deconvolution of individual components and structures in this terrain.

Introduction

The Ishtar Terra highland region on Venus displays evidence of extensive compressional tectonic deformation [Barsukov et al., 1986; Basilevsky et al., 1986]. Akna, Freyja, and Maxwell Montes represent the highest topography on the planet (6 to 11 km above the mean planetary radius) and have been interpreted as orogenic belts arising from horizontal compressional deformation normal to their strike [Crumpler et al., 1986; Vorder Bruegge et al., 1988], which has also influenced surrounding regions, such as Fortuna Tessera immediately to the east of Maxwell Montes in central Ishtar Terra (Fig. 1). Fortuna is elevated above the surrounding plains (Fig. 2) and is characterized by a tessera pattern (terrain dominated by intersecting ridges with a variety of complex, angular relationships) mapped as a single unit [Barsukov et al, 1986; Sukhanov, 1986; Basilevsky et al., 1986]. This pattern of intersecting ridges has previously been interpreted as resulting from independent stages of deformation involving the reorientation of stresses [Ronca and Basilevsky, 1986]. The evolution of Maxwell Montes has been interpreted as the westward transport and compression of crustal materials between two converging shear zones [Vorder Bruegge et al., 1988]. In this paper, we analyze the detailed patterns within Fortuna Tessera and interpret the structural origin of these patterns and their correlation with topography and crustal thickness.

Fortuna Tessera Description

Several characteristic geomorphic-tectonic units have been identified within Fortuna Tessera on the basis of patterns of ridges and other features occurring at the kilometer-to-hundreds-of-kilometers scale(Fig. 3). Maxwell Montes is characterized by long, linear ridges that parallel the strike of the mountain belt (Fig. 1). The topography of Maxwell Montes is asymmetric (Figs. 2 and 3b), with a steep western slope (2° across 200 km) and a more gentle eastern slope (1° across 300 km). In the vicinity of the 6 km altitude contour, this eastern slope levels off and a change in morphology is observed to the Arcuate-Ridged Tessera (Fig. 3), characterized by short-to-intermediate length (50 to 100 km) parallel ridges which strike in approximately the same direction as the ridges on Maxwell Montes. The origin of the ridges is interpreted to be similar to those in adjacent Maxwell Montes and the other orogenic belts in Ishtar, that is, predominantly folds [Crumpler et al., 1986], although they have clearly been dissected to some degree by cross-faults. The Arcuate-Ridged Tessera unit tends to wrap broadly around Maxwell Montes, and lies mostly on a broad plateau that slopes very gently to the east between 5 and 6 km altitude (Fig. 2). The observed wrap-around of the ridges is paralleled by a wrap-around of topographic contours such that these ridges run parallel to the contours, as they do in Maxwell Montes.

The Normal Tessera unit consists of orthogonal to obliquely oriented sets of ridges and valleys with spacings of 5-25 km and occurs in the eastern portion of the region at elevations of 1-4 km (Figs. 2, 3) surrounded by plains at lower elevations. Tessera typically occur elsewhere as isolated patches of elevated topography with 1 to 2 km of relief above surrounding plains. The origin of the basic tessera terrain, and its structural fabric, is not fully understood, although a variety of processes may be operating, including analogies to the terrestrial sea-floor fabric, horizontal compression, vertical uplift, and gravity-driven deformation [Basilevsky et al., 1986; Bindschadler and Head, 1988; Sukhanov, 1986]. In the Normal Tessera unit, the elements of the tessera generally strike NW-SE and NNE-SSW on a NNW-trending slope (Fig. 2).

The Chevron Tessera (Fig. 3) is characterized on a small-scale (10's of km) by a typical tessera-like pattern of intersecting ridges and on a larger scale (100s of km), by a very high level of disruption and large chevron-like features hundreds of kilometers across, giving the region a highly

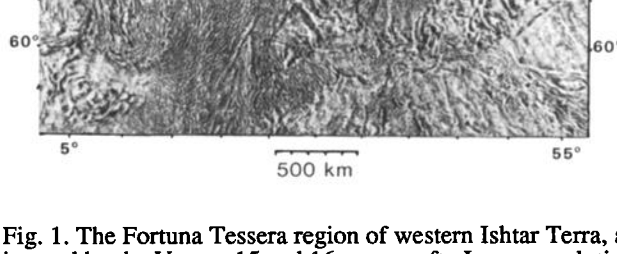

Fig. 1. The Fortuna Tessera region of western Ishtar Terra, as imaged by the Venera 15 and 16 spacecraft. Image resolution is between 1 and 2 km per pixel. In general, bright features are east-facing slopes and dark features are west-facing slopes.

