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Structural evolution of western Fortuna Tessera, Venus

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Abstract. Western Fortuna Tessera, Ishtar Terra, records polyphase deformation. Structures include: ribbons forming long, narrow, steep-sided troughs that reflect surface layer extension; N-trending folds related to Maxwell Montes deformation; short, wide, NW-trending graben that reflect late local extension; and, within the southwestern map area, gentle, E-trending warps, which postdate ribbon structures. Flood lava flows postdate deformation. Ribbon structures change orientation radially from NNE to WNW. These observations caution against the correlation of Fortuna Tessera with tessera elsewhere on Venus and against the proposal that tessera forms a global stratigraphic layer.

Introduction

Fortuna Tessera, east of Maxwell Montes, is a region of elevated (~4 km above mean planetary radius) deformed crust. Deformation styles in Fortuna identified in *Venera 15/16* images led to the term "tessera terrain" to describe intersecting ridges and troughs [*Barsukov et al. 1986*]. Researchers subsequently mapped Fortuna Tessera as a single map unit [*e.g., Vorder Bruegge and Head 1989, Kaula et al. 1992*], and they have denoted Fortuna as the stratotype for a global stratigraphic unit for the oldest visible terrain on Venus [*Basilevsky and Head 1995, Basilevsky et al. 1997*]. However, structural mapping of western Fortuna indicate that this region records a unique history of polyphase deformation with a late stage related to Maxwell Montes deformation. Therefore western Fortuna cannot represent a global stratotype locality for tessera terrain.

Structural elements and map units

We mapped structural features in western Fortuna on Magellan cycle-1 (left-look) SAR (Synthetic Aperture Radar) F-MIDRPs in both hard copy and digital format (Fig. 1). Interactive Data Language (IDL) software was used to manipulate the images to determine fine scale features and differentiate map elements. The map area is bounded on the west by Maxwell Montes and a caldera, to the south by Sedna Planitia, and to the southeast by Sigrun Fossae. Within the map area a range of geologic features with different orientations variably record extensional and contractional deformation. Flood lava flows from Cleopatra Crater and a western caldera embay structural lows indicating volcanism postdates deformation.

Ribbons. Ribbons are characterized in this type area as a fabric of sharp, parallel, closely spaced, radar-dark and radar-bright paired linears (Figs. 1 and 2a) [*Hansen and Willis 1996*]. Ribbon troughs are marked by paired radar-dark linears (facing E) and radar-bright linears (facing W). Mean trough widths are 1-2 km and mean trough spacings are 1.6-3.3 km (Table 1). Trough lengths range up to 170 km; many troughs are structurally disrupted and embayed by flood lava flows and are interpreted to have been originally longer. Paired trough-bounding linears parallel one another and merge into V-shaped terminations. Trough walls dip 85-90°, and trough depths are shallow (0.15-0.5 km) [*Hansen and Willis 1997*].

Thin Ribbons. Thin ribbons, located mostly in the central and eastern map area (Figs. 1 and 2b), are defined by paired bright and dark linears similar to ribbons and parallel local ribbon fabrics. Thin ribbons are shorter (up to 70 km long), thinner (< 1 km), and less closely spaced (~3-5 km) than ribbons. Their paired nature is not always obvious; in some cases a single dark or bright linear is apparent or the linear changes from dark to light along trend. This might result from the fact that the trough width is near the limit of image resolution, the high angle between thin ribbons and radar look direction, and/or trough deformation.

Ultrathin ribbons. Ultrathin ribbons occur in the southeast and east-central map area (Figs. 1 and 2c). They parallel nearby ribbons, and are defined by paired bright and dark linears. They are shorter (≤30 km) and narrower (0.6-0.9 km) than thin ribbons, and they display a more anastomosic character. Ribbons, including thin and ultrathin ribbons, form a radial pattern changing in trend from NNE in the southwest, to NW in the southeast, to WNW in the northeast (Fig. 1). Although parallel lines can appear radial as an artifact of sinusoidal projection, the amount of radial trend is too great to be attributed to a projection artifact.

