CHOCOLATE TABLET BOUDINAGE ON VENUS. B. K. Banks and V. L. Hansen, Department of Geological Sciences, Southern Methodist University, Dallas, TX 75275. (banksb@mail.smu.edu; vhansen@mail.smu.edu)

The recognition of ribbon structures and how they interact with other structures on crustal plateaus provides geodynamic constraints on crustal plateau formation and evolution [1,2,3]. The proposed model for ribbon formation -- that ribbons represent extension of a thin, brittle upper layer above a ductile substrate -- accounts for the observed surface features of ribbons at the type area, southern Fortuna Tessera, where the near vertical walls bounding ribbon troughs represent discontinuities produced during tensile fracture of the brittle layer. [1,2]. In other areas, ribbons are also formed by extension along shear fractures [1,2]. Detailed analyses of ribbons and how they interact with other structures are provided by Hansen & Willis [1,2].

The existence of a single set of ribbons has been documented and discussed. However, two orthogonal sets of ribbons are recognized to be common on crustal plateaus. In this paper we describe these surface features and suggest that experimental and theoretical results of two-dimensional layer-parallel extension termed chocolate tablet boudinage can be employed to explain the existence of two sets of ribbons.

A common feature observed in crustal plateaus is the existence of two regularly spaced, nearly orthogonal (~70-90 degrees) sets of paired radar-bright and radar-dark lineaments that define opposite facing, steep walls of linear troughs interpreted as ribbon structures. In Tellus Tessera and Alpha Regio, two ribbon sets are pervasive over much of their areas. Additionally, two orthogonal sets of ribbons are displayed locally in Ovda Regio.

In Tellus two overlapping suites of ribbons trend NW and NE (e.g., 33.2 N/79.8 E). Both ribbon sets are regularly spaced, each with a similar fracture wavelength, as defined by ridge width, of approximately 1-2 km. Neither lineament suite is dominantly pervasive in this location such that ribbon troughs of one suite can not be traced continuously across the area but are often interrupted by ridges and troughs of the opposing suite. However, the overall trend of the ribbon suites are continuous. Although some ridges are observed to follow both the NW and NE trending suites in alternating intervals such that the trace of the ridge walls take on a stairstep pattern in plan view, the dominant result of the intersection of equally spaced, orthogonal ribbon troughs is that ridges are dissected into equidimensional blocks that resemble squares in plan view and cubes in three dimensions. Where one trough intersects another, there may be a change in elevation between the two troughs.

Another area of Tellus (34.6 N/79.4 E) displays NW- and NE-trending ribbon troughs that lie on the crest of a broad NW-trending antiform. Lava has completely flooded the fold valleys on both sides of the antiform and has partially flooded the crest of the antiform where the fold axis of the antiform plunges below the lava flood plane such that rhombohedral- and parallelogram-shaped blocks stand out above lava-flooded ribbon trough floors. Ribbon fracture spacing in this area is regular with wavelengths on the order of 2-4 km. Paired lineaments that define opposite facing trough walls are matched and appear consistent along trend. Individual ribbon troughs can not be traced continuously but are often cut by troughs and ridges of the opposing set of ribbons. The two nearly orthogonal sets of ribbon troughs dissect ribbon ridges into rhombohedral- and parallelogram-shaped blocks.

Alpha Regio displays two orthogonal sets of lineament pairs defining ribbon troughs and ridges. Both ribbon suites are regularly spaced with a fracture wavelength of 1-3 km. Although both ribbon sets are recognized at different places thoughout Alpha, it is difficult to unambiguously distinguish both sets in a single location. This may be due to local absence of one of the ribbon sets, the dominance of one set over the other in specific locations, the interaction of other structures with ribbons that obscures one set of ribbons, the radar incidence angle which may act to obscure one set of ribbons, or a combination of more than one of these reasons.

Ovda Regio also exhibits two orthogonal sets of ribbons locally exposed throughout this region. In eastern Ovda Regio (7.2 S/101.0 E) a NW-trending suite of ribbons occurs with NE-trending ribbons, each set with an average fracture wavelength of approximately 1-2 km. The NE-trending ribbons should not be confused with the NE-trending folds of approximately the same wavelength. Lineaments in this area that define trough walls of both sets of ribbons are traceable across ridges and troughs of the opposing ribbon suite.

Deformation controlling the formation of a single set of ribbons is analogous to one-dimensional boudinage such that unidirectional layer-parallel extension of a brittle surface layer results from layer-normal uniaxial compression involved in a flattening type of bulk deformation [1]. To explain the existence of two orthogonal sets of ribbons recognized on crustal plateaus, experimental and theoretical results of chocolate tablet boudinage can be employed.

Ramberg [4] was the first to develop a thorough and rigorous evaluation of boudins including theoretical and experimental analysis. He concluded that boudins separated by a single set of tension fractures suggests uniaxial layer-parallel extension along fractures oriented perpendicular to the direction of maximum tension. Ramberg commented that boudins are often roughly equidimensional in the plane of the competent layer, often shaped like rhombs or parallelograms and are separated by two orthogonal sets of extension gaps. He suggests that three-dimensional boudin structure indicates two-dimensional expansion in the boudin plane, a result of two-dimensional tension parallel to the boudin plane. Similarly, on Venus a single set of ribbons determined to have formed simultaneously suggests two-dimensional chocolate tablet boudinage. Ribbon troughs represent boudin necks whereas ribbon ridges are boudin blocks.

Experimental models of chocolate tablet boudinage performed by Ghosh [5] provide an excellent analog to the proposed model for ribbon formation on Venus. His experimental boudinage of a thin brittle surface layer takes place due to the shear stress exerted on the bottom of the layer (plaster of Paris) resulting from plastic flow of the underlying ductile substrate (slab of pitch). The layer of plaster of Paris was a free surface layer such that shear stress could not be accumulated on the upper surface. Shear stress causing extensional fracture of the layer was introduced only at the brittle-ductile transition. This makes Ghosh's experiment a wonderful analogy for deformation of a brittle surface layer on Venus. In mathematical models developed to study boudinage [e.g. 4,5], the brittle layer was always imbedded in a viscous matrix. Even so, theoretical results substantiate experimental results. Some may argue that because ribbon formation is proposed to occur during upwelling while the plaster of Paris deforms during gravitational collapse, the analogy fails. However, the important factors are the stress-strain relations responsible for deformation. Both the proposed model of ribbon formation and Ghosh's experimental chocolate tablet boudinage involve layer-parallel extension due to bulk flattening of a brittle surface layer [3,5].

Boudin length is controlled by boudin thickness because accumulated tensile stresses will decrease with increasing boudin thickness such that wide boudins represent the deformation of a thick brittle layer and narrow boudins suggest a thin brittle layer [4]. Accordingly, the fracture spacing of ribbons as determined by the width of ribbon ridges is indicative of the brittle surface layer thickness; the larger the fracture wavelength of a suite of ribbons, the greater the depth to the BDT. Because the working model of crustal plateau evolution that takes into account ribbon formation suggests that the brittle layer thickness as determined by the depth to the BDT increases with time [3], it follows that ribbons with similar wavelengths formed broadly synchronously. In each of the areas described above, where two orthogonal sets of ribbons exist, the fracture wavelength of each ribbon suite is similar. This suggests that they formed during the same general time span. Additionally, where there exists a change in elevation at the intersection of two ribbon troughs, the deeper trough floor represents extension at a later time than does a shallower trough floor, when the depth to the BDT was deeper. However, if extension occurred over a span of time that experienced an increase in the depth of the BDT, trough floors of two or more elevations would be predicted.

The combined analysis of Ramberg and Ghosh demonstrates that chocolate tablet boudinage formed under unequal layer-parallel extension resulting from a flattening bulk deformation produces two orthogonal sets of fractures. The two sets of fractures can not form strictly simultaneously. Assuming a homogenous, isotropic brittle layer, the first set will be oriented perpendicular to the orientation of greatest principal tensional stress. However, Ghosh [5] determined that anisotropy in a deforming brittle layer and not the orientation of greatest principal tensional stress may determine the orientation of extension such that one should be careful when assigning principal stress directions to ribbon deformation. The width of the initial boudins will be reduced by successive mid-point fracturing. When the boudins are sufficiently long compared to their width, tensile stress along the long axis of the boudin may become larger than in the principal tension direction resulting in a second set of extension fractures oriented normal to the first. Fracture formation continues to alternate between the two sets as the orientation of the greatest tensile stress changes until boudins have reached a stable size such that tensile stress necessary for fracture is not attained [4,5].

During unequal layer parallel extension, a single stage of deformation sequentially produced the two orthogonal sets of ribbon troughs recognized in radar images of Tessera terrain on Venus. Extensional fracturing first divided the brittle layer into long, thin ridges. When local tensional stress along a line parallel to the length of the ridges (always in the middle of the ridge) became greater than tension along the far-field principal tension direction, extensional fractures developed perpendicular to the first ribbon set. Upon continued deformation, successive mid-point fracturing divided ridge blocks into progressively smaller sizes. The increase in the depth of trough floors through time was determined by the rate of deformation compared to the rate of increase in the BDT depth. This is what led to the blocky, stepped pattern of troughs and ridges recognized in Tellus Tessera.

In Alpha Regio, where it is difficult to distinguish two sets of ribbons in one location, unequal layer parallel extension may still account for the existence of the two ribbon suites even though one ribbon set may be absent at a given location. The nearly identical fracture wavelengths of the two ribbon suites suggests broadly synchronous formation. However, where extension in one direction is favored or prohibited by local strain characteristics, the formation of both sets may be impossible even under a far-field unequal layer-parallel tension regime.

References: [1] Hansen & Willis (1996) Icarus 123, 296-312. [2] Hansen & Willis (in press) Icarus. [3] Phillips & Hansen, submitted to Science. [4] Ramberg (1955) J. Geol. 63, 512-526. [5] Ghosh (1988) J. Struct. Geol. 10, 541-553.