RIBBON TERRAIN FORMATION AND IMPLICATIONS FOR LITHOSPHERE EVOLUTION, VENUS.

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The term tessera has been used to describe regions of deformed Venusian crust exhibiting two or more intersecting sets of structural elements [*e.g.*, 1-2]. However, tessera includes terrains formed by a variety of spatially- and temporally-discrete tectonic processes [3]. In this paper, we elaborate on previous reconnaissance treatment of ribbon fabrics which characterize crustal plateaus [3]. Herein we: (1) refine the geometric description of ribbons resulting from detailed mapping and radargrammetric analysis in southwestern Fortuna Tessera; (2) present a model for ribbon formation; (3) constrain temporal relations between ribbons, folds and lenticular graben; and (4) outline implications of ribbons for crustal plateau formation and lithospheric evolution. Southwestern Fortuna Tessera is well suited for characterization of ribbon geometry because: (1) the area hosts ribbons and folds in near orthogonal relation, allowing detailed analysis of ribbons as they cross fold crests and troughs; (2) volcanic lava flows locally embay synformal fold valleys and ribbon troughs, providing a cross-section of ribbons, and (3) the radar look direction is nearly orthogonal to ribbons, allowing radargrammetric analysis to constrain the three-dimensional ribbon geometry.

Ribbons, characterized in the type area southeast of Maxwell Montes, comprise a fabric of alternating, para-llel, closely-spaced, sharp, radar-dark and radar-bright lineaments [3]. Individual lineaments exhibit sharp—constant, not gradational—brightness contrasts with adja-cent materials. Lineaments show a distinct dark-bright pairing defining a system of slopes that themselves define a series of alternating ridges and troughs. Local embay-ments by lava flows confirm the inferred low topography of the troughs. Troughs are generally 1-2 km wide, with intervening ridges ~1-3 km wide. Troughs range in length from 30 to 170 km, although most are disrupted by subse-quent deformation and volcanism (especially those ~30 km), and are interpreted to have originally been longer. Ribbon troughs typically cut at a high angle across open, east-trending, folds. The troughs appear sinuous as a result of radar layover. Other evidence of layover occurs at embayments of lava flows into ribbon troughs; west-facing radar-bright scarps which define the eastern bound-ary of ribbon troughs overlay part of the flooded trough, locally obscuring the real embayment shoreline [3].

Although trough width varies somewhat along trend, paired trough-bounding lineaments—lineaments that mark opposite sides of the same trough—remain essentially parallel and matched along their length, even as they track across topo-graphic fold crests and valleys. In contrast, lineament pairs that bound either side of a ridge are not parallel or matched, although they maintain the same regional trend. No correlation exists between trough widening and fold crests which would be expected if ribbon troughs represent graben defined by normal faults [4-6]. Instead trough-bounding lineament pairs are deflected equally at fold crests due to layover, indicating that the lineament structures are near-vertical. Trough-bounding lineament pairs terminate by merging into a V-shape. Trough bottoms are flat, smooth, and notably devoid of interior lineaments, in marked contrast with lenticular graben. Lenticular graben parallel the trend of ribbon troughs, cutting at high angles across the crests of folds; however, lenticular graben host numerous interior lineaments (interpreted as accommodation structures), they are shorter and wider than ribbons, and they typically cut single fold crests indicating that they post-date folds.

Radargrammetric calculations constrain the depth of ribbon troughs and the dip of the trough-bounding structures. Assuming symmetry of paired trough-bounding lineaments constrains ribbon depth to 0.15 - 0.30 km, and paired trough-bounding structures to 85-90° dips, essenti-ally vertical structures [7]. These depths are independently confirmed (0.15-0.4 km) by using trough embayment relations outlined previously [3] and new radargrammetric constraints on antiform height and therefore fold limb dip. Shallow depths are consistent along individual ribbon troughs and within adjacent troughs.