Graben. Graben trend NW (Figs. 1 and 2d). Although graben were described by *Kaula et al.* [1992] as spaced ~60 km apart, we did not observe regular spacing. Graben parallel local ribbon structures, and trend normal to fold crests. Graben differ from ribbons in their aspect ratios, with lengths 20-60 km and widths generally > 5-7 km. Graben are typically widest at the crests of folds, and host numerous subparallel interior linears that we interpret as accommodation structures

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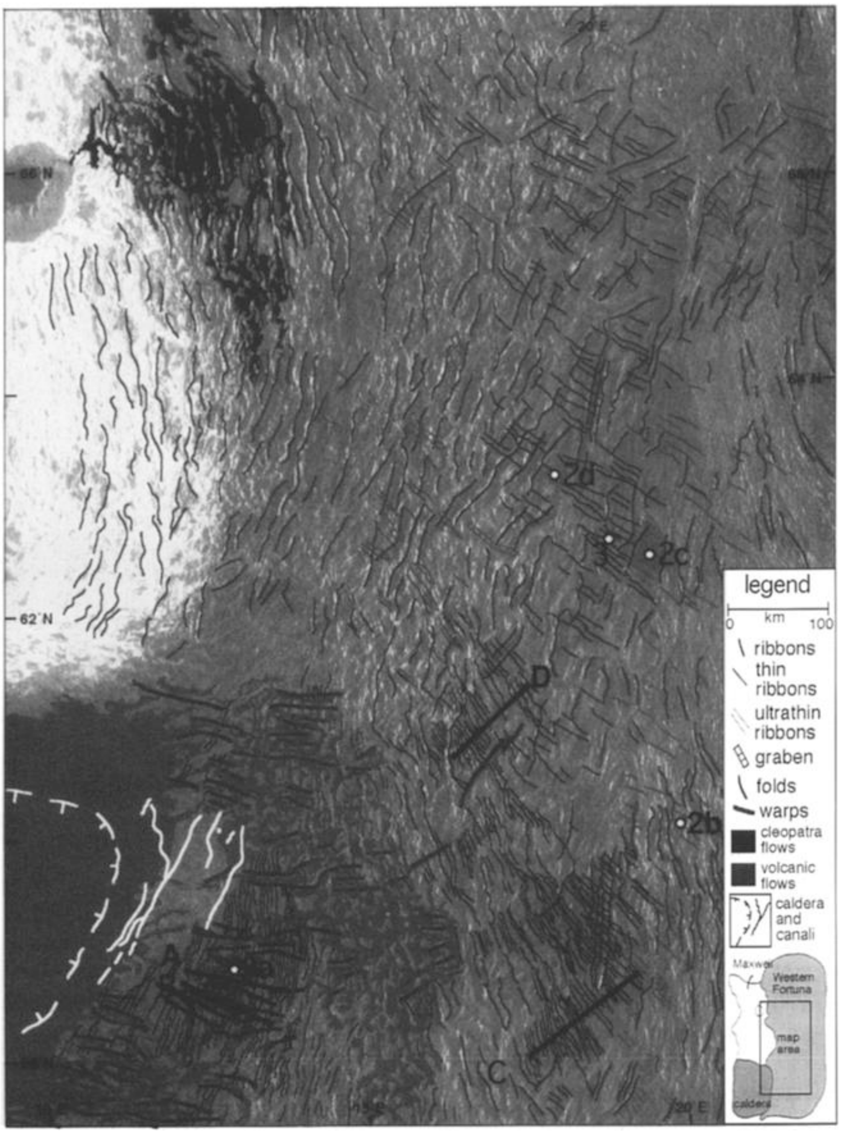

Figure 1. Geologic map of the western Fortuna Tessera and eastern Maxwell Montes. Numbers refer to locations of images in figure 2. Letters refer to profiles in Table 1. Structural elements are distinguished by black and gray lines of different line weights (see legend). Base image composite from F-MIDRPs 65N006;1, 65N018;1, 60N005;1, and 60N016;1; reprojected in sinusoidal format at 62.5N/15.9E.

because they parallel the main graben-bounding faults. The widening of the graben across fold crests indicates that the graben walls dip moderately and postdate folds [*e.g., Baldwin 1971, McGill 1971, Golombek 1979*]. Accommodation structures would be expected due to space problems inherent to graben formation [*e.g., Price and Cosgrove 1990*].

