CHOCOLATE TABLET ASPECTS OF TECTONICS OF MESHKENET TESSERA ON VENUS

J. RAITALA
Department of Geosciences and Astronomy, University of Oulu, Finland

(Received 23 September, 1996; accepted 12 December 1996)

Abstract. The intrablock deformation of Meshkenet Tessera on Venus is mostly due to responses of the uppermost surface bedrock to tensional stresses. It is found that complex deformation structures within the highland blocks resemble those of formed in chocolate tablet boudinaging which has taken place after original parallel faulting and bar-like crustal block formation. The high-angle tessera structures with varying cross-cutting relations define styles and locations of multiphase deformation most evidently related to local relaxation of tessera topography. Series of progressive or superposed fracturing events with alternating fault directions took place at high angles during this relaxational deformation. Compressional ridges often surround these tesserae.

Key words: Planetary tectonics, Venus.

1. Introduction

Meshkenet Tessera is a 1600 km long and 50 to 340 km wide highland surrounded by plains of Tethus Regio (Figures 1, 2; Barsukov et al., 1986; Basilevsky et al., 1986; Burba, 1988; Head, 1989; Vorder Bruegge and Head, 1989; USGS Map, 1989; Ansan et al., 1991; Solomon et al., 1992; Raitala, 1994a,b). Major troughs divide it into NWW–SEE oriented, en echelon bar-like blocks, possibly more closely connected at one time (Raitala, 1994b). Along the troughs there are indications of strike-slip movements resulting in the en echelon pattern (Ansan et al., 1991; Raitala, 1994a,b). Individual blocks have pronounced fault patterns on their surfaces. Even though the fracture orientation may vary from block to block, they are parallel or perpendicular to the main troughs and have complex mutual cross-cutting relations. These roughly E–W and N–S ridge-valley patterns are possibly produced by relatively uniform tectonic processes. Differences in fracture strikes are interpreted to indicate either strike-slip or rotational "bookshelf" faulting (cf. Lajtai, 1969; Tchalenko, 1970; Deng et al., 1979; Mandl, 1987; Ansan et al., 1991; Raitala, 1994b).

Details of block-interior structures of Meshkenet Tessera with their locations, shapes, geometries, dimensions and mutual relations were studied from Magellan (Saunders et al., 1992) and Venera 15/16 (Barsukov et al., 1986; Basilevsky et al., 1986) data together with the areal topography and morphology in order to identify tectonic events. Observations are discussed in terms of chocolate tablet boudinage in order to gain insight to tessera development.

Earth, Moon and Planets **74:** 191–214, 1996.

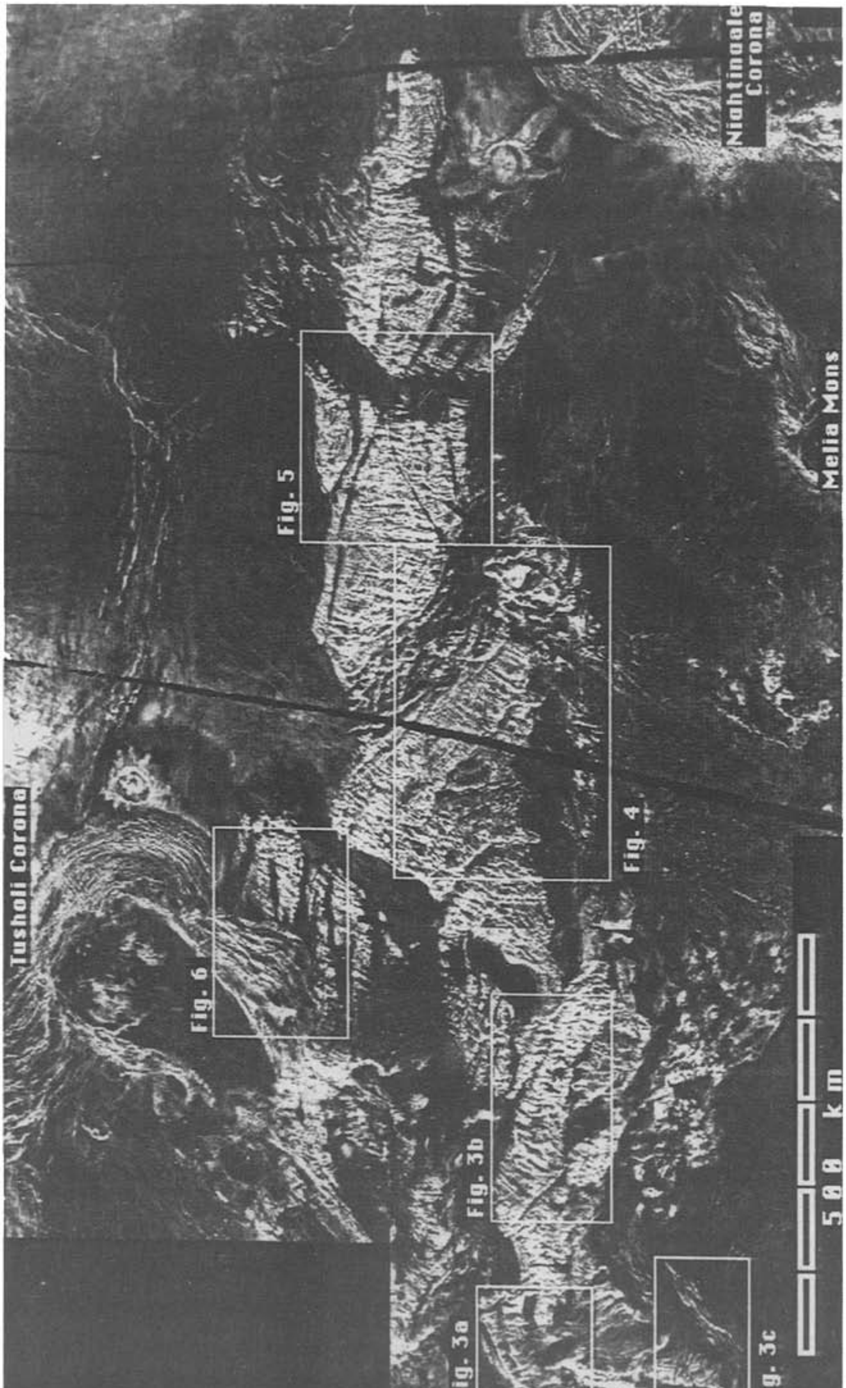

Figure 1. Major semiparallel troughs cut Meshkenet Tessera into several bar-like blocks with WNW orientation. The main trough spacing is roughly 100 km. The floors of these main troughs are mostly covered by lavas. Locations of other figures are indicated by quadrangles.