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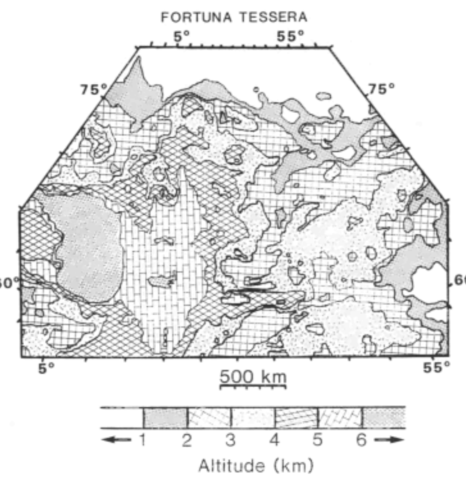

Fig. 2. Topography of Fortuna Tessera as obtained by the Venera 15 and 16 spacecraft. Contour interval is 1 km relative to 6051.0 km. Vertical accuracy is 50 m.

buckled appearance (Fig. 1). At the western edge of this unit (> 5 km elevation) the typical tessera pattern of short (less than 50 km), intersecting ridges is predominant, while further east (< 5 km) this small-scale pattern continues, but the large-scale deformation characterized by the chevrons dominates the texture. The chevrons consist of either individual scarps (sometimes with over 1 km of relief) or paired, facing scarps that form large valleys. Scarps may represent the edges of individual crustal blocks [Sukhanov, 1986], rifted graben walls [Kozak and Schaber, 1989], or deformational fronts associated with crustal imbrication, as suggested by Head [1988a] for similar scarps north of Freyja Montes. The chevrons themselves may be similar to the syntaxis structures seen in adjacent highly deformed regions [Head, 1988b]. Below 4 km, the large-scale chevrons persist, but the small-scale texture consists of narrow, parallel ridges, some continuous for over 100 km, only occasionally dissected by shorter, narrow ridges. The easternmost Chevron Tessera occurs below 3 km in a north-south trough apparently flooded with smooth plains materials and bounded by large-scale chevron-type scarps. Some small areas of tessera-like patterns also occur within the trough. Eastwards of this trough the topography rises, and the morphology becomes that of the Normal Tessera unit (Fig. 3). No large-scale chevron-like features are seen in the Normal Tessera, and the topography no longer slopes W-E, but to the NNW (Fig. 2). The Plumose Ridges and the Ridge Belt unit (Figure 3) consist of areas of parallel ridges individually up to 100 km in length and 5 to 15 km wide, but make up only a small part of the region and are described elsewhere [Vorder Bruegge and Head, 1988].

Discussion

Orientation and Origin of Structural Patterns. Previous workers [Solomon and Head, 1984; Vorder Bruegge et al., 1988] have interpreted the ridges on Maxwell Montes to be folds with the axis of greatest principal stress oriented generally perpendicular to the strike of the folds. Since these ridges approximately strike N30W, then the axis of greatest principal stress is interpreted to have been oriented along a trend of N60E.

The Arcuate-Ridged Tessera is characterized by similar but shorter ridges than those observed on Maxwell Montes. On the basis of the similar morphology and spacing we interpret these ridges to be folds, and since they also parallel the topographic slope, and their strike is identical to that of the ridges on Maxwell, we interpret the ridges of the Arcuate-Ridged Tessera to be the result of the same compressional deformation which formed the folds on Maxwell Montes. In addition, these ridges are also aligned with several large chevron features in the Chevron Tessera and the ridges in the Plumose Ridges unit. Thus, most of the units west of and including the Chevron Tessera are characterized by large-scale topography and features which tend to strike in a NNW-direction, suggesting that their tectonic evolution may be related to compressional deformation with the maximum principal stress oriented generally N60E. In contrast, the Normal Tessera in eastern Fortuna Tessera is characterized by topography which slopes NNW-SSE and lacks a dominant NW-SE trend of ridges, suggesting a tectonic evolution that is different from that of the region to the west.

