Venus Trough-and-Ridge Tessera: Analog to Earth Oceanic Crust Formed at Spreading Centers?

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One type of tessera terrain on Venus, the trough-and-ridge tessera, exhibits a distinctive morphology composed of throughgoing generally parallel linear valleys and shorter orthogonal valleys and ridges. The similarity of this pattern to oceanic crustal topography and morphology is examined. Oceanic crust on Earth is characterized by a distinctive orthogonal pattern, with transforms and fracture zones in one direction and linear abyssal hills developed parallel to the rise crest in the other. Similarities between the components of the tessera terrain and terrestrial seafloor fabric and structure are found in terms of linearity, parallelism, length, width, spacing, orthogonality, and general morphology. A difference is that trough and ridge tessera tend to occur as plateau-like regions at intermediate elevations (average ~2 km) above the surrounding plains, while terrestrial seafloor ranges in elevation from that observed at rise crests and oceanic plateaus such as Iceland, down to depths of several kilometers on the abyssal floors, where the orthogonal pattern is often masked by sedimentation. On the basis of the similarities it is proposed that trough-and-ridge tesserae may have originated through processes analogous to those responsible for the ocean floor fabric on Earth, forming at a rise crest similar to divergent boundaries on the Earth's seafloor, and evolving to its present morphology and configuration through processes of crustal spreading. The plateau-like nature of the trough-and-ridge tesserae distribution could be the result of localized crustal thickening in the spreading process, producing elevated Iceland-like plateaus whose texture is preserved from subsequent lowland volcanic flooding. Some regions of more complex tessera patterns may result from deformation of the basic trough-and-ridge pattern of tesserae. This hypothesis can be tested with global high-resolution imaging and altimetry data and gravity data from the Magellan mission.

1. INTRODUCTION

Tesserae ("tile" in Greek; also informally called "parquet") is an upland terrain type occurring in areas known to be distinctive on the basis of Pioneer Venus altimetry, roughness, and reflectivity data [Head et al., 1985; Bindschadler and Head, 1989a,b]. This terrain was shown by Venera 15/16 radar images to have a distinctive morphology and texture dominated by closely spaced intersecting grooves and ridges that produce a variety of patterns (hence the term tessera) including orthogonal, diagonal, chevron, and chaotic [Barsukov et al., 1986; Basilevsky et al., 1986; Sukhanov, 1986; Bindschadler and Head, 1988b,c]. The spacing between ridges in tesserae terrain varies but generally is in the range of 5-20 km. Ridge heights are generally not more than several hundred meters [Basilevsky et al., 1986]. Tesserae occur in both small isolated patches and in large regional configurations that comprise about 15% of the area north of 30°N. The morphology of tesserae has been interpreted to be related to deformation which has acted with primarily horizontal components over broad areas (the areaal deformation of Basilevsky et al. [1986], but the origin of the deformation is still controversial.

A range of models for tesserae origin has been outlined and summarized by Bindschadler and Head [1988c] and includes (1) horizontal compression and crustal thickening due to asthenospheric currents [Basilevsky, 1986; Pronin, 1986]; (2) vertical uplift due to shallow mantle processes [Phillips, 1986; Bindschadler and Parmentier, 1987]; (3) gravity-driven deformation manifested as gravity sliding [Sukhanov, 1986; Kozak and Schaber, 1986; Markov et al., 1989; Smrekar and Phillips, 1988] or gravitational relaxation [Bindschadler and Parmentier, 1987]; (4) seafloor spreading where structural patterns are related to rise-crest processes [Bindschadler and Head, 1988c]. Recent work by Head and Crumpler [1987] suggests that divergence and crustal spreading is occurring on Venus in Western Aphrodite Terra, to the south of the region covered by Venera 15/16 data, although the global extent and significance of this process is uncertain [Kaula and Phillips, 1981]. Analysis of terrestrial spreading centers extrapolated to Venus conditions [Sotin et al., 1988; 1989a,b] shows that the gravity and topography data for western Aphrodite are consistent with a spreading hypothesis. There is also evidence that some of the equatorial regions thought to represent crustal spreading have the same radar characteristics as the tesserae in the north [Bindschadler and Head, 1988a,d; Sotin and Head, 1989]. The purpose of this paper is to investigate further the general similarity of morphology between the trough-and-ridge tesserae and the fabric of the ocean floor and to investigate one of the hypotheses for tesserae origin, that is, that the tesserae texture might be related to a crustal fabric produced at spreading centers.