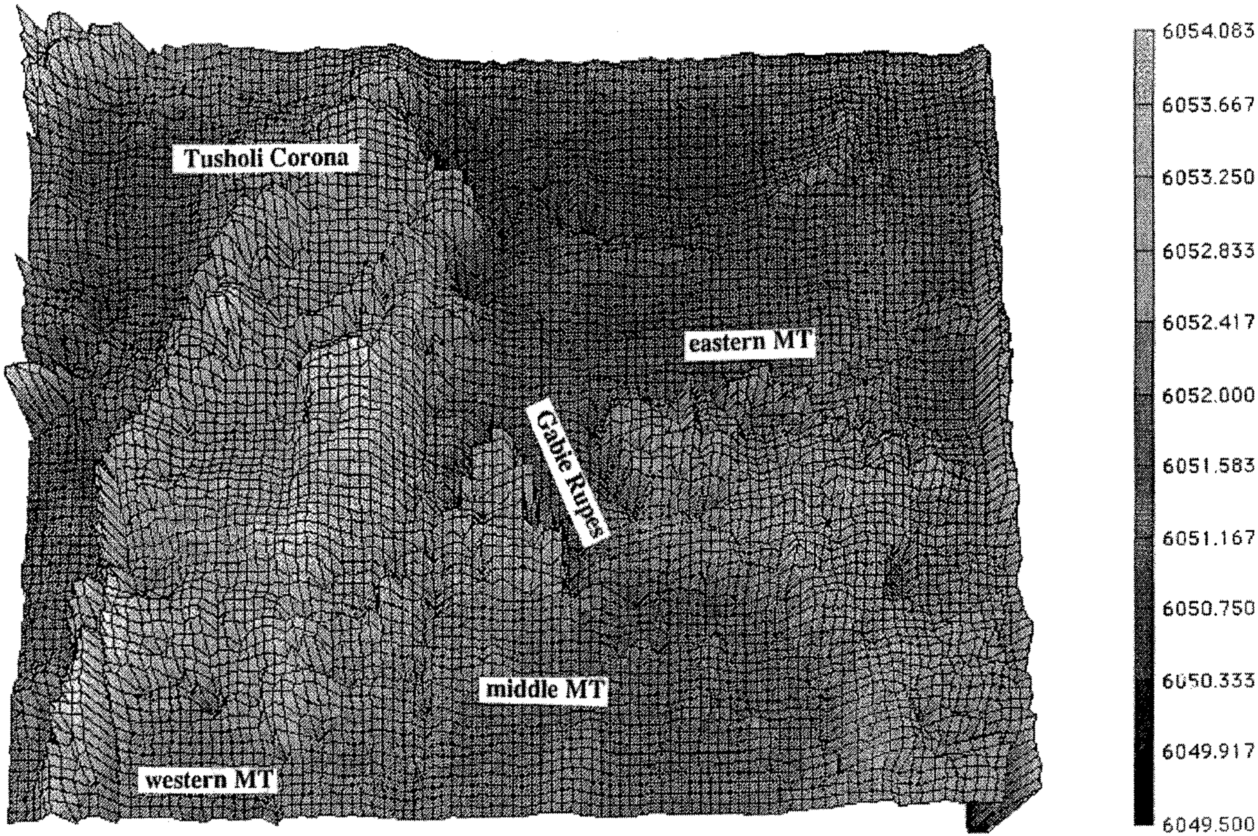

Figure 2. The topography of Meshkenet Tessera is highly variable as shown by the Magellan altimetry data. The western tessera area is the highest one, while the middle and eastern areas are slightly lower. The middle part of Gabie Rupes stands slightly higher than its edges. The doughnut-like high area between western Meshkenet Tessera and Tusholi does not show up in the radar imagery (cf. Figure 1). The area covered is roughly that of Figure 1.

2. Meshkenet Tessera

2.1. THE WESTERNMOST BLOCK

Western Meshkenet Tessera is 2.5 to 3 km high (Figures 1, 2; USGS Map, 1989). Its elongated westernmost part has several massifs separated by depressions or faults (cf. Figure 1). The NW edge is a major NE-SW scarp with several parallel faults (F and P, respectively, in Figure 3a). High-angle faults of the fault zone form a conjugate systems with scarp-parallel faults. These two conjugate fault sets cut almost rectangular tessera blocks in places. Some scarp-parallel faults are older troughs (p1 and p4 in Figure 3a) while other faults (p2 and p3) may be even younger than the perpendicular ones. In spite of the image distortions caused by the radar imaging geometry it is obvious that there are either small offsets along the faults or some fault-bounded blocks are tilted. Age relations between faults indicate sequential and/or relaxational type of the tessera deformation.

The western block is divided into two parts by a long N40° W to N80° W fault trough (Figure 3b), which has numerous cross-cutting high-angle ridges and valleys. There are also numerous trough-parallel faults on the adjoining terrain and the whole tessera is patterned by the two conjugate fracture sets with various cross-cutting relations. Some cross-cutting fractures seem continue onto the lavas which cover the fault trough. These fresh-looking structures are among the youngest fractures identified. Some crossing structures have offsets along the trough scarp, possibly indicating a strike-slip movement (A in Figure 3b). In the middle and southern parts of the NW–SE fault there are lava-filled depressions with relative young conjugate structures continuing from the adjoining tessera onto the lava plain. The main fault represents one of the main rupture deformation phases across the block. Together with the fault-parallel and conjugate ridge-valley fractures it preceeds the activation and formation of the minor faults identified from the lava surface.

The NE border fault of the western block is defined by a lava-filled trough and trough-parallel wrinkle ridges. It is sharp and well-defined fault in the southeast, where it runs across a set of conjugate ridges and valleys (B in Figure 3b). The sigmoidal, ∫-shaped ridges most evidently indicate dextral fault movements. Even though the Magellan radar imaging geometry may cause high ridge crests to move westward, or towards the imaging radar, and their lower parts to move eastward, or away from the radar, a strong case can be made for the drag bending of ridges by dextral strike-slip fault deformation. This is evident when comparing these structures to the other cross-cutting fractures along the middle-block fault which do not display such a strong bending even if they have exactly the same relation to the radar geometry. The crossing, or younger ridges running across the fault show that activity continued after or postdated the main fault formation. Wrinkle ridges and ridge belts of the southern lava plains close to the southern margins of the highland parallel the tessera edges (Figure 3c; cf. also Bindschadler et al., 1992) as if

Figure 3a.

Figure 3. The northwesternmost Meshkenet Tessera (Figure 3a) has troughs and faults (p) which are parallel to the tessera edge scarps (F and P) and which are cut by fractures of a wide high-angle fault zone. There are various cross-cutting relations between the two conjugate fault sets indicating that there are both relatively old (p1 and p4, for example) and relatively young (p2 and p3) faults in the sets. Dense patterns of two cross-cutting faults mostly strike along or across the main border and interior faults of the of the middle western block (Figure 3b). The dense pattern of NNE-SSW faults are cut by the NW–SE-oriented main faults. The northeastern main fault has numerous ∫-shaped conjugate ridges (B), which may denote a westward movement of the whole southwesternmost block related to the more northern area. There are some perpendicular (A′) as well as parallel (A) more recent faults on the lava-covered fault trough surfaces indicating later faulting as well along the main fault as also across the block. The planitia ridge belts border tessera boundary as being compressional (arrows in Figure 3c) structures, possibly due to the down-hill movements or relaxation of the high-lying tessera crust. There are also wrinkle ridges which extend tessera fractures onto the lava surface of the planitia area (broken lines).

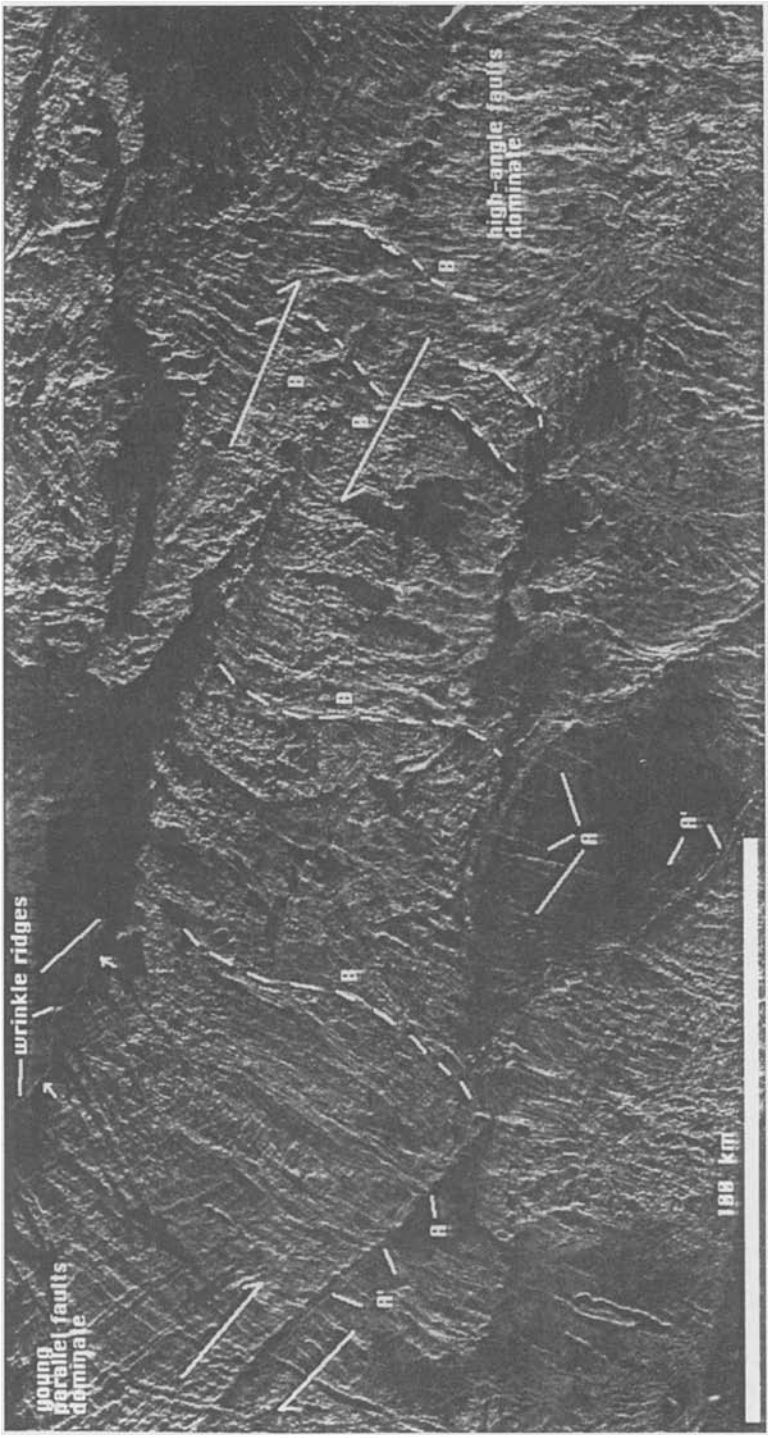
high-angle faults
dominate
wrinkle ridges
young
parallel faults
dominate
B
A
A'
100 km

Figure 3b.