The deformation in the Chevron Tessera is complex but may be best defined by the large-scale chevron features. While the chevrons appear to be the result of some form of horizontal buckling, the small-scale tessera areas appear to be continuous blocks simply bounded by chevrons, not formed simultaneously with them [Sukhanov, 1986]. The steep topographic slope, the wide range of elevations, and the complexity of patterns within this unit indicate that simple compressional deformation and east-west convergence of material cannot solely account for the variety of features and orientations observed here. Instead, an overprinting of numerous tectonic events are more likely to be responsible for the observed surface deformation and topography.

The similarity of the small-scale, tessera-like pattern in the Chevron Tessera and the Normal Tessera leads us to suggest that the Chevron Tessera consists of individual blocks of Normal Tessera-like terrain that have been rifted, rotated, and that have collided along margins now represented by the chevrons. The deformation associated with chevron formation is concentrated along the margins of these blocks at first, as in the Chevron Tessera, but over time, continued compressional deformation and crustal thickening extends to the interior of these blocks and completely overprints the original pattern. We interpret this to account for the gentle transition in topography and morphology from the Chevron Tessera into the Arcuate-Ridged Tessera to the west, where the Normal

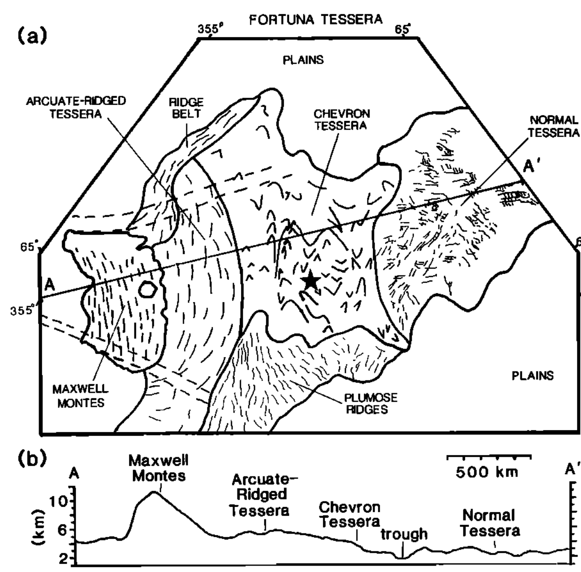

Fig. 3. a. Geomorphic map of Fortuna Tessera. Units are defined in text. General ridge trends indicated in each unit. Dashed lines represent shear zones to the north and south of Maxwell Montes and star within Chevron Tessera indicates location of proto-Maxwell Montes, as described in text. b. Topographic profile (A-A') across Fortuna Tessera.

Tessera pattern may have been completely overprinted, and a high plateau is present.

The fan-like pattern of the Plumose Ridges unit appears to represent some rotation and convergence between the Chevron Tessera and the Arcuate-Ridged Tessera. The extreme northwest corner of this unit occurs at an apex where the Chevron Tessera and Arcuate-Ridged Tessera meet. The north-south strike of the ridges in this unit is indicative of east-west compression, as observed in the adjacent units, and the splaying out of the ridges to the south (Figure 1, 3) suggests that the apex represents the focus of deformation between these two units with larger amounts of convergence in the northern areas of plumose ridges than the southern areas.

Relationship of Tectonic Units and Topography. Topography decreases systematically across Fortuna Tessera from Maxwell Montes through the Arcuate-Ridged Tessera and into the Chevron Tessera (Figure 2, 3). The individual blocks of Normal Tessera-like terrain within the Chevron Tessera are at elevations similar to the Normal Tessera. The only areas in the Chevron Tessera that are lower than typical Normal Tessera areas are the areas between the individual blocks, bounded by the chevrons. This is consistent with the interpretation that the large-scale chevrons represent gaps between blocks of Normal Tessera. The increase in topography from the Chevron Tessera into the Arcuate-Ridged Tessera is also consistent with the suggestion of crustal thickening accompanied by tectonic overprinting of Normal Tessera-like areas to create the patterns observed in the Arcuate-Ridged Tessera.