Folds. Folds are marked by N-trending linears with gradational radar brightness, and are notably absent in the southeast. They correlate with arcuate ridged terrain [*Vorder Bruegge and Head 1989*] and subparallel ridged terrain [*Bindschadler and Head 1991*], and they mark the dominant trends of *Riley and Anderson* [1994] and *Riley et al.* [1995]. *Keep and Hansen* [1994] mapped these folds into the study area from Maxwell Montes. These features are interpreted as folds due to their anastomosing character and a gradual transition in radar brightness in a direction normal to their trend, becoming progressively more radar-dark away from the spacecraft [*Vorder Bruegge and Head 1989, Bindschadler and Head 1991, Kaula et al. 1992, Keep and Hansen 1994*]. Wavelength is locally variable, but *Keep and Hansen's* [*1994*] measurements of 6-10 km is a good estimate throughout most of the map area (not all folds are mapped in Fig. 1, giving the appearance of wider spacing). Fold crests are 50-250 km long. Shorter folds occur primarily in the east and south where they are obscured by more closely-spaced ridges. The folds exhibit numerous smaller scale folds(?) that commonly (but not always) parallel the large folds. Because the width of these structures is close to image resolution, positive identification is difficult. The folds record E-W contraction.

Warps. Warps, which occur only in the southwest, define E-trending ridges and valleys. Warps have wavelengths of ~15 km and lengths of ~50-200 km. We interpret the warps as folds, due to the gradual increase in radar brightness from troughs to ridges [*Ford et al. 1993*]. Using radargrammetry, *Hansen and Willis* [*1997*] constrained antiform heights as ~1 km above lava flooded synform valleys. Taking 1 km half amplitude together with wavelength yields interlimb angles of 140-150°, hence the term "warp". Warps differ from folds in

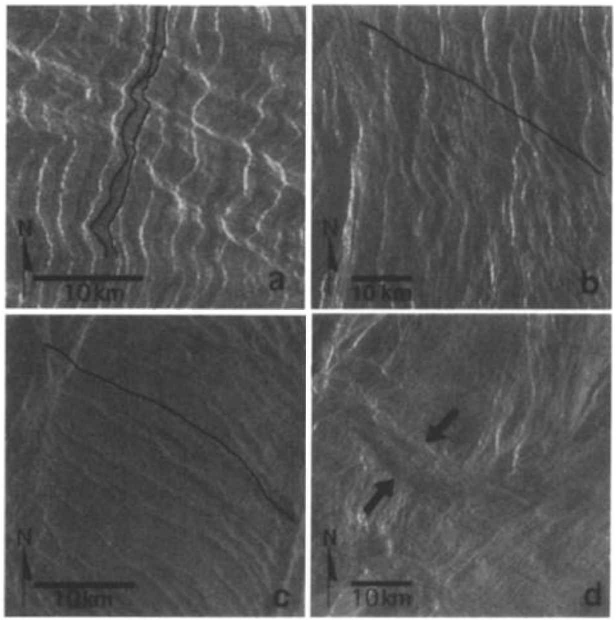

Figure 2. Examples of NW-trending linears (see text). a) ribbons [from F-MIDRP.60N016;1; center 59.1N/18.7E]; lines mark the trough walls of one ribbon. b) thin ribbons [from F-MIDRP.60N016;1; center 60.2N/20.6E]; line parallels thin ribbons. c) ultrathin ribbons [from F-MIDRP.65N018;1; center 62.6N/20.4E]; line marks one ultrathin ribbon. d) graben [from F-MIDRP.65N018;1; center 63.2N/18.75E]; arrows point to the graben walls; the graben is between the arrows. Ribbons parallel the graben.

their broad character and lack of small-scale parasitic structures. Along the ridges ribbons are deflected west, toward the spacecraft, the result of radar foreshortening due to higher elevations at the warp crests. Flood lava flows from a caldera to the west embay many of the warp valleys. Some warps can be traced into the south-central map area, a topographic low that is extensively flooded.