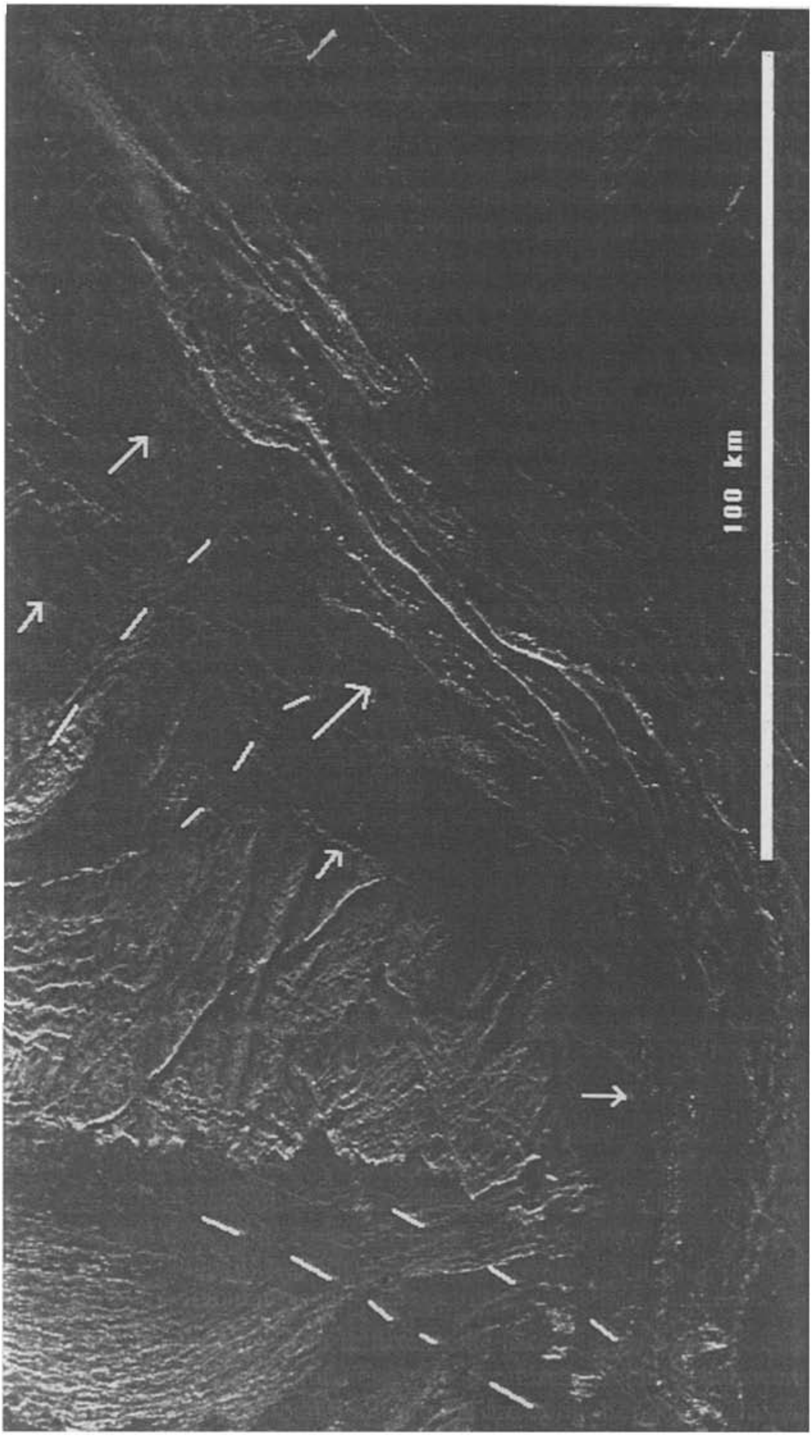

Figure 3c.

there had been rather late, or at least post-lava-emplacement, compression directed from within the tessera block into the surrounding lava field. Some tessera fractures may also continue as compressional wrinkle ridges on lava surfaces indicating late (re)activation of these fractures.

2.2. Middle Blocks

Slightly arcuate troughs, semiparallel to Gabie Rupes, divide the middle tessera area into a few blocks (Figures 1, 4; USGS Map I-2041, 1989). The troughs and Gabie Rupes are all wider at their SE end. The western tessera edge is distinct with tessera terraces. All faults seem to end at the western lava plain which indicates that this lava emplacement has occurred after the faulting.

Surface pattern comprises of ridges and valleys which indicate two fracture directions perpendicular and parallel to Gabie Rupes and other main troughs (Figure 4). It extends over the blocks with slightly varying orientation and with varying cross-cutting relations. The faults parallel to the longer edges of the Meshkenet Tessera highland's bar-like blocks are mostly straight, while the perpendicular structures are more winding, or ʃ-shaped in places. This winding may have been slightly affected by the radar imaging geometry, in which fault ridges crossing low troughs and high ridges may assume a topography-related appearance. In spite of this the winding may be true because it is not found in all similarly oriented faults but only along some of youngest-looking fault zones where ʃ-shaped ridges have counterparts on both sides of the crossing faults. This does thus indicate horizontal displacements (Figure 4) along these crossing faults.

In the northeastern middle area of Meshkenet Tessera (Figure 4) the two high-angle fault sets have various cross-cutting relations. Some edge-parallel faults are younger than the cross-cutting ones while some others are older (Figure 4). Various cross-cutting, and thus also age, relations between the two fracture sets are common. Some fresh-looking parallel faults are connected to Gabie Rupes as if being part of it. The oldest parallel faults are lava-filled troughs with numerous cross-cutting perpendicular ridges. Even though most fractures do not indicate clear movements along faults, some ridges bend at troughs as indicating frictional strike-slip drag along the fault. Their en echelon arrangement indicates a E–W shear in the block movement. The main troughs have formed when the tessera blocks moved apart during a series of strike-slip movements (Raitala, 1994b). Rotation may increase faulting by promoting extra fracturing and trough opening (Mandl, 1987). Intrablock structures may then reflect tensional rupture of the high-lying surface.

The southern middle Meshkenet Tessera area has young, arcuate extensional lava-filled grabens with orientations from NNW–SSE in the southeast to NWW–SEE in the west. These interact with winding N–S faults, which cut the ridge-valley, or fault-graben, pattern perpendicular and parallel to the main troughs (Figure 4). The graben-cutting winding faults are younger than the orthogonal faults because

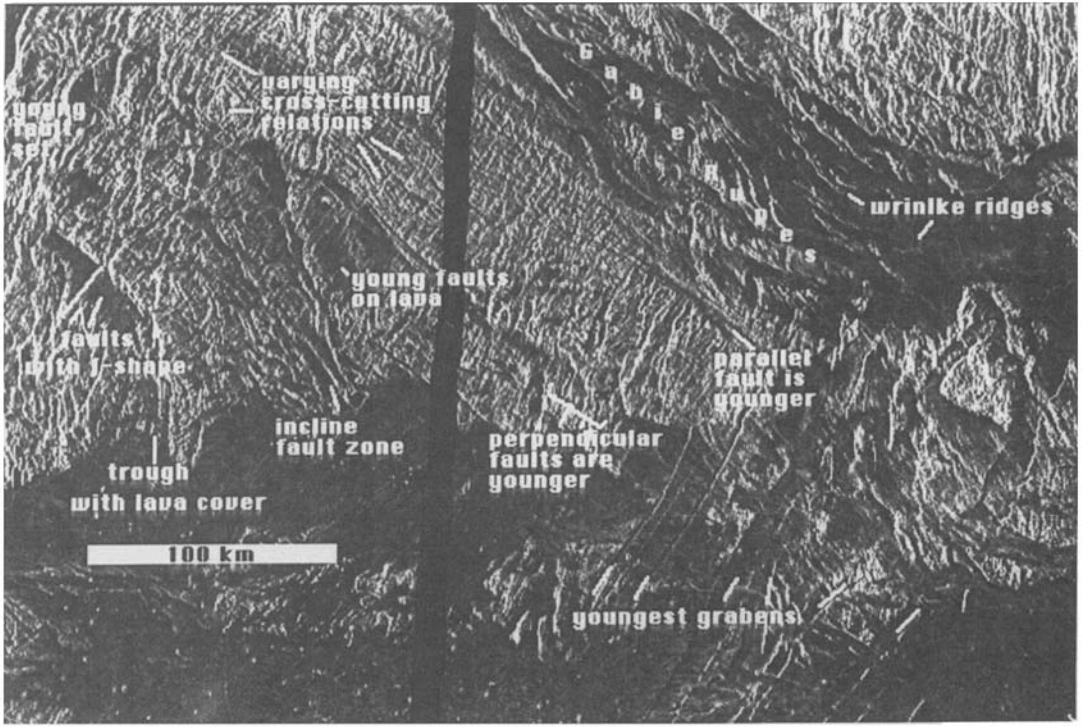

Figure 4. The strikes of the structures in the middle Meshkenet Tessera area display two high-angle fault directions: one fault set is parallel to Gabie Rupes and the other is perpendicular to that direction. The cross-cutting relations vary highly from place to place indicating multiple faulting phases in both directions. Lava-filled main troughs have some ʃ-shaped ridges at their borders as well as some younger fault sets cross-cutting their lava surfaces. The young graben and fracture orientation follows partly that of older fractures in this middle area but there are a few inclined fault zone. Within the easternmost reach of the area there is a set of the youngest grabens which seem to cut across most previous structures excluding lavas and wrinkle ridges of the eastern Gabie Rupes. A fresh-looking, inclined fracture set forms slightly winding zones across the tessera area. Their ʃ-shaped outlook may indicate the existence of rather late movements along the faults themselves as well as along their conjugate faults parallel to Gabie Rupes (cf. Raitala and Törmänen, 1989).

they cut across them. They interact with older fractures by assuming an old strike for some distance. Some young N–S ridges cross the main troughs in places within the western middle Meshkenet Tessera where they form wrinkle ridge-like zones. A major lava-flooded trough surface is transsected by various fault-related wrinkle ridges indicating probably one of the youngest phases of regional multitemporal deformation. Young linear NNE-SSW grabens (Figure 4) which cut through the easternmost part of the middle Meshkenet Tessera area represent an individual tectonic phase of their own which is related to Nightingale Corona (Figure 1).