2. CHARACTERISTICS OF TESSERA ON VENUS AND THE TROUGH-AND-RIDGE TERRAIN IN LADM TESSERA

Pioneer Venus data show that tesserae terrain lies at higher (generally 2 ±1 km) elevations than the surrounding plains and that it is characterized by relatively higher values of surface roughness at the centimeter-scale and the meter to decimeter scale [Head et al., 1985; Bindschadler and Head, 1989b] than most other surface units. Gravity data for one of the major regions of tesserae (Tellus) led Sjogren et al. [1983] to suggest that Tellus is compensated at relatively shallow depths. The range of surface morphology observed in the tesserae led...
Fig. 1a. Location and setting maps. Global map of Venus showing the location of Laima Tessera and its relation to Ishtar Terra to the north and to Aphrodite Terra to the south. Areas indicated in black lie below the 0-km datum. Contour interval is 1 km. Box shows location of Figure 1b.

Bindschadler and Head [1988b; also Models for the origin and evolution of tessera terrain, Venus, submitted to Journal of Geophysical Research, 1989] to propose a three-part classification scheme, outlined in order of increasing complexity of structural patterns: (1) subparallel ridged terrain (subparallel linear ridges with narrow zones of disruption oriented at a variety of angles to the ridges; type area Western Fortuna Tessera); (2) trough and ridge terrain (large troughs in one direction, smaller ridges and valleys in the other, generally orthogonal direction; type area Eastern Laima Tessera); and (3) disrupted terrain (complex and chaotic orientation of short to intermediate length ridges and troughs; type area central Tellus Regio). In this analysis, the general characteristics of the type example of the trough-and-ridge terrain (Eastern Laima Tessera) (Figure 1) are assessed.

Laima Tessera covers over $2 \times 10^6$ km$^2$ and lies south of Fortuna Tessera and Eastern Ishtar Terra (Figure 1). It is bounded on the east by a generally north-south trending ridge belt (Kamari Dorsa), and along the rest of its borders it has a transitional boundary where the topography descends toward the surrounding plains and appears to be embayed by them, particularly to the south and west (Figure 1b). The major morphologic pattern associated with Laima Tessera is a structural fabric composed of two elements (Figures 1b-1c). One of these elements consists of WNW to NW trending long and throughgoing lineaments and faults [Basilevsky et al., 1986; Sukhanov et al., 1987] and large troughs up to 30 km in width. The second is a NNE to NE trending set of much shorter linear elements of alternating ridges and valleys spaced 6 to 12 km apart and oriented locally orthogonally to the larger WNW trending structures.