Any model for ribbon formation must address the following geometric constraints: ribbon structures are comprised of 1-2 km wide, 0.15-0.4 km deep troughs with paired parallel and matched steep sides, smooth flat floors, V-shaped terminations, and lengths up to 170 km long resulting in length:width aspect ratio of ~50-100:1. Ridges which separate troughs are 1-3 km across. Paired trough-bounding lineaments are parallel and matched, paired ridge-bounding lineaments are not. The opening of tensile fractures within a brittle layer above a sharp brittle ductile transition (BDT) over a ductile substrate, such as a brittle chocolate layer above a caramel base, would result in formation of the observed ribbon geometries (Fig. 1). Because trough-bounding lineaments are originally connected along near-vertical tensile fractures and separated due to extension and trough formation, the trough-bounding lineaments should be matched, near-vertical structures that merge into V-terminations, as observed. The lineament would be expected to show sharp contrast changes with adjacent material. The troughs would be flat-bottomed and smooth with the depth of the troughs equal to the thickness of the brittle surface layer. Ridge width between adjacent ribbon troughs defines structural wavelength and likely relates to brittle layer thickness and strength. Constraints derived from Mohr-circle analysis predicts the formation of tensile fractures at shallow depth ($\leq$ 1.5 km).

The relative timing of fold and ribbon formation is critical to strain history and therefore to understanding tectonic processes of crustal plateau formation. Formation of the folds prior to ribbon formation would require that the ribbons form as the result of consistent vertical displacement along closely-spaced, near-vertical faults (Fig. 2a). This scenario does not address the observed matching and parallelism of structures across troughs, and it requires justification of a completely unrealistic regularity of fault geometry and displacement, and physically ridiculous dissection of the crust into long narrow, yet thick, crustal packages. If, however, ribbon structures result from the extension of a brittle layer above a ductile substrate as proposed, they must form *prior to* fold formation because a shallow BDT and underlying ductile substrate could not support large-scale folds. The penetratively developed fabric of the ribbons (small wavelength) as compared with the folds (longer wavelength) also supports this temporal relation. Thus we propose that ribbons formed by extension of a thin brittle layer above a ductile substrate, and that the region was later folded as the depth to the BDT increased (Fig. 2b).

Ribbon structures occur within each of Venus' crustal plateaus except Phoebe Regio, and therefore the presence of these distinctive structural fabric places important constraints on crustal plateau evolution. Ribbon structures at some crustal plateaus show more complexity in their trough-bounding structures than the ribbon at Fortuna Tessera. For example, at Thetis Regio, ribbon structures have long aspect ratios, yet they locally include interior lineaments and parallel, rather than V-shape, ter-minations. We interpret these features as accommodation structures formed within normal fault bounded troughs (Fig. 1). Normal fault-bounded ribbon structures would be predicted with both a deeper depth to the BDT and a broader, rather than sharp, BDT. Ribbon trough forma-tion, whether by opening of extension fractures or by trough formation by normal faults, requires a ductile sub-strate at relatively shallow depth (Fig. 1). Opening of extension fractures would be favored with a sharp BDT at a shallower depth, whereas a broader and deeper BDT would favor normal faults. In both cases the ribbon structures must predate fold formation. Thus ribbon terrain, which characterizes crustal plateaus, records early extension of a thin brittle layer above a ductile substrate. Broad scale folding or warping of the surface could result only as the depth to the BDT increased with time. Formation of len-ticular graben across fold crests must have occurred syn-chronous with, or after, folding because the graben cut the fold crests. Thus, ribbon-bearing tessera terrain within crustal plateaus record widespread early extension and an increasing depth to the BDT with time. The surface strain history is inconsistent with crustal plateau formation by downwelling, yet might be predicted by crustal plateau formation by magmatic underplating [8,9].