2.3. Northeastern Blocks

Northern Meshkenet Tessera (Figures 1, 5; USGS Map I-2041, 1989) consists of several bar-shaped, triangle and wedge-shaped blocks divided by E–W, N60°–80° W and N50°–70° E troughs. The sharp-edged ENE–WSW -trending trough (D's in Figure 5) is the most fresh-looking one and cuts across all other tessera structures. It is fairly distinct while most of the NW–SE troughs are more degraded, resembling lava-flooded graben depressions (B's in Figure 5). These wider throughs are cut by perpendicular wrinkle ridges in many locations, especially in the middle of the area. The major blocks have several strong, areally alternating fracture patterns across them (C and E in Figure 5). The majority of the ridges and valleys are linear structures with N–S or NEN–SWS trends. Some fractures also have a WNW–ESE orientation along the blocks. Zones with alternating parallel ridges and valleys of similar size are mostly areally concentrated within block interiors, where they cross-cut other structures similar in relative appearance and thus also in tectonic importance.

The southern area (Figure 5) has wide, lava-flooded WNW-ESE grabens and indications of different tectonic phases. Wrinkle ridges are younger than the lavas they locate on. One trough has numerous penetrating perpendicular wrinkle ridges deforming its lava surface due to later tectonics (middle B, ridges E in Figure 5), while the southern trough in the same figure is only partly deformed at its eastern end by these ridges (lower trough B and its crossing ridges E in Figure 5). Some ridges bend as if they would be drag structures caused by movements along the trough. Sinusoidal ∫-shape ridges indicates deflection along the trough which is caused by dextral strike-slip movements along a fault. The last tectonic phase is defined by the straight, narrow graben (D in Figure 5) which crosses older lavas and tessera block fractures. Some N–S ridge-valley bands seem to extend across the block boundary into the southern lava plain while there are also E–W structures continuing the overall strike of main troughs on the eastern lava surface. They are more numerous at the trough continuation as well as on the southern side of the tessera block (Figure 5).

Several deformation phases can easily be identified from the northern tessera area (Figure 5). Long, tessera block-parallel, lava-flooded troughs (B in Figure 5) cut the fractured tessera border area into bar-like blocks indicating the oldest

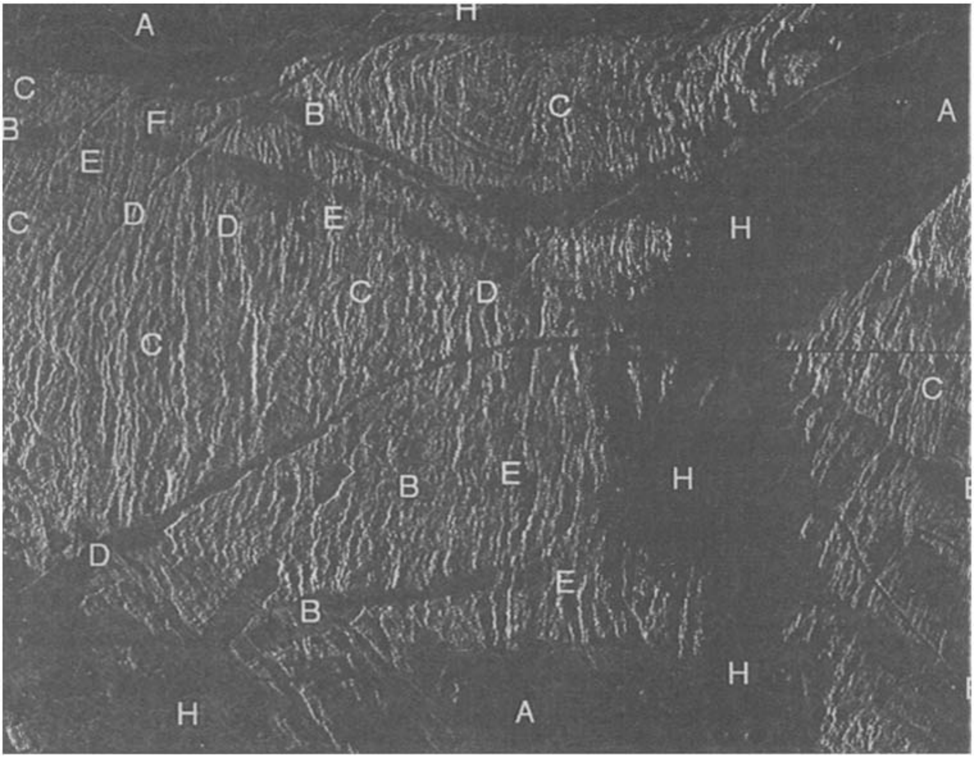

Figure 5. The multiple, or superposed, fault deformation is the most obvious within the northern Meshkenet Tessera (C). Lava-filled faults (B) contribute to bar and wedge-like tessera block formation. Younger fractures (E) cross major lava-filled troughs in several places and relatively fresh-looking grabens (D) represent an another, more recent fault generation. There are rather complicate cross-cutting relations between various tessera fractures, faults and grabens. Edge-parallel, lava-flooded troughs cut most of the two perpendicular fracture patterns. Some more recent high- and low-angle fractures (F) cut lavas in places while even youngest grabens are covered by wrinkle ridge-patterned (H) lavas of the surrounding plains (A).

deformation phase. Lavas in these troughs cover most of the high-angle fractures, but some fault-related wrinkle ridges are seen on the lavas in places (E in Figure 5). Lavas cover also most of the low-angle faults (C in Figure 5) but some traces of these faults are seen to cross the lava surface in troughs (the westernmost graben B). The covered fractures represent the existence of two older fault activity phases while the lava-crossing fractures indicate later fault re-activation (F in Figure 5). Narrow, arcuate young grabens cross all the previous structures (D in Figure 5) being among the youngest tessera faults. Even these relatively young grabens are covered by the lavas of the northern lava plains. Linear E–W -trending wrinkle ridges located on the lava plains along the tessera block boundary and continuing between some tessera fractures (A and H in Figure 5) represent the youngest tectonic activity of the area.

2.4. The Tusholi Blocks

The tessera blocks which are located to the east from the eastward-facing Tusholi scarp are separated by lava-filled, E–W oriented troughs, the strike of which approximately continue that of the main Meshkenet Tessera ones (Figures 1, 6). This Tusholi tessera area with its fault grabens may be considered to be a remote extension of the main Meshkenet Tessera area. Beside the E–W grabens there are also more N–S oriented fractures approximately perpendicular to the troughs. The high-angle fractures adopt an $\int$-shape at most of the E–W troughs. This $\int$-shape matches well with bending due to dextral strike-slip fault movements. The relative tessera block movements can be interpret to have been dextral, the southernmost blocks having the largest relative movement from east to west. There fact that tessera troughs do not continue across the Tusholi scarp suggests that the scarp is more recent (Figures 1, 6). There have even been proposals of underthrusting of the tessera terrain below the Tusholi formation (Black and Raitala, 1993).

3. Main Block Tectonics

The obvious regularity in the fracture spacing within every tessera area studied (Figures 3–6) reflects the degree of uniformity in tessera layers and in their tectonic deformation (Zuber, 1987; Zuber and Parmentier, 1990; Banerdt and Golombek, 1988; Banerdt and Sammis, 1992). A common explanation for en echelon block formation is needed, as the blocks retain their parallel orientation, as if the main faults were formed by rather uniform large-scale forces in a laterally homogenic material. Various stresses (cf. Ansan et al., 1991) may have contributed to the deformation of Meshkenet Tessera. The en echelon block configuration can be explained by pure right-lateral strike-slip faulting caused by N–S compression (Barsukov et al., 1986, Raitala, 1994b), a 'bookshelf'-type dextral faulting and anticlockwise rotation (cf. Mandl, 1987), E–W compression (Basilevsky et al., 1986, Raitala, 1994a,b) or horizontal forces (Head, 1989). Inclined faults and triangular blocks of northern Meshkenet Tessera may indicate some additional N–S compression and adjoining movements. More complicated fracture sets found within tessera block interiors then display more local deformation of the uppermost tessera crust.