Cleopatra lava flows. Cleopatra lava flows originate from a narrow channel along the northeast rim of Cleopatra Crater and embay fold valleys on eastern Maxwell Montes [*Kaula et al. 1992, Keep and Hansen 1994*]. Cleopatra and related lava flows are thus younger than the N-trending folds.

Caldera structures disrupt preexisting fabrics, and caldera-derived flood lava flows surround the topographically high type area of the ribbon fabric and locally penetrate E-trending synform valleys. Flows abut Maxwell Montes structures and embay N-trending folds.

Geologic history

The spatial distribution of structures, the orientation of the principal strain axes associated with each suite of structures, and cross-cutting relations allow us to differentiate polyphase deformation within the study area. Folds and warps may locally spatially overlap in the south-central map area. Warps are limited to the south whereas the folds occur to the north where they continue eastward into folds related to Maxwell Montes deformation [*Keep and Hansen 1994*]. Graben are limited to the north and can be traced locally as a structural unit to the east into the structural province of Maxwell Montes [*Kaula et al. 1992*]. In contrast, ribbon structures occur throughout (and beyond) the study area.

Ribbon and related structures are interpreted as a structural suite due to their parallel trends and similar structural character. Ribbon trough formation resulted from the opening of tensile fractures within a homogeneous, isotropic, brittle membrane above a sharp brittle-ductile transition over a ductile substrate, such as a brittle chocolate layer above a caramel base [*Hansen and Willis 1996, 1997*]. Ribbon spacing (ridge width) indicates that the strong layer was 0.2-0.6 km thick, yet the dominant wavelength for the folds or warps requires a deeper depth to the crustal plastic-viscous transition [*Hansen and Willis 1997*]. Thus the ribbons must form *prior to* warp or fold formation because a shallow brittle-ductile transition and underlying ductile substrate could not support large-scale warps or folds. Accepting that ribbon walls originated as tensile fractures of a brittle layer above a ductile substrate requires a homogenous, isotropic material at the scale of thousands of square kilometers during ribbon formation. If folds or warps predated ribbon formation, the brittle ribbon structures should have been deflected or influenced by pre-existing structural heterogeneity. However, if ribbons formed first and were later shortened along folds and warps the observed continuity of ribbon structures and geometric character would be preserved. Thus we interpret that ribbons predate both warps and folds.

Because the ribbon troughs represent open fractures, the width of the troughs records extension (~53-76%) relative to the undeformed length represented by the ridge widths (Table 1). The narrower troughs and wider spacing of thin and ultrathin ribbons record less extension than ribbons. The radial pattern defined by ribbons and related structures (Fig. 1) reflects hoop extension, with a central focus northwest of the map area. Thin ribbons occur primarily in the outer part of the radial pattern; this distribution is consistent with thin ribbons forming at the same time and by the same general mechanism as the ribbons, yet recording less overall extension.