Although crustal plateaus are not individually large enough to date using crater density [10], the character of craters within crustal plateaus constrains the local surface history. Impact craters within crustal plateaus are generally undeformed, and if deformed, they are affected only by late lenticular graben [11]. Thus ribbon and fold formation likely predates the average surface age of Venus as defined by global crater density [12]. The absolute time of ribbon and fold formation are unconstrained, however. Ribbon and fold deformation is not particularly complex and therefore evidence of craters that existed prior to this deformation should be preserved—unless the craters were destroyed not by ribbon and fold formation, but rather by processes that lead up to the formation of these structures. If ribbon formation requires shallow (0.15-0.4 km) depth to BDT, as proposed, then craters that existed prior to ribbon formation would likely be annealed in a crust with such a shallow BDT. In fact it is possible that the BDT was even shallower than 0.15 km prior to ribbon formation and that the upper crust was effectively mechanically annealed throughout regions that host ribbon terrain. Such annealing would erase earlier craters, and mechanical annealing would explain how shallow delicate ribbon structures form such long features which are unaffected by mechanical inhomogeneities.

In order for a heat source to be able to affect the upper crust and to effectively mechanically anneal the surface, the lithosphere must have been much thinner than at present. Crustal plateaus are similar in planform to volcanic rises, and if they both result from magmatic underplating, then the difference between these tectonic features should be lithospheric thickness. Crustal plateaus formed at a time in the past when the lithosphere was thin, whereas volcanic rises, which are presently thermally supported, reflect thick lithosphere [8,9]. Phoebe Regio, characterized by a complex pattern of graben, formed during a time of intermediate lithospheric thickness.

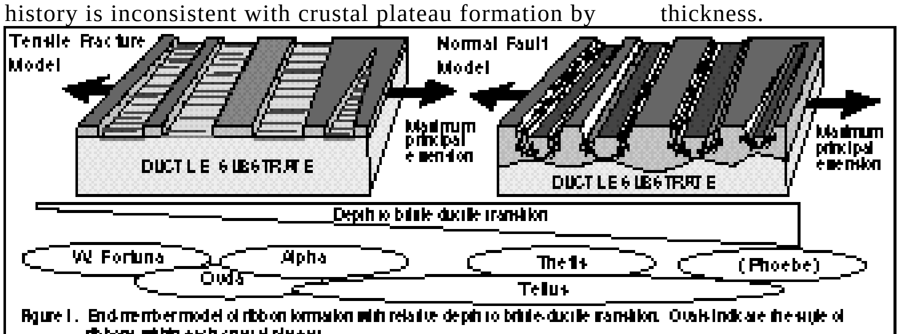

Figure 1. End-member model of ribbon formation with relative depth to brittle-ductile transition. Ovals indicate the style of ribbons within each crustal plateau.

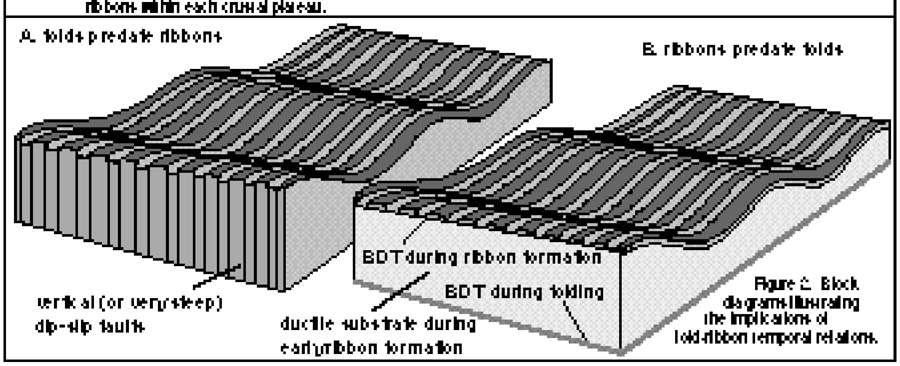

Figure 2. Block diagrams illustrating the implications of fold-ribbon temporal relations.

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