The troughs/lineaments (Figures 1 and 2a-2c) are characterized by their linearity, significant length, and morphologic variability along strike. The individual features themselves (Figures 2b-2c) have three modes of expression: (1) trough-shaped in cross section, with inward dipping walls and a flat floor which usually appears to be covered by smooth plains units of probable volcanic origin [Basilevsky et al., 1986; Sukhanov et al., 1987] (Figures 2b-2c, marked T); (2) grooved-shaped in cross section, where the inward dipping walls converge without the development of a flat floor (Figures 2b-2c, marked G); and, (3) lineaments, where a linear feature is observed, but topography is not as distinct as in the case of the troughs and grooves (Figures 2b-2c, marked L). Troughs range...
in width from about 8-30 km with most in the range of 10-12 km. In some cases the trough walls become irregular and convex outward, and a bead-like appearance results (Figures 1 and 2c, marked B). These bead-like or oval structures range in width from 15 to 45 km and in length from 30 to 50 km and appear to be more common in the southern part of Laima Tessera than in the northern. Often, the flat-floored trough narrows and the walls merge into a single linear valley, generally less than 8 km in width. A cross section across the strike of the troughs (Figure 2d) shows that the troughs average less than 500 m deep along this profile but that the most prominent trough (Baba-jaga Chasma) approaches 1 km depth where it crosses this profile. The range and frequency distribution of trough/lineament lengths are related in part to their preservation, since many can be seen to be embayed by plains units surrounding Laima Tessera (Figure 1). Several troughs completely cross the width of Laima Tessera, and one (Baba-jaga Chasma) extends for a distance of about 1400 km. Most of these features are less than 750 km in length, and there is a distinct difference in the length and continuity north and south of Baba-jaga Chasma (Figure 1).

The major troughs generally parallel each other (Figure 1) with the distance between any two being similar along their strike. The spacing between successive major trough/lineaments in a traverse normal to the strike of the features, however, is variable. A NNE oriented transect across eastern Laima Tessera shows that the spacing ranges from 20 to 100 km with an average spacing for 13 troughs of about 50 km. Detailed examination of the areas between major troughs often reveals the presence of much more subtle linear features oriented parallel and subparallel to the troughs and producing minor disruptions in the orthogonal fabric (Figures 1 and 2b, marked D).

The second structural element occurs in the terrain between the troughs/lineaments and is characterized by parallel ridges and valleys oriented generally perpendicular to the troughs/lineaments, giving the impression of a corrugated appearance. The flanks of the ridges and valleys are often sharp and linear and are interpreted to be fault bounded, in contrast to the hills and swales typical of the mountain belts of Ishtar Terra which are interpreted to be anticlines and synclines [Crumpler et al., 1986]. Therefore the hills and valleys of the corrugated terrain appear to be more similar to horsts and graben than to anticlines and synclines (Figure 2).

In many cases, particularly where the edge of the corrugated terrain is defined by a trough, individual linear elements do not appear to cross from one domain across trough/lineaments into the adjacent corrugated segment. In other cases, particularly where the edge of a portion of the corrugated terrain is defined by a lineament, many linear segments can be traced across the structure, whereas others terminate against it. Few corrugated elements carry further than across one trough/lineament zone (see map patterns in Figure 1). Many elements terminate against the more subtle lineaments between major troughs/lineaments (see particularly central Laima Tessera, Figure 1).
The lengths of the valleys and ridges in the corrugated terrain are thus generally comparable to the separation distances between the WNW oriented troughs/fractures. These distances are commonly in the range 20 to 100 km and are much shorter than the WNW oriented troughs/fractures. The separation distances of the hills range from about 6 to 12 km, averaging about 8-10 km, in general agreement with the average 8 km crest-to-crest distance found for Laima Tessera by Ivanov [1988].

Although Laima Tessera itself is surrounded by plains interpreted to be of volcanic origin [Basilevsky et al., 1986], the tessera terrain itself does not appear to display evidence of abundant volcanic centers except for the smooth flat floors of the trough/fracture zones, and the beaded areas or ovals within these zones (Figure 1). A few elongate dome-like features, having dimensions of 40 km x 70 km, are oriented parallel to the fabric of the corrugated terrain and are of possible volcanic origin (Figure 2a). Smaller dome-like hills (<20 km diameter) interpreted to be of volcanic origin are noted adjacent to the tessera and are sometimes associated with smooth plains in the tessera in general [Shyuta et al., 1988; Aubele, 1989]. The abundance of domes within the tessera itself, however, cannot be easily determined because of the extremely rough topography comprising the corrugated terrain (Figure 2).