Faulting has had several complex, superimposed or multitemporal events. Parallel to subparallel major dextral shear faults (Raitala, 1994b) across Meshkenet Tessera resulted in a number of bar-like blocks, which represent re-located remnants of a previous, more uniform tessera unit (Figure 7a,b). The en echelon arrangement was due to this dextral shearing together with an additional rotational component (cf. Mandl, 1987). In addition to the most important E–W shear faulting a partial 'bookshelf'-type mechanism may have added some nuances because fracture orientations slightly vary from one block to another and the fault geometries do not

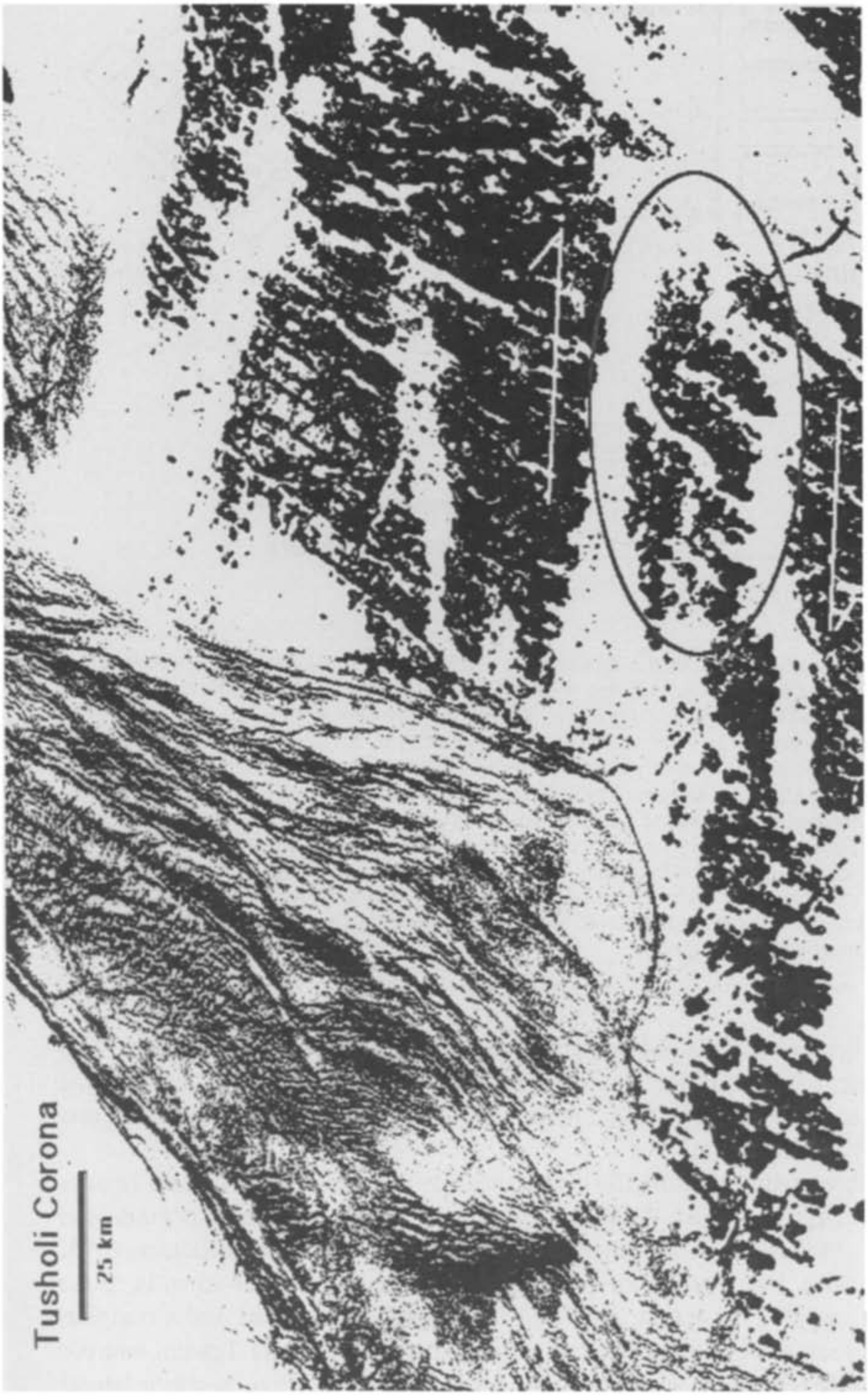

Figure 6. This image of the area representing the southern Tusholi ridge belt and scarp (in the upper left) together with its near-by tessera units (on the right and lower part) is made by decreasing image tones to black (Tusholi and tessera ridges) and white (valleys and lava planitiae). There is a clear difference in texture between the more rough blocky outlook of the tessera ridges and the more smooth appearance of the Tusholi ridges. All tessera structures end abruptly at the Tusholi scarp. The grey-lined ovoidal area displays how the structures across tessera blocks turn to be more sigmoidal at the edges of straight lava-filled fault troughs which divide these tessera blocks into several bar-like units. Arrows indicate dextral movements along the lava-covered faults.

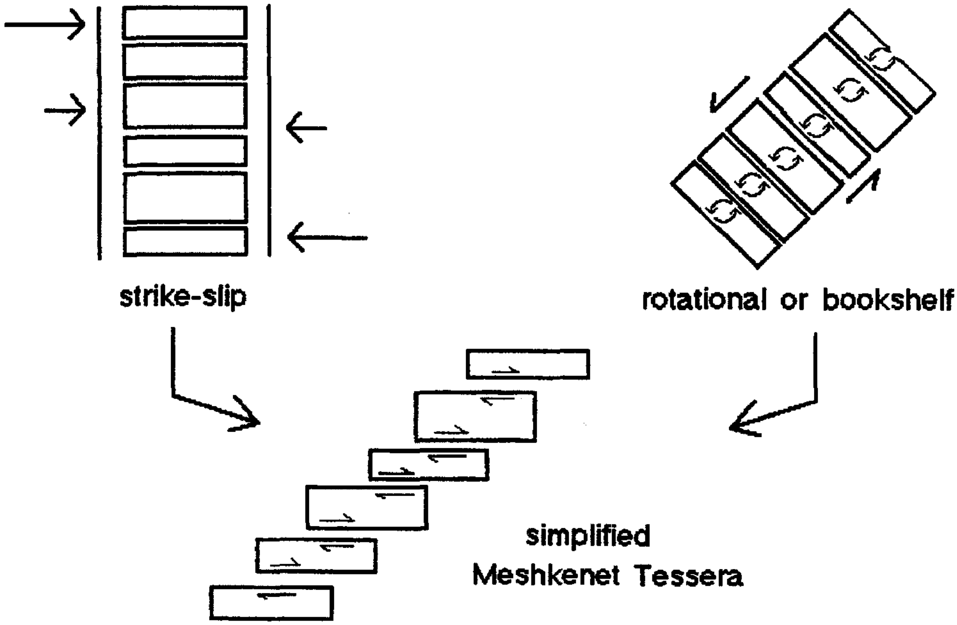

Figure 7a.

Figure 7. Generalized sketch of the development of en echelon structures during an early phase Meshkenet Tessera deformation. This step-wise configuration consists of bar-like blocks and mostly dextral, parallel faults between them (Figure 7a). The proposed movements may include the alternative that the southernmost blocks were moved westward relatively to the more northern tessera blocks (Figure 7a, upper left side), evidently due to the obstruction by Ishtar Terra in the north, as indicated by structural units at Tusholi Corona (Figure 6; Black and Raitala, 1993). Another possibility is the domino-like rotation of the blocks (Figure 7a, upper right side, cf. Mandl, 1987). The tectonic sketch of the area (Figure 7b) is drawn on the simplified radar image background where radar-dark lava plains are black. The present interpretation favours the first alternative (Figure 7a, upper left side) where main troughs are interpreted as strike-slip faults (cf. Raitala, 1994b). Domino-like rotation may have taken place but it has not played a major role in main deformation. The area covered in Figure 7b is roughly that of Figure 1.

quite match, assuming that the movements along the faults were reversed only by a simple shear. Lateral faulting with accompanying slight rotation will explain some of the observed differences (e.g. Freund, 1974; Ron et al., 1984; Garfunkel and Ron, 1985; Mandl, 1987).

