RIBBON TERRAIN: FINGERPRINT OF ANCIENT MANTLE UPWELLINGS AND CRUSTAL PLATEAUS, VENUS.

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Introduction. Crustal plateaus, steep-sided plateau-shaped regions that host extensive deformation fabrics, are arguably the least understood large-scale tectonic feature on Venus. Early analysis of Magellan SAR imagery supported mantle downwelling models because crustal plateau structures appeared to record contraction followed by extension [1]. However, recognition of “ribbon” structures [2, 3] has reinvigorated the upwelling hypothesis, albeit with some modification. Ribbons [2, 3], which are widespread in all crustal plateaus except Phoebe Regio are linear, steep-sided (>85°), shallow (<0.5 km), flat-bottomed troughs, commonly 1-3 km wide and spaced ~1-3 km apart (e.g., “steep troughs” [1]; “narrow troughs” [4]). Detailed geometric characteristics defined through rigorous photogrammetric analysis of ribbons structures in the type location, southwestern Fortuna Tessera, leads to a model of ribbon formation by opening of tensile fractures within a brittle layer above a ductile substrate [3]. Elsewhere, such as Thetis Regio, ribbon fabrics form by shear-fracture failure of a brittle layer above a ductile substrate. In this contribution we explore further characteristics of ribbon terrain structures and present additional support for the brittle layer model of ribbon formation.

Distribution. Ribbon terrain comprises a pervasive, penetratively developed fabric across each of the crustal plateaus except Phoebe Regio. Ribbon patterns vary among crustal plateaus. In Thetis Regio ribbons generally trend north with fanning preserved on the eastern and western margins. Ribbons in eastern Ovda describe a broadly radial pattern [5, 6]. Central and western Ovda Regio and western Fortuna Tessera preserve fanning ribbon patterns. Tellus Tessera and Alpha Regio each host two prominent orthogonal ribbon suites. Orthogonal, or near orthogonal ribbon suites are also preserved locally in Ovda and Thetis regiones.

Folds are commonly, although not in all cases, spatially correlative with ribbons. In general folds are more organized (sub-parallel) and longer along plateau margins and describe two or more orientations in plateau interiors [e.g., 5, 6].

Strain. Extension recorded by ribbon structures varies from 50-80% as recorded by tensile-fracture ribbons in western Fortuna Tessera [3, 7] to 10-50% extension recorded by shear-fracture ribbons in eastern Ovda Region [8, 9].

The amount of shortening represented by folds can be estimated using wavelength and amplitude. Fold wavelengths range from 10-30 km. Fold amplitudes are probably < 4 km (crustal plateaus lie 2-3 km above adjacent plains and fold crests and troughs are locally preserved at the surface); thus folds record <<5-10% shortening. The presence of thrust faults would increase shortening estimates.

Temporal relations. Field observations, experiments and theoretical analysis indicate that structural wavelengths of both contractional and extensional structures reflect the thickness of the mechanical layer involved in deformation [10, 11]. Wavelength:layer thickness ratios have proved valid for thin-section, hand-sample, and outcrop scale features [e.g., 10, 12-16] as well as map-scale features on Earth and Venus [e.g., 17-19], thus there is no reason to expect that such an analysis should not be valid for ribbon structures whose wavelengths are bracketed by scale-lengths of previous studies. The structural wavelength of both tensile-fracture and shear-fracture ribbons reflects brittle layer thickness and thus depth to a crustal brittle-ductile transition (BDT). Tensile-fracture ribbon ridge wavelengths of 1-3 km indicate competent layer thickness of ~0.5 km during ribbon formation [3]; shear-fracture ribbons wavelengths of ~1.5-3 km (eastern Ovda) and ~3.5-4.5 km (Thetis Regio) reflect competent layer thickness of ~0.5-2 km [3, 8, 9]. In contrast, fold wavelengths of 10-15 km yield competent layer thickness of ~6 km [20]. These values indicate that the thickness of the competent layer was different during tensile-fracture and shear-fracture ribbon and fold formation. In cases where ribbons trend perpendicular to spatially correlative long wavelength folds, ribbons and folds are consistent with formation within a similar strain regime, and therefore these structures could have formed synchronously [3]. However, the difference in ribbon and fold wavelength requires different layer thickness, and thus likely diachronous formation, with ribbons pre-dating folds. Indeed experimental results indicate that synchronous formation of boudin and fold structures results in similar wavelengths in extensional boudins and contractional folds [21].