In summary, the trough and ridge type of tessera in Laima Tessera is characterized by a distinctive pattern of throughgoing troughs/lineaments, and orthogonally oriented ridges and valleys comprising the corrugated terrain (Figure 2). We now proceed to examine the basic characteristics of the terrestrial seafloor in order to compare and contrast the characteristics.

3. Nature of the Seafloor Formed at Spreading Centers

The terrestrial seafloor possesses three major landforms in areas of oceanic ridges: (1) the linear rise crest at the spreading
Fig. 2a. Venera 15/16 images and sketch maps of the troughs/fractures and the corrugated terrain in Laima Tessera. T, troughs; G, grooves; L, lineaments. Southeastern Laima Tessera, centered on 51°, 48°N; width of image is 500 km. The generally orthogonal nature of the fabric is clearly visible, with troughs (paired dark lines parallel to the long axis of photo with hatchures indicating depressions) and parallel fractures (dark lines) orthogonal to the shorter, more closely spaced linear hills of the corrugated terrain. Note also the circular depression of probable impact origin and the two linear hills.
Fig. 2b. East central Laima Tessera, centered on 55°, 52.5°N; height of image is 180 km. Note the trough-like nature of the major trough/fracture in the southeastern part of the image (Mots Chasma), how it widens in the central part and then changes to a narrow fracture in the northwest. Most elements of the orthogonal corrugated terrain terminate against the trough/fracture, while some extend across it.

Fig. 2c. Central Laima Tessera, centered on 48°, 53.5°N; height of image is 110 km. Note the variation in width of the trough (Baba-jaga Chasma), the development of small oval structures filled with volcanic plains (center), and its evolution into a fracture on the northwest side of the image. Corrugated terrain is oriented generally normal to the trough/fracture. A mountain 40 x 50 km, of possible volcanic origin, is located in the southeast.

Fig. 2d. Venera 15/16 altimetry profile across Laima Tessera showing the topography associated with named troughs and chasma (labeled above profile) and unnamed troughs or trough extensions (labeled TR below profile). Location of profile shown in Figure 1.
fracture zone contains a central trough 5-20 km in width that has regional inward dipping convex-downward slopes down to the trough floor. Subsidiary basins, troughs, and ridges are present along the valley floor. Floor depth is a function of transform offset and may be as much as several thousand meters [Fox and Gallo, 1986] due to differences in age and subsidence level across the fracture zone. Ocean floor topography typically changes across the fracture zone due to the juxtaposition of crust and lithosphere of different ages. Transverse ridges often parallel the edge of the fracture zone valley (Figure 3a). The actual movement at any given time occurs primarily along a narrow transform fault zone (TFZ), but the movement can migrate and such migration tends to produce a broader transform tectonized zone (TTZ) (Figure 3a). Talus and sedimentation often obscure the details of the floor structure, and volcanism is often localized within fracture zones [Lowrie et al., 1986]. Fracture zones are observed to change their morphology along strike. A sonograph mosaic of the Charlie-Gibbs transform and fracture zone in the North Atlantic (Figure 3b) shows its distinctly linear appearance over short distances and its complexity along strike and along its flanks [Searle, 1979].

In map view, fracture zones can be linear, arcuate, or slightly sinuous, depending on a number of factors including changes in spreading rate, location and variability of poles of rotation, and interplate and intraplate deformation subsequent to crustal formation [Cande et al., 1988]. On Earth, fracture zones (FZ) reach thousands of kilometers in length and are apparently limited only by the width of the ocean basin.

The spacing between major FZs is relatively constant.
between any pair of adjacent FZs, but the spacing between FZs is variable along the length of an oceanic rise. Fracture zone spacing increases with spreading rate [Fox and Gallo, 1984; Sandwell, 1986; Abbott, 1986]. Average spacing in the North Atlantic is about 55 km [Macdonald, 1986; Vogt, 1986]. In regions of complex plate interactions, there are fracture zones which converge toward each other, such as the Mendocino and Blanco FZs bounding the Gorda plate [Stoddard, 1987].