General Tectonic Evolution. Evidence has been presented [Vorder Bruegge et al., 1988] supporting the interpretation that Maxwell Montes originated east of its present location, in Fortuna Tessera, as a longer, linear orogenic belt due to compressional deformation (A in Figure 4). Subsequent to the formation of 'proto-Maxwell', continued east-west compressional deformation was accompanied by westward transport of 'proto-Maxwell' between two converging shear zones (Figures 3, 4). As the growing orogenic belt was transported west and further wedged between the converging shear zones, strike-slip faulting acted to shorten Maxwell in a N-S direction, leading to its present rectangular shape (B in Figure 4). Lateral transport of crustal materials over distances of 1000 km or more are implied by the geometry of the present and reconstructed mountain range, with 'proto'-Maxwell Montes originating at the location indicated by the star in Figure 3. Such intense deformation and transport implies that

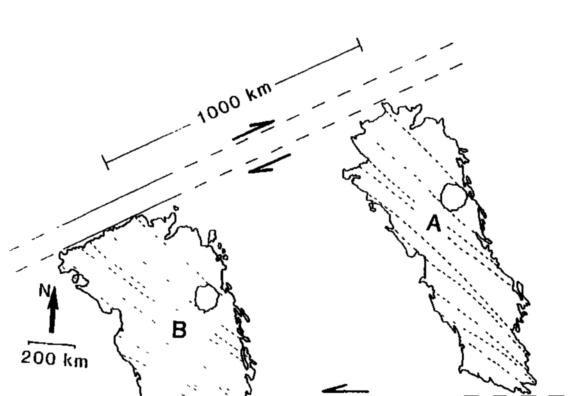

Fig. 4. Sketch map showing present Maxwell Montes ("B") bounded by two converging shear zones (after Vorder Bruegge et al., 1988). Sense of shear along these zones is indicated by the arrows. Proto-Maxwell Montes is placed at an appropriate position ("A") within the shear zones based on the geometry of these zones, the reconstruction, and the assumption of no rotation during lateral transport. Location "A" corresponds to the star in Figure 3.

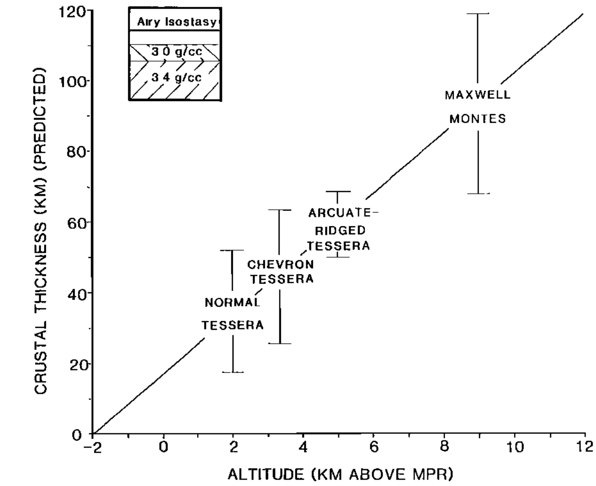

Fig. 5. Predicted crustal thicknesses versus topography of geomorphic units in Fortuna Tessera, based on an Airy isostatic model assuming a basaltic crustal layer of density 3.0 g/cc overlying a mantle of density 3.4 g/cc. This model assumes a crustal thickness of 15 km for areas at the mean planetary radius.

the region involved in the deformational processes must be more extensive, particularly across the area of tectonic transport to the east of Maxwell Montes.

The morphological patterns observed in the units to the east of Maxwell Montes, particularly the Arcuate-Ridged Tessera, bear out this implication since they show extensive evidence of compressional deformation and crustal convergence oriented along an E-W trend. Material similar to the low-lying Normal Tessera, to the east, appears to have been deformed and shortened in central Fortuna Tessera, with buckling and rotation of tessera blocks and the formation of chevron structures. At higher elevations to the west, intensive compressional deformation has caused the production of the anticlines and synclines of Arcuate-Ridged Tessera which has wrapped around the highly deformed and transported Maxwell Montes. Thus the entire region of Fortuna Tessera from the Chevron Tessera in the east, to Maxwell Montes in west, has undergone extensive horizontal compression.

Prediction of Crustal Thickness. The lateral transport of Maxwell Montes across Fortuna Tessera [Vorder Bruegge et al., 1988] suggests that crustal thickening through processes such as folding, thrusting, and stacking were active throughout the Arcuate-Ridged Tessera, and perhaps into the Chevron Tessera. It is possible to make first-order estimates of the amount of crustal thickening occurring in this region using some simple assumptions about crustal characteristics and isostasy.

We have used a simple Airy isostatic model in which we assume a basaltic crust with density 3.0 g/cc overlying a mantle with density 3.4 g/cc. This model ignores any topographic support that might arise from dynamic forces. The topography is simply supported by a thicker, buoyant crust at depth. We have also assumed that the average elevation on the planet (0 km) has a crustal thickness of 15 km, consistent with modelling of the Venusian surface layers based on the spacing of surface features and other aspects which predict a surface layer between 10 and 20 km thick [Zuber, 1987; Solomon and Head, 1984; Grimm and Solomon, 1988].

On the basis of these assumptions Normal Tessera would have an average crustal thickness of about 35 km, Chevron Tessera about 40 km, Arcuate-Ridged Tessera about 60 km, and Maxwell Montes about 95 km (Figure 5). A similar crustal thickness beneath Maxwell Montes was suggested by

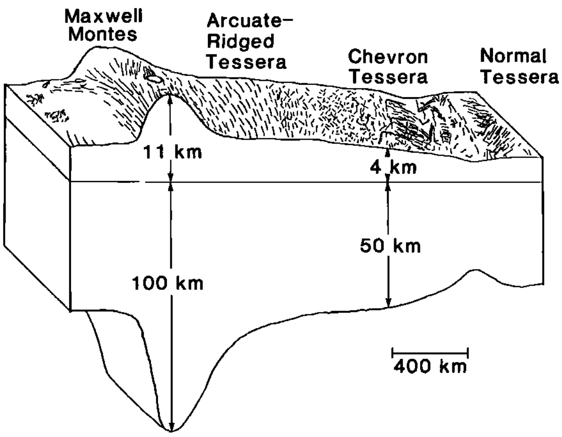

Fig. 6. Block diagram reflecting the morphological, topographic, and crustal thickness variations across Fortuna Tessera. Vertical scale shows two typical values at points along profile and changes at mean planetary radius (solid line).

Morgan and Phillips [1983]. These predicted crustal thicknesses show a systematic trend of increasing crustal thickness from east to west (Figure 6). This E-W increase of average crustal thickness from 15 km in the plains to 95 km at Maxwell Montes is consistent with the systematic change in the intensity of deformation as mapped in the morphology of the surface units, and with the direction of tectonic transport described above [Vorder Bruegge et al., 1988].

Conclusions

A systematic change in tectonic morphology from Normal Tessera to Maxwell Montes is evident across Fortuna Tessera (Figure 3). This is accompanied by a systematic increase in topography from east to west across Fortuna Tessera (Figure 2, 3). This correspondence suggests that these two properties are linked through the deformational process affecting them. The deformational process that created the observed morphology and topography was predominantly east-west compression and lateral convergence of crustal materials across western Fortuna Tessera. This lateral convergence of crustal materials produced the observed ridge patterns as folds and generated the increased topography and crustal thickening by folding, thrusting, and stacking. An Airy isostatic model can be used to predict the amount of crustal thickening throughout this region, and suggests that crustal thicknesses vary from 20 km beneath portions of the Chevron Tessera to 95 km beneath Maxwell Montes. The style of compression and crustal thickening apparently involves involves large-scale convergence over several thousand km and the accretion of terrain elements or blocks of tessera to form the highlands. This style of deformation shares similar elements with other orogenic belts of Ishtar Terra [Head et al., 1989], and appears to represent one distinctive component and style of highland formation on Venus.

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R.W. Vorder Bruegge and J.W. Head, Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912.

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