Folds and warps postdate ribbon structures. Folds appear to disrupt the warps, and therefore likely formed after the warps. However, their temporal relations are difficult to constrain because these structures are mostly spatially separate. Using *Venera 15/16* data, *Vorder Bruegge and Head* [1989] proposed that the entire Fortuna area displays crustal thickening and horizontal convergence resulting in crustal shortening and the formation of Maxwell Montes. *Keep and Hansen* [1994] used *Magellan* data to conclude that fold fabrics on the slopes of Maxwell Montes extend at least 200 km into western Fortuna Tessera. In the eastern and soouthern map area, the folds are more obscured, but they have the same character, trend, and spacing as in Maxwell Montes. Therefore it seems likely that

Table 1. Ribbon Measurements

	mean (km)		mode (km)		minimum (km)		maximum (km)		extension
	ridge	trough	ridge	trough	ridge	trough	ridge	trough	(%)
Transact A (98.2 km)	1.6	1.3	1.2	1.2	0.6	0.6	3.6	2.4	76
Transact B (89.9 km)	2.5	1.4	2.4	1.2	1.0	0.6	4.7	3.0	58
Transact C (125.4 km)	2.5	1.5	1.2	1.2	0.4	0.6	7.1	3.6	65
Transact D (97.0 km)	3.3	1.8	2.4	1.8	1.2	0.6	9.5	3.6	53

the folds in the map area were formed during the contraction that contributed to Maxwell Montes formation.

As noted by *Kaula et al.* [1992], graben cut the fold crest and formed by extension either synchronous with or after fold formation. Merging of graben into ribbons suggests that some graben reactivated ribbon structures.

The youngest local features are volcanic flows from Cleopatra Crater, and the caldera structures and associated volcanic flows. Both flood units are confined to fold and warp valleys and ribbon troughs, indicating that volcanism is late relative to deformation. Cleopatra and caldera lava flows do not interact, thus their relative ages are indeterminate.

Following the justification that ribbons formed before the folds we can independently constrain the depth of local ribbon troughs. Locally fold crests appear shifted into ribbon troughs. If ribbons predate folds, the shift should be primarily a result of radar layover [*Ford et al. 1993*]. Fold crests that lie along ribbon ridges should be at higher elevation than fold crests within ribbon troughs. Knowing the shift distance, the radar look direction, and the distortion in the sinusoidal projected images caused at the high latitudes of Ishtar Terra, we constrain ribbon depth to range from 0.25 to 0.5 km at the most pronounced areas—serving as an upper limit of ribbon depth. These measurements agree with the characterization of ribbon terrain elsewhere and support a shallow décollement at their formation [*Hansen and Willis 1996, 1997*].

Implications

Western Fortuna records polyphase deformation that is uniquely defined by the combination of radially-distributed extensional ribbons, E-trending contractional warps, N-trending contractional folds related to Maxwell Montes formation, and late local graben formation. Ribbons and related structures formed early; their formation is likely not related to Maxwell deformation because ribbon fabrics extend well beyond the spatial distribution of Maxwell structures and topography. The E-trending warps are consistent with formation within the same general strain regime as ribbon structures and they may well record local deformation broadly related to the process responsible for ribbon formation. Both the character and the orientation of the N-trending folds reflect a different local and regional bulk strain regime than the ribbons, and thus record polyphase deformation.

The N-trending folds are most simply correlated with Maxwell Montes folds of similar character, spacing and trend. The late graben reflect a bulk strain regime which is at least consistent with that described by the N-trending folds and hence the graben could also have formed during late-stage Maxwell Montes evolution [*Kaula et al. 1992*]. Therefore, ribbons and related structures, and possibly the E-trending warps, record one deformation event, and the N-trending folds and the late graben record a second distinct deformation event. The effects of these two events locally spatially overlap, resulting in polyphase deformation. Therefore, consideration of western Fortuna tessera as a global stratotype [*e.g., Basilevsky and Head 1995, Basilevsky et al. 1997*] is not warranted. The younger N-trending folds are likely correlative with Maxwell Montes structures and formed during the evolution of this unique feature on Venus. Ribbon terrain fabric has been noted, however, within crustal plateaus and in large arcuate inliers which might represent flooded crustal plateaus [*e.g., Phillips and Hansen 1994*]. Thus southwestern Fortuna Tessera may represent a crustal plateau which has locally become involved in Maxwell Montes deformation.

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References Cited

Baldwin, R. B., Rima Golcenius II, *J. Geophys. Res.*, *76*, 8459-8465, 1971.