A distinctive linear fabric of abyssal hills occurs parallel to the rise crest and normal to the fracture zones (Figures 3a and 3b). Along the Mid-Atlantic Ridge (MAR), normal faults that dip toward the rift valley develop within 1-5 km of the spreading axis. This faulting creates the inner walls of the rift valley. Adjacent to this in some areas, in a zone 10-20 km wide, occur the relatively flat, faulted terraces, outwardly bounded by the outer wall, the rift mountains, and the abyssal hills [Macdonald, 1986]. The major scarps are generally continuous along the 40-60 km length between fracture zones [Macdonald, 1986]. The nature of the transformation of the rift valley outer wall into the abyssal hills is a matter of controversy but may involve tilting of the rift valley walls back to a horizontal position [Verosub and Moores, 1981], or overprinting by outward dipping normal faults [Macdonald and Atwater, 1978], or a combination of both. The presence and wide occurrence of abyssal hills distally from oceanic rises was noted early in the exploration of the ocean floor, and they were used in the definition of morphotectonic provinces [Hess, et al., 1959] which cover up to 80% of the sea floor [Menard and Mammerickx, 1967]. Abyssal hills are elongate, oriented generally parallel to regional magnetic anomalies, and normal to fracture zones and possess relief of 40-1000 m and widths of 2-35 km [Krause and Menard, 1965]. Sonographs of the Mid-Atlantic Ridge show the linear nature and relatively regular spacing of abyssal hills (Figure 3c [Laughton, 1981]). R. A. Pockalny et al. (A morphological comparison of abyssal hill topography using high-resolution, multibeam bathymetry data, submitted to Journal of Geophysical Research, 1989) reviewed three models for the formation of abyssal hills: (1) the horst and graben model [Needham and Francheteau, 1974], where abyssal hills were formed by inward and outward dipping normal faults; (2) the listric fault model [Harrison and Stieltjes, 1977], where listric faulting occurs to offset the effects of the inward facing faults of the rift valley walls, rotating crustal blocks and producing hills shaped triangularly in cross section, which result from the rotated half grabens; (3) the episodic magmatism model [Kappel and Ryan, 1986; Pockalny et al., 1987; Barone and Ryan, 1988], where abyssal hill topography is generated by the interplay between episodic magmatism and extensional tectonism.

Recent work (R. A. Pockalny et al., submitted manuscript, 1989; P. J. Fox, personal communication, 1989) has shown that the spacing of abyssal hills is inversely related to spreading rate. Slow spreading ridges (<30 mm/yr) have relatively high abyssal hills (about 200 m) and an average...
spacing of 10 km. Abyssal hills derived from slow to intermediate spreading ridges (~40 mm/yr) have an average spacing of 8.2 km. Abyssal hills associated with intermediate-to-fast ridges (~100 mm/yr) show an average spacing of 4.4 km, and those from fast spreading ridges (~160 mm/yr) are less elevated (50-60 m) and less widely spaced (average spacing of 4.2 km). Overall, the variation in the length of abyssal hill ridges along strike is 10 km to 40-50 km.

In some cases, the basic orthogonal pattern can be modified by several processes. Acton et al. [1988] described a complex curved seafloor fabric in the Galapagos rise which they interpreted to be caused by rift propagation and changes in
spreading rate. Menard [1984] showed that serrate ridges and transforms could develop during asymmetrical spreading. Stoddard [1987] described sinuous and complex patterns of magnetic lineations and abyssal hills on the Gorda plate located between the convergent Blanco and Mendocino fracture zones, and he analyzed models related to mechanisms of rotation of rigid subplates and nonrigid deformation to explain the origin of these patterns on the plate moving toward the apex of the two fracture zones.