Areal shear (Ansan et al., 1991) is indicated in the northern Fortuna Tessera (Vorder Bruegge and Head, 1989; USGS Map, 1989), Audra Planitia (Raitala and Törmänen, 1989; Raitala, 1994a) and the Tusholi scarp (Black and Raitala, 1993; Raitala, 1994a). Large-scale horizontal movement on Venus may directly relate to vertical mantle convection translated into lateral ones (Head and Crumpler, 1990; Solomon et al., 1992). Stresses originating from Fortuna Tessera and the major coronae (Stofan et al., 1992) have been able to contribute to major lateral movements and break the original tessera into pieces resulting in block formation


Nightingale Corona
Melia Mons
Tusholi Corona
Ishtar Terra
200 km

Figure 7b.

under repetitive parallel direct shears (Raitala, 1994b). Some of the youngest graben faults which geometrically relate to coronae indicate such connections. Corona-radial and -concentric structures are controlled by forces related to that particular corona. Ridges connecting two adjoining coronae have also clear corona-related aspects (Stofan et al., 1992). Definite genetic evidences of their origin remain, however, obscure due to volcanism and our incomplete understanding of the style of Cytherean geologic development.

4. Intra-Block Tectonics

4.1. Chocolate Tablet Boudinage

The even distribution of individual faults in two orthogonal or almost-perpendicular fault sets within Cytherean tessera highland blocks is confirmed by the observations described in previous chapters. Actually, the faulting has been more complicated if the whole time sequence is taken into account with re-activation of various faults and their varying cross-cutting relations. The studied Venusian intra-tessera fault sets resemble chocolate tablet boudinage fractures which are formed in several terestrial geological locations and obtained in laboratory experiments. Such chocolate tablet boudinage structures are caused by a layer-parallel extension in two directions, resulting in boudinaging, or a series of three-dimensional blocks in the surface layer (Ramsay and Huber, 1983; Hatcher, 1990, pp. 404–406). Two such sets of boudin neckline fractures at right angles to each other have been described by a number of authors (e.g. Ramberg, 1955; Ramsay, 1967; Casey et al., 1983; Ghosh, 1988) as developing in relaxational or superposed deformations, elongating the rocks in two surface- parallel dimensions (Figure 8). This chapter summarises some of the results obtained by the other authors and tries to understand how closely they could be matched with observations of Venusian intra-tessera faults.

Structure sets resembling those formed in chocolate tablet boudinaging experiments (Ghosh, 1988) were found and mapped from the Magellan radar imagery. The planview of these structure sets is well displayed on the elevated tessera blocks, the surfaces of which are defined by two fracture sets, or boudin axes or neck lines, approximately at a high angle or perpendicular to each other. The fractures have these two orientations over the whole Meshkenet Tessera, with some slight rotation from place to place. It seems like fault and boudinage formation within Meshkenet Tessera have been associated to the partial relaxation of the high topography. Long axis of boudins parallel main fault troughs while neck lines roughly transverse them. If both structures developed during a progressive deformation, the bedrock lineation has been greater in the direction parallel to the main troughs than perpendicular to them. The chocolate tablet fractures were thus formed by a series of superposed deformations, with the development of a second, third etc. generation of neck structures sub-normal to the previous boudin axes. Even if the actual initi-

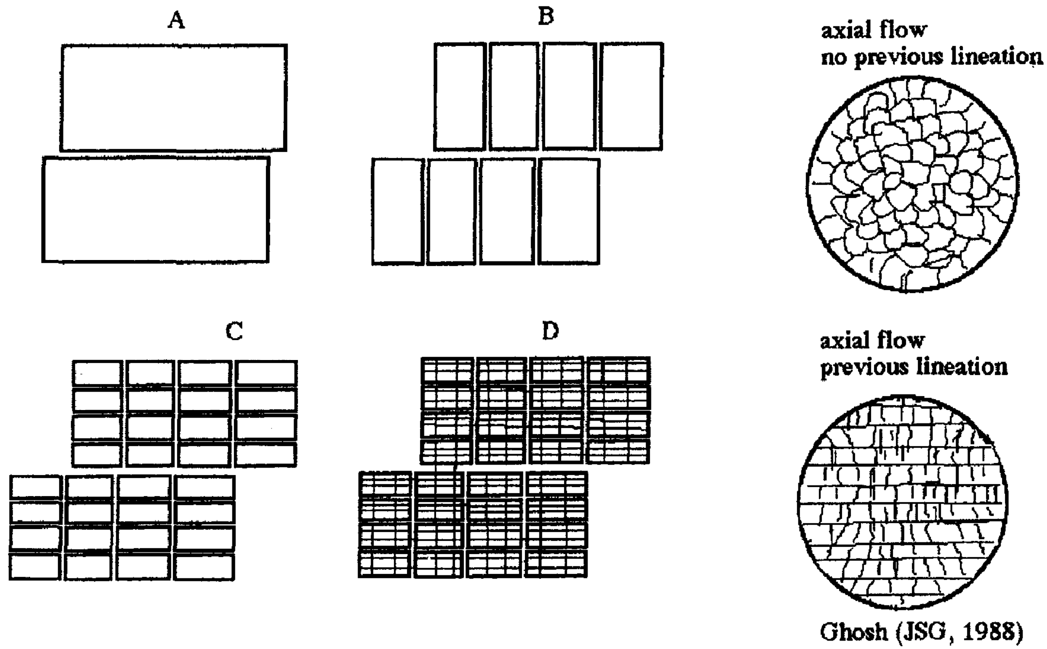

Figure 8a. Practically uniform structure geometry and appearance over large areas indicate wide uniform stress field during a certain tectonic phase. This may have been the case if the main troughs and blocks were more original and due to large-scale tectonic forces originating from surrounding areas (Raitala, 1994a) while intra-block fractures were derived from partial relaxation of previous high-lying surface patterned by the preceeding lineation and laying on a surface-parallel less viscous matrix (Ghosh, 1988). Intra-block fractures have complex cross-cutting relations with each other and with main faults (Figure 8a, cf. also Figures 2–5). Fracturing, as found in laboratory-scale chocolate tablet experiments without any preceeding lineation (Figure 8a, upper right) and with a preceeding lineation (Figure 8a, lower right; Ghosh, 1988), indicates that both the preceeding parallel faults and the bar-like shape of the Meshkenet Tessera blocks have been important during the late relaxational deformation of the area (Figure 8b). The uppermost tessera crust was tensional over a hypothetical, weak intracrustal or lower crustal layer (Buck, 1992) while ridges and ridge belts along tessera boundary (Figure 3c) were compressional (Bindschadler et al., 1992). Present approach does not allow to draw any conclusions of the crust/lithosphere - astenosphere boundary (question marks in Figure 8b; cf. also dry diabase studies of Mackwell and Kohlstedt, 1993) during the rise and relaxation of the high elevation (Vorder Bruegge and Head, 1991).

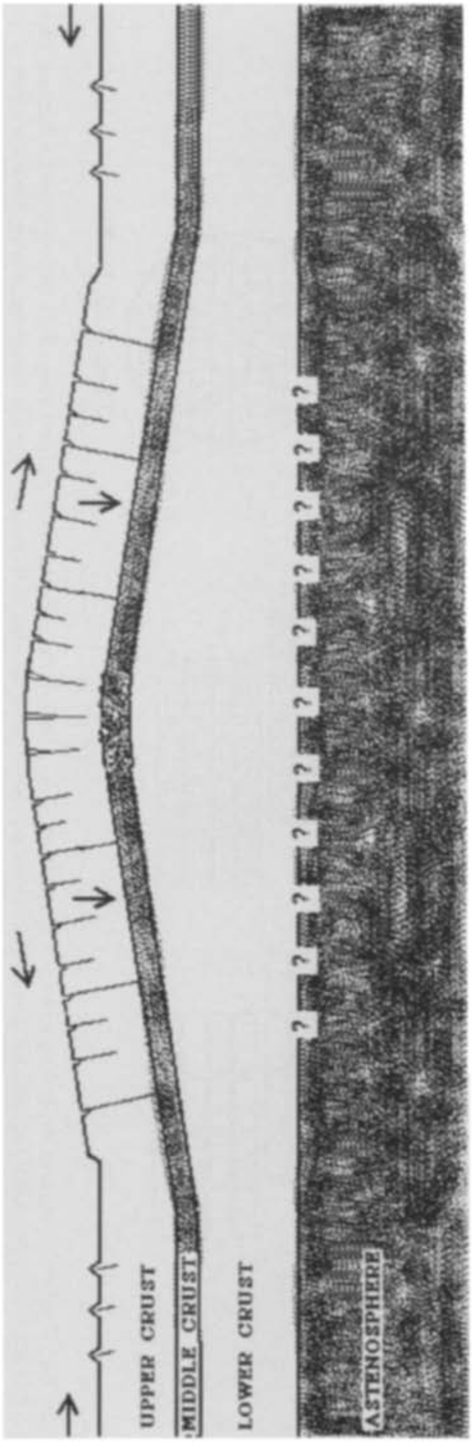

Figure 8b.

ation of chocolate tablet boudinage on Meshkenet Tessera remains obscure, some statements can be made.

A matrix flow which is equal in all directions results in extensional brittle surface fractures without any preferred orientation (Ramberg, 1955). The remarkable uniformity in the direction of the two prominent boudin axes over whole the Meshkenet Tessera does thus not depend only on boudinage caused by axially symmetric matrix flow. Relaxation of a previous topography can not be the sole cause of the simultaneous development of two orthogonal surface fracture sets (cf. Ramsay, 1967; Sanderson, 1974). Unequal layer-parallel matrix flow results in fractures perpendicular to the maximum extension and the preceeding anisotropy and the contrast in ductility in different directions in a lineated surface rock greatly affects the development of boudinage (Ghosh, 1988). The first boudinage formation represents the first-phase viscous matrix drag effects on the surface, where fracturing depends on the stress rate and the dimensions and physical properties of the uppermost rocks. Later superposed deformation structures do not depend so much on the principal matrix flow but on the shape and orientation of the first generation boudins.

The boudinage fracturing of Meshkenet Tessera could have taken place due to a viscous force acting from below. Tessera areas represent elevated surface units on a planet with its surface temperature close to the Curie point, i.e. the temperature where rock crystals can become re-disoriented if they have any previous magnetic orientation. The high surface temperature together with the 15°/km to 20°/km temperature gradient results in thin, brittle uppermost units overlying more mobile layers. A viscous drag is imposed on the surface plate if the underlying viscous layers stick firmly enough to the brittle unit floating on this viscous material (Ghosh, 1988).

4.2. Various Cases of Boudinaging

An axially symmetric extension or subsurface flow crack the surface randomly with no preferred orientation (Ghosh, 1988). Roundish or polygonal boudins are then common, with radial fractures found only in a peripheral zone where radial stresses vanish leaving only the tangential ones. Perpendicular extensional fractures are thus formed only within narrow rectangular bars. A lineated surface plate and an axial flow in the subsurface layer produces fractures parallel to the lineation. A continuous matrix flow opens up gaps between the bars and breaks parallel boudins into rectangular parts by perpendicular fractures. The first fracture set is controlled by the lineation and the second set by the long axis of the first (Figure 8a; Ramberg, 1955; Ghosh, 1988).

Non-uniform extension is also possible if tensional fractures are first formed at right angles to the greatest tension and later, with progressive deformation, perpendicular to the direction of medium stress. A relaxational deformation is able to produce two sequential sets of orthogonal fractures if the plate is first cut into narrow strips perpendicular to the maximum tensional stress and parallel to the medium tensional stress. The actual stress direction is unimportant, as in the case of a narrow crustal bar a perpendicular fracture set is independent of the angle of maximum extension, as if entirely controlled by the bar geometry. Progressive deformation then results in second fractures just at right angles to the first set. This is evident during superposed deformation of a chocolate tablet boudinage, where the long, narrow first set boudins are cut by the second generation structures despite the orientation of the strain directions (Ghosh, 1988). Each one of the boudin blocks are further extended and subsequently broken by the next-generation fractures.

Previous weak zones, lineations or faults in the underlying stratum result in fracture formation parallel and perpendicular to the preceeding structures, producing longitudinal and transverse fractures. The lineation being roughly perpendicular to the maximum tension, longitudinal fractures are generated first. If the lineation roughly parallels the maximum tension the first fracture direction depends on the surface rock tension strengths in the two directions.

The two conjugate fracture sets are formed either successively by a progressive deformation or as the result of unrelated superposed deformations. The first case allows some conclusions regarding the stress field, but the second case gives only some hints of the stresses involved. All previous or additional structures further complicate the situation and make detailed analyses more difficult. Boudinage in narrow bars oblique to a matrix layer with uniaxial extension produces second generation perpendicular boudins. The final geometry of such structures is independent of whether the two sets are due to superposed or progressive deformation (Ghosh, 1988).

4.3. Boudinage Tectonics

The primary main faults of Meshkenet Tessera were generated by independent faulting of surface layer. Any additional subsurface flow may then have been caused either by layer-normal compression or by gravitational relaxation of high elevation. The surface can be explained to display two-dimensional boudinaging of a brittle layer under relaxation deformation with tension in the underlying matrix (Figure 8). The two high angle fracture sets and the lack of roundish boudins indicate either preceeding lineation or that the surface-parallel flow was directional rather than equal in all directions. The two fracture sets are not simultaneous, but rather progressive or superposed.

Tension produces extensional fractures and bars or boudins at right angles to the maximum tension. They are also controlled by the physics and dimensions of the rocks. If tension continues and the bars generated are long and narrow, the local medium range stress component along the boudin increases to break the boudin bars into smaller rectangular pieces. These two successive alternative fracturing steps result in a complex boudinage faulting in two intersecting directions. Large differences in tensile strength in different directions modify the boudinaging. A pre-existing lineation reduces the surface plate strength so that the first set of fractures may develop perpendicular to either the maximum or medium stress depending on the lineation and relative stresses. The second fracture set develops at right angles to the first.

If two deformations are successive but unrelated, the first faulting and later boudinage event are more or less unrelated, so that neither of the sets is indicative of the second stress direction. Two superposed separate events of tension produce two boudin fault sets roughly at right angles to each other, especially if the first faults produce long, narrow bars and the second phase is uniform enough over the whole area. Even if the second-generation boudin formation is oblique to the tension, the boudin direction will be defined by the first faults.

5. Concluding Remarks

Being relative restricted in size Meshkenet Tessera does not fall to any of the three types of highland areas defined by Solomon et al. (1992). Most closely it may resemble the Ovda type with rather shallow apparent depth of compensation, complex tectonics and limited volcanism (Bindschadler et al., 1992; Smrekar and Phillips, 1991). Meshkenet Tessera has many tectonic structures similar to those of other Ovda- type highlands. The clear pattern of parallel troughs dividing the lenghty highland into bar-like blocks, which preceeds perpendicular fracture sets caused by lateral extension, is, however, characteristic to the area (Raitala, 1994b). Tectonic events may thus be qualitatively similar to those found from other highlands of this type and only the actual sequence is different due to local crustal and stress environment.

While planitia ridge belts around tesserae are of compressional origin (Bindschadler et al., 1992), the fractures within Meshkenet Tessera are associated with tensional stress (Solomon et al., 1992; Bindschadler et al., 1992), initiated first by upward swelling and then deformed by partial relaxation of the high topography. Observed crossing high angle fractures, resembling those of chocolate tablet boudinaging, mainly display, with some additional local variations, the two sets of boudin axes, where long faults parallel block boundaries and neck fractures run across them.

The very first phase of areal deformation may have had several phases including upward swelling, fracturing and dextral shear faulting contributing to parallel block formation (Figures 7, 8; cf. also Ansan et al., 1991). An upswelling mantle plume together with a massive partial melting in the plume head results first in a broad domical uplifted crustal plateau (Herrick and Phillips, 1990; Phillips et al., 1991; Solomon et al., 1992). With vanishing plume activity the high topography begins to collapse resulting the tension within the blocks to be a uniform layer-parallel tension. Surface fracturing then depends on the stresses due to the lower crustal creep and the dimensions and physical properties of the surface bedrocks (Phillips et al., 1991; Solomon et al., 1992).

Without any preceeding lineation, a uniform layer-parallel tension should have resulted in fracture opening without any preferred main orientation (cf. Ghosh, 1988). The observed two perpendicular fault sets of possible chocolate tablet boudinaging of Meshkenet Tessera were initiated and guided by previous parallel faults or other such inhomogeneities or lineations in the surface bedrock layers. The observed two perpendicular fracture sets suggest that most orthogonal fractures of Meshkenet Tessera are due to two-dimensional boudinage in the brittle surface layer with one parallel pre-boudinage lineation. Previous strike-slip faulting may have caused or increased the linearity of the surface material and increased its pre-boudinage inhomogenity and lineation. Existence preceding two or more incline lineations might otherwise have diverted the angle between the two fracture sets away from 90°.

Extension of the originally fault-lineated rocks resulted in the boudin axes running parallel to the lineation and the neck lines at a high angle to it. The deformation due to the partial relaxation of the high topography resulted in the development of two fracture sets. The formation of fault-parallel boudinage represents the first main tectonic phase, in which a layer-parallel underlying strain resulted in parallel fractures. Pre-existent anisotropies affected the development of boudin set formation by means of a progressive or continued deformation. All the boudin sets were originally controlled by the main block properties and geometry. The second, third etc. generations of boudin fractures resulted in superposed deformations in a progressive or continuous series so that the later, superposed structures were alternatively perpendicular and parallel to the first one. The extension may have varied between parallel and perpendicular to the lineation, or else the matrix flow was higher along the lineation than across it. In both cases relaxation may have produced tensional fractures, while the transverse flow would have caused perpendicular structures.

Boudinage of a surface layer consists of successive mid-point fracturings. If there is a large matrix deformation before any fracturing takes place, tensional fractures will develop at once. This was not the case in Meshkenet Tessera, which has main cross-cutting parallel primary faults, although simultaneous fracturing may have played some role within individual blocks. In the case of chocolate tablet boudinage, pre-existing faults and lineation may have given rise to the two sets of extension fractures running parallel or perpendicular to them. Boudins will first form more easily along the lineation than across it, even if the lineation is not normal to the maximal tension. In addition to the prominent fault-parallel fracturing, perpendicular fractures are well-developed within the Meshkenet blocks, indicating at least a two-phase boudinaging.