In the case of two intersecting ribbon suites, a different conclusion can be drawn. Detailed analysis of intersecting ribbon structures in Tellus Tessera and Alpha Regio indicates that the wavelengths (ridge width) of the two ribbons suites are not significantly different, indicating that these perpendicular ribbon suites deformed a layer of similar thickness, and therefore could have formed synchronously [22]. The block-shaped ridges that result from intersecting ribbon suites may be analogous to chocolate tablet boudinage. Although mutually perpendicular ribbons structures could reflect two distinct episodes of extension oriented 90° to one another, due to the mechanical inhomogeneity that develops as a result of initial boudin formation, the second extension could be at shallow angles to the primary extension direction and still result in perpendicular boudins (chocolate tablet boudins) [23].

Formation and implications. Further investigation of ribbon-fold fabrics across crustal plateaus is consistent with recent proposals that ribbons record early surface layer extension followed by minor contraction. Intersecting ribbon suites can be accommodated within this general deformation model. Thus the pervasive development of ribbon structures across crustal plateaus provides strong support for models of plateau formation via mantle upwelling.

It has been suggested that ribbon structures may represent the surface expression of subsurface dikes (McKenzie, pers. comm.), and thus ribbons could (although this would not require that they do) post-date spatially correlative folds. The small spacing between ribbons troughs, and the typical consistency of ribbon ridge width across a region [4, 7, 9] are not consistent with ribbons representing subsurface dikes. Because dikes form successively with individual dikes generally cooling before new dikes are emplaced, dikes commonly intrude "cheek and jowl" [24]. Venus ribbon structures are more closely spaced and more consistent in their spacing than dikes within dike swarms denoted on Earth and Venus [e.g., 25-27]. Furthermore, one would have to attribute the orthogonal relations typically described by two ribbon suites to coincidence following a model of ribbon formation by subsurface diking. A survey of mafic dike swarms on Earth indicates that orthogonal dikes are the exception not the rule [28].

If ribbon structures do represent subsurface dikes, they would represent truly pervasive invasion of the crust by dikes based on the number of ribbons and their development across entire plateaus. Thus, whether ribbon-dikes formed prior to, or after, folds (which, recall, record only minor crustal shortening) they would provide strong support for models of crustal plateau formation above mantle upwellings rather than mantle downwellings. Dike swarms, particularly swarms exposed over extensive regions and that describe radial or fanning patterns, reflect mantle upwelling, at depth [25-27, 29]. Although local mantle upwellings can occur in broadly downwelling environments, they result in very little (comparatively) magmatism [e.g., 30]. Thus, even if ribbon structures are dikes (which evidence does not support), the implication would be that crustal thickening associated with plateau formation resulted from mantle upwelling, not mantle downwelling.

Summary. Thus the geometric and kinematic data assembled to date support ribbon formation by extension of the thin brittle layer above a ductile substrate. This model accommodates tensile-fracture ribbons, shear-fracture ribbons and intersecting ribbon suites. Wavelength:layer thickness analysis indicates a brittle layer thickness of ~0.3-2 km with ribbons pre-dating folds. Intersecting ribbon suites form broadly synchronously. Extension estimates indicate that surface extension ranges from 10-80% followed by local contraction of <10%. Thermal-mechanical analysis of ribbon structures [31] indicates that ribbon formation at geologically reasonable time scales likely requires surface temperature of ~1000K, a value consistent with atmospheric studies [32]. The presence of tensile-fracture ribbons requires a virtually intact crust with few pre-existing fractures, suggesting that the local crust may have been thermomechanically annealed prior to ribbon formation [3].

Our work supports earlier suggestions that ribbon terrain represents a characteristic fingerprint of ancient mantle plumes formed at a time when the Venus lithosphere was thin, and the surface temperature significantly hotter than present. We also support the proposal that southwestern Fortuna Tessera represents an ancient crustal plateau. Cross-cutting relations indicate that Maxwell Montes structures overprint western Fortuna structures [7]. We further propose that Ishtar Terra is broadly comprised of eastern Ishtar, an ancient crustal plateau formed above a mantle upwelling, and that western Ishtar formed somewhat later, above a mantle downwelling [e.g., 33]. Previously thickened crust of western Fortuna Tessera was presumably drawn into the broad mantle downwelling responsible for the formation of western Ishtar Terra. The crustal plateau defined by western Fortuna Tessera may contribute to Maxwell Montes' extreme elevation.

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