Barsukov, V. L., 29 others, The geology and geomorphology of the Venus surface as revealed by the radar images obtained by the Veneras 15 and 16, Proc. *J. Geophys. Res. Suppl.*, *91*, p. D378-D398, 1986.

Basilevsky, A. T., and Head, J. W., Regional and global stratigraphy of Venus: A preliminary assessment and implications for the geologic history of Venus, *Planet. Space Sci.*, *43*, 1523-1553, 1995.

Basilevsky, A. T., Head, J. W., Schaber, G. G., and Strom, R. G., The resurfacing history of Venus, in\ *Venus II*, S. Bougher, D. Hunten, and R. J. Phillips, Eds., (Univ. of Arizona Press, Tucson, 1997) pp. 927-951.

Regional and global stratigraphy of Venus: A preliminary assessment and implications for the geologic history of Venus, *Planet. Space Sci.*, *43*, 1523-1553, 1995.

Bindschadler, D. L., and Head, J. W., Tessera terrain, Venus: Characterization and models for origin and evolution, *J. Geophys. Res.*, *96*, 5889-5907, 1991.

Ford, J. P., Plaut, J. J., Weitz, C. M., Farr, T. G., Senske, D. A., Stofan, E. R., Michaels, G. and Parker, T. J., (Eds.), Guide to Magellan Image Interpretation, *JPL Publ.*, 93-24, 148pp., 1993.

Ghent, R. R., and Hansen, V. L., Structural analysis of central and eastern Ovda Regio, Venus, *Lunar and Planet. Sci. Conf. XXVIII*, 409-410, 1997.

Golombek, M. P., Structural analysis of lunar grabens and the shallow crustal structure of the moon, *J. Geophys. Res.*, *84*, 4,657-4,666, 1979.

Hansen, V. L., and Willis, J. J., Structural analysis of a sampling of tesserae: Implications for Venus geodynamics, *Icarus*, *123*, 296-312, 1996.

Hansen, V. L., and Willis, J. J., Ribbon Terrain formation, southwestern Fortuna Tessera, Venus: Implications for lithosphere evolution, *Icarus*, submitted 1997.

Kaula, W. M., Bindschadler, D. L., Grimm, R. E., Hansen, V. L., Roberts, K. M., and Smrekar, S. E., Styles of deformation in Ishtar Terra and their implications, *J. Geophys. Res*, *97*, 16,085-16,120, 1992.

Keep, M., and Hansen, V. L., Structural history of Maxwell Montes, Venus: Implications for Venusian mountain belt formation, *J. Geophys. Res.*, *99*, 26,015-26,028, 1994.

McGill, G. E., Attitude of fractures bounding straight and arcuate lunar rilles, *Icarus*, *14*, 53-58, 1971.

Phillips, R. J. and Hansen, V. L., Tectonic and magmatic evolution of Venus, *Ann. Rev. Earth Planet. Sci.*, *22*, 597-654, 1994.

Price, N. J. and Cosgrove, J. W., *Analysis of geological structures*, Cambridge University Press, Cambridge, England, 1990.

Riley, K. M., and Anderson, R. C., Lineament analysis of Fortuna Tessera; A preliminary evaluation of a complex ridged terrain, Venus, *Lunar and Planet. Sci. Conf. XXV*, 1133-1134, 1994.

Riley, K. M., Anderson, R. C, and Peer, B. J., Lineament analysis of Fortuna Tessera, Venus: Results from an ongoing study, *Lunar and Planet. Sci. Conf. XXVI*, 1171-1172, 1995.

Stofan, E. R., Senske, D. A., and Michaels, G., Tectonic features in Magellan data, *in*, Ford *et al.*, *Guide to Magellan Image Interpretation*, *JPL Publ.*, 93-24, 93-108, 1993.

Vorder Bruegge, R. W., and Head, J. W., Fortuna Tessera, Venus: Evidence of horizontal convergence and crustal thickening, *Geophys. Res Lett.*, *16*, 699-702, 1989.

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