Acknowledgements

The Magellan and Venera 15/16 data were provided by NASA JPL and RPIFs and by the V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry of the USSR Academy of Sciences, respectively. I extend my warmest thanks to colleagues at these institutions as well as to Dr. Martin Black and Mr. Timo Tokkonen of University of Oulu who helped to develop ideas and exploit the data. The research was financially supported by Finnish Academy.

References

Ansan, V., Masson, Ph. and Sotin, C.: 1991, 'Tectonic Analysis of Meshkenet Regio of Venus from Venera 15 and 16 Data.', *Lunar and Planetary Science* **XXII**, 29–30.

Banerdt, W. B. and Golombek, M. P.: 1988., 'Deformational Models of Rifting and Folding on Venus', *J. Geophys. Res.* **93**, 4759–4772.

Banerdt, W. B. and Sammis, C. G.: 1992, 'Small-Scale Fracture Patterns on the Volcanic Plains of Venus', *J. Geophys. Res.* **97**, 16,149–16,166.

Barsukov, V. L., Basilevsky, A. T., Burba, G. A., Bobinna, N. N., Kryuchkov, V. P., Kuzmin, R. O., Nikolaeva, O. V., Pronin, A. A., Ronca, L. B., Chernaya, I. M., Shashkina, V. P., Garanin, A. V., Kushky, E. R., Markov, M. S., Sukhanov, A. L., Kotelnikov, V. A., Rzhiga, O. N., Petrov, G. M., Aleksandrov, Yu. N., Sidorenko, A. I., Bogomolov, A. F., Skrypnik, G. I., Bergman, M. Yu., Kudrin, L. V., Bokshtein, M. A., Kronrod, M. A., Chochia, P. A., Tyuflin, Yu. S., Kadnichansky , S. A. and Akim, E..L.: 1986., 'The Geology and Geomorphology of the Venus Surface as Revealed by the Radar Images Obtained by Veneras 15 and 16', *J. Geophys. Res.* **91**, D378–D398.

Basilevsky, A. T., Pronin, A. A., Ronca, L. B., Kryuchkov, V. P., Sukhanov, A. L. and Markov, M. S.: 1986, 'Styles of Tectonic Deformations on Venus: Analysis of Veneras 15 and 16 Data', *J. Geophys. Res.* **91**, D399–D411.

Bindschadler, D. L. and Parmentier, E. M.: 1992, 'Mantle Flow Tectonics: The Influence of a Ductile Lower Crust and Implications for the Formation of Topographic Uplands on Venus', *J. Geophys. Res.* **95**, 21,329–21,344.

Black, M. and Raitala, J.: 1993, 'Crustal Bending at Tusholi Scarp and Salme Dorsa', *EOS* **84**, 378.

Buck, W. R.: 1992, 'Global Decoupling of Crust and Mantle: Implications for Topography, Geoid and Mantle Viscosity on Venus', *Geophys Res. Lett.* **19**, 2,111–2,114.

Burba, G. A.: 1988, *Names of Venus' Surface Structures*, Nauka, Moscow (in Russian).

Casey, M., Dietrich, D. and Ramsay, J. G.: 1983, 'Methods of Determining Deformation History for Chocolate Tablet Boudinage with Fibrous Crystals', *Tectonophysics* **92**, 211–239.

Deng, Q. D., Chang, Y., Hsu, K. and Fan, F.: 1979. 'On the Tectonic Stress Field in China and its Relation to Plate Movement', *Phys. Earth Planet Inter.* **18**, 257–273.

Freund, R.: 1974, 'Kinematics of Transform and Transcurrent Faults', *Tectonophysics* **21**, 93–134.

Garfunkel, Z. and Ron, H.: 1985., 'Block Rotation and Deformation by Strike-Slip Faults 2. The Properties of a Type of Macroscopic Discontinuous Deformation', *J. Geophys. Res.* **90**, 8,589–8,602.

Ghosh, S. K.: 1988, 'Theory of Chocolate Tablet Boudinage', *J. Structural Geol.* **10**, 541–553.

Hatcher, R. D.: 1990., *Structural Geology*, Merril Publishing Co., Columbus, Ohio.

Head, J. W.: 1989., 'Basic Assemblages of Geologic Units in the Venus Northern Hemisphere', *Lunar Planet. Sci.* **XX**, 392–393.

Head, J. W. and Crumpler, L. S.: 1990, 'Venus Geology and Tectonics: Hotspots and Crustal Spreading Models and Questions for the Magellan Mission', *Nature* **346**, 525–533.

Lajtai, E. Z.: 1969, 'Mechanics of Second Order Faults and Tension Gashes', *Geol. Soc. Am. Bull.* **80**, 2,253–2,272.

Mackwell, S. J. and Kohlstedt, D. L.: 1993, 'High Temperature Deformation of Diabase: Implications for Tectonics of Venus', *EOS Trans.* **74**, 378.

Mandl, G.: 1987, 'Tectonic Deformation by Rotating Parallel Faults: The "bookshelf" Mechanism', *Tectonophysics* **141**, 277–316.
Raitala, J.: 1994a, 'Crustal Tectonic Zone on Venus', *Earth, Moon and Planets* **64**, 155–164.
Raitala, J.: 1994b, 'Main fault Tectonics of Meshkenet Tessera on Venus', *Earth, Moon and Planets* **65**, 55–70.
Raitala, J. and Törmänen, T.: 1989, *Tectonics of Meshkenet Tessera*, 10th Vernadsky-Brown Microsymposium, Abstracts, Vol. 2, pp. 45–46.
Ramberg, H.: 1955, 'Natural and Experimental Boudinage and Pinch-Andswell Structures', *J. Geol.* **63**, 512–526.
Ramsay, J. G.: 1967, *Folding and Fracturing of Rocks*, McGraw-Hill, New York.
Ramsay, J. G. and Huber, M. I.: 1983, *Modern Structural Geology*, Academic Press, New York.
Ron, H., Freund, R. and Garfunkel, Z.: 1984, 'Block Rotation by Strike-Slip Faulting: Structural and Paleomagnetic Evidence', *Geophys. Res.* **89**, 6,256–6,270.
Sanderson, D. J.: 1974, 'Patterns of Boudinage and Apparent Stretching Lineation Developed in Folded Rocks', *J. Geol.* **82**, 651–661.
Saunders, R. S., Spear, A. J., Allin, P. C., Austin, R. S., Berman, A. L., Chandler, R. C., Clark, J., DeCharon, A. V., Jong, E. M., Griffith, D. G., Gunn, J. M., Hensley, S., Johnson, W. T. K., Kirby, C. E., Leung,K. S., Lyons, D. T., Michaels, G. A., Miller, J., Morris, R. B., Morrison, A. D., Piereson, R. G., Scott, J. F., Shaffer, S. J., Slonski, J. P., Stofan, E. R., Thompson, T. W. and Wall, S. D.: 1992., 'Magellan Mission Summary', *J. Geophys. Res.* **97**, 13,067–13,090.
Smrekar, S. and Phillips, R. J.: 1991, 'Venusian Highlands: Geoid to Topography Ratios and Their Implications', *Earth Planet. Sci. Lett.* **107**, 582–597.
Solomon, S. C, Smrekar, S. E., Bindschadler, D. L., Grimm, R. E., Kaula, W. M., McGill, G. E., Phillips, R. J., Saunders, R. S., Schubert, G., Squyres, S. W. and Stofan, E. R.: 1992, 'Venus Tectonics: An Overview of Magellan Observations', *J. Geophys. Res.* **97**, 13,199–13,255.
Stofan, E. R., Sharpton, V. L., Schubert, G., Baer, G. Bindschadler, D. L., Janes, D. M. and Squyres, S. W., 1992, 'Global Distribution and Characteristics of Coronae and Related Features on Venus: Implications for Origin and Relation to Mantle Processes', *J. Geophys. Res.* **97**, 13,347–13,378.
Tchalenko, J. S.: 1970, 'Similarities between Shear Zones of Different Magnitudes, *Geol. Soc. Am. Bull.* **81**, 1,625–1,640.
USGS: 1989, Map I-2041, Topographic Map of Part of the Northern Hemisphere of Venus, V15M 90/0 RKT.
Vorder Bruegge, R. W. and Head, J. W.: 1989, Multi-Stage Tectonic Evolution of Eastern Ishtar Terra, Venus', *Lunar Planet. Sci.* **XX**, 1,162–1,163.
Vorder Bruegge, R. W. and Head, J. W.: 1991, 'Processes of Formation and Evolution of Mountain Belts on Venus', *Geology* **19**, 885–888.
Zuber, M. T.: 1987, 'Constraints on the Lithospheric Structure of Venus from Mechanical Models and Tectonic Surface Features', *J. Geophys. Res.* **92**, Suppl., 541–551.
Zuber, M. T. and Parmentier, E. M.: 1990., 'On the Relationship between Isostatic Elevation and the Wavelength of Tectonic Surface Features on Venus', *Icarus* **85**, 290–308.