In summary, oceanic crust is commonly characterized by a distinctive orthogonal pattern (fracture zones and abyssal hills) whose orthogonal elements differ in their characteristics in the two directions (Figure 3). We now proceed to compare the general fabric of the ocean floor to the fabric of the trough-and-ridge tessera on Venus.

4. COMPARISONS

The basic dimensions, spacing, and geometric characteristics and relationships between the terrains examined on Venus and Earth are summarized in Table 1, and this provides a basis for comparison of similarities and differences between the two terrains. There are numerous similarities between the components of the trough-and-ridge tessera terrain type and basic terrestrial seafloor fabric and structure.

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<th>Table 1. Comparison of Dimensions of Venus Troughs and Ridges and Earth Fracture Zones and Abyssal Hills</th>
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4.1. Orthogonal orientation of different components. Oceanic abyssal hills and fracture zones bear relationships to each other similar to those of elements in the corrugated terrain and troughs in the tessera, i.e., a much greater length of troughs and fracture zones, and orientation of the shorter corrugated terrain elements and abyssal hills orthogonal to troughs and fracture zones.

4.2. Fracture zones and troughs/fractures. Oceanic fracture zones and tessera troughs/fractures are similar in their general linearity, in their often arcuate tendency, in their length (measured in hundreds of kilometers with the largest extending over 1000 km across the width of Laima Tessera), and in the width of the central trough (Figures 1, 3a, and Table 1). On Earth, the "transform domain" is defined as the width of the portion of the seafloor oriented perpendicular to the strike of the FZ that is affected by the presence of the FZ itself (i.e., thinned oceanic crust) (see Figure 3a). With existing Venus imaging data, we can see surficial expressions of troughs/ridges but not the more subtle effects of the fracture zone thermal structure. Additional high-resolution altimetry data are required to determine the actual width of the zones or domains in which the troughs occur, but preliminary analysis of Venera 15/16 altimetry data (Figure 2d) suggests that they may be wider than the trough observed in the images. The two features (FZs and troughs/fractures) are comparable in their general parallelism and spacing, although detailed analyses of tessera terrain are required to establish the full range and variability of trough/fracture spacing on Venus. The two features are also comparable in their general morphology (Figures 1-3), with both having similar shapes and along-strike variations (changes in strike, basins).

4.3. Abyssal hills and corrugated terrain. Oceanic abyssal hills are similar to the ridges and valleys of the corrugated terrain in their distinct parallelism and their consistent occurrence and relatively constant widths over large areas (Figures 2, 3a, and 3c). They are also similar in terms of the fault-like boundaries of the valleys and ridges, in their spacing (Table 1), and in their relation to the troughs/fracture zones (predominantly terminating against them). More detailed analyses of the spacing of the elements of the corrugated terrain are needed to establish variability within and between domains and between different areas of tessera and to compare these to terrestrial data which show relations of spacing to spreading rates (R. A. Pockalny et al., submitted manuscript, 1989). Additional data (radar interferometry) are also needed to establish the heights and slopes of the elements of the corrugated terrain on Venus.

Significant differences exist between the environment and characteristics of the Earth's seafloor and the general environment of Venus and the trough-and-ridge tessera as seen in Laima Tessera.

4.4. Differences in environment between Venus and Earth. Venus is characterized by much higher surface temperatures than the Earth (450°C) and the lack of oceans. These factors have potentially important influences on seafloor spreading processes in terms of crustal formation processes, crustal modification processes, and hydrothermal cooling. Assessment of terrestrial spreading centers under Venus environmental conditions [Sotin et al., 1988, 1989a,b] indicates that the major differences between Venus and the Earth would be the influence of the enhanced surface temperature on upper mantle temperatures on Venus and the resulting increase in crustal thickness and elevation of isostatically compensated topography. Crust on Venus produced at average spreading centers would be about 15 km thick, in contrast to the average crustal thickness on Earth of about 5 km. Along-strike variations in upper mantle temperatures at Venus spreading centers (e.g., Icelandic-like hot spots) could produce enhanced crustal thickness and increased isostatically compensated topography (e.g., Icelandic-like plateaus). Application of these concepts to Western Aphrodite Terra (Figure 1a), proposed as a site of crustal spreading on Venus [Head and Crumpler, 1987], showed that the topography and gravity data for Ovda Regio in Western Aphrodite were consistent with the hypothesis of crustal spreading [Sotin et al., 1988, 1989a,b]. Specifically, much of the crust on the flanks of Western Aphrodite may be about 15 km average thickness and could be produced by crustal spreading. Ovda Regio, a central oval-like plateau along the Aphrodite rise, appears to be an area of enhanced crustal
Tessera terrain in general lies at elevations of 2 km (±1 km standard deviation [Bindschadler and Head, 1989b]) above the mean planetary radius, while most plains units (which do not show the distinctive patterns of the trough-and-ridge tessera) lie at or within 1 km of mean planetary radius. Two types of topographic boundaries are observed at the edge of the trough-and-ridge tessera terrain: (1) abrupt, where the edge is marked by a distinctive topographic change over relatively short distances and by a zone of deformation, as in Kamari Dorsum at the eastern edge of Laima Tessera (Figure 1), and (2) transitional, where the trough-and-ridge tessera terrain slowly decreases in elevation and is embayed by the volcanic deposits forming the lowland plains, as in southern and western Laima Tessera (Figure 1). There are several possible explanations for these observations, many of which can be tested with existing data and data from the upcoming Magellan mission: (1) the trough-and-ridge tessera are high because of enhanced crustal thickness due to increased crustal thickness production along strike at the spreading center (the Iceland hot spot effect). This would require evidence that this process is operating at spreading centers and would predict that the terrain is in isostatic equilibrium. (2) The trough-and-ridge tessera are high because of enhanced crustal thickness related to deformational processes operating subsequent to its formation in the spreading center environment. This would seem to require significant surface deformation reflecting the deeper processes of crustal thickening. (4) The trough-and-ridge tessera are completely unrelated to processes associated with crustal spreading and the morphological and geometrical similarities are unrelated in terms of processes of formation.

Explanations 1-3 must also account for the apparent lack of the trough-and-ridge pattern in the lowlands, while no such explanation is required for 4. The apparent lack of trough-and-ridge pattern in the lowlands could be due to volcanic flooding of the pattern, as suggested by the embayment relationships along the southern and western margins of Laima Tessera (and preferential preservation of tessera terrain in areas of younger and/or thicker crust). In this case, lava thicknesses in the range of several hundred meters would be required to cover the texture, and one would expect to see transitional areas and patchy areas of exposed trough-and-ridge tessera. Sukhanov [1986] cited the patterns of irregular polygons in volcanic plains units that are adjacent to some tessera as evidence for regions of buried tessera. On the basis of the distribution of these patterns, he proposed that the actual abundance of tessera might be a factor of two more than what is presently exposed, perhaps representing some global process of "tesserization." Comprehensive analysis of existing and Magellan data will be required to evaluate fully this possibility. Alternatively, if the trough-and-ridge pattern is produced preferentially in regions of thicker crust, perhaps there is some factor in the production of normal thickness crust at Venus spreading centers (different thermal regime or different ratio of extrusion to intrusion) that might result in the lack of production or preservation of the orthogonal texture (i.e., thicker crust is better preserved than thinner crust, or only thick crust exhibits the orthogonal texture). Additional analyses and data are clearly required to test these ideas and to establish the relationship of the trough-and-ridge tessera to the surrounding plains.

Several additional properties of tesserae may help to resolve the origin of the trough-and-ridge tesserae. Tesserae in general are characterized by distinctive and anomalously high surface roughness at a range of scales from centimeters to decameters compared to plains units in general [Bindschadler and Head, 1989b]. Localized volcanism and pervasive faulting producing rift mountains/abyssal hills are responsible for the abnormally rough topography at the centimeter to decameter scale seen on the seafloor [Gallo et al., 1984, Figures 8-9; Searle, 1984], which is very similar to the type of pervasive roughness seen in the tesserae terrain [Bindschadler and Head, 1989a, 1989b]. High-resolution data obtained by the Magellan mission will permit the correlation of areas of enhanced surface roughness with specific geologic features and will allow further evaluation of the similarities and differences between the features on Venus and Earth.

Line-of-sight (LOS) gravity data exist for all or part of several tessera regions (Tellus Regio, Laima Tessera, and Alpha Regio) [Sjogren et al., 1983]. Maps of LOS gravity anomalies show that these three regions are characterized by very small anomalies despite their topographic elevation, in contrast to the very large anomalies associated with other areas of high topography, such as Beta Regio. The small LOS gravity anomalies, together with the high topography characteristic of the tesserae, may indicate compensation due to crustal thickness variations or shallow mantle processes. More widespread coverage and higher resolution gravity data will be of extreme importance in distinguishing between models for the formation and evolution of tessera in general, and trough-and-ridge tessera in particular.

5. DISCUSSION AND CONCLUSIONS

On the basis of the similarities in morphology, geometry, and spacing, it is concluded that processes analogous to those responsible for the ocean floor fabric on Earth are good
candidates for origin and production of the trough-and-ridge tessera terrain type on Venus. In this model, elongate troughs are analogous to fracture zones, and linear elements of the corrugated terrain to abyssal hills; the trough-and-ridge tessera originated at a rise crest analogous to divergent boundaries and spreading centers on the Earth's seafloor and evolved to its present morphology and configuration through similar processes of crustal spreading.

If trough-and-ridge tessera fabric is produced by crustal spreading, where is the spreading center located in Laima Tessera? On the basis of the asymmetry of the fabric, candidate spreading centers would be expected to be found parallel to the corrugated terrain and normal to the trough/fractures, oriented in an approximately NNE-SSW direction (Figure 1c). If the crust and lithosphere is relatively old, topographic variations due to thermal evolution may no longer be detectable. At active spreading centers on Venus topographic rises should be preserved and detectable for relatively slow spreading rates [Kaula and Phillips, 1981; Phillips and Malin, 1983]. Alternatively, regional slopes might provide information on the direction to higher, younger crust and lithosphere. Preliminary analysis of topographic contour maps (500-m contour interval) has revealed no distinctive local rises, but more detailed analysis is underway using individual altimetry profiles. Although there does not appear to be a systematic trend in regional topography in an E-W direction, the extent of volcanic flooding of Laima Tessera appears to be greater in the west (Figure 1c), suggesting that the eastern portion of Laima may be slightly higher, and thus a candidate for younger crust and lithosphere. The eastern boundary of Laima Tessera is characterized by a complex NNW striking ridge belt and a topographic drop of several kilometers, suggesting the presence of a tectonic boundary (Figure 1c). Detailed mapping from Venera 15/16 altimetry and images of Laima Tessera is presently underway to document topographic trends and to locate possible spreading centers.

The trough-and-ridge tessera terrain in Laima Tessera lies between Ishtar Terra in the north (a region of compressional deformation and crustal thickening [Crumpier et al., 1986; Vorder Bruegge and Head, 1989]), and equatorial regions of extensional deformation [Schaber, 1982] in Aphrodite Terra to the south (Figure 1a). Patterns of topography, morphology, and structure comparable to terrestrial spreading centers have been observed in the Western Aphrodite Terra region several thousands of kilometers to the south of Laima Tessera [Crumpier et al., 1987; Head and Crumpier, 1987; Crumpier and Head, 1988] (Figure 1a). Although high-resolution images of the Venera 15/16 mission are not available at these low latitudes, evidence exists from Pioneer Venus and Arcido data for the presence of a spreading center. Observations from Western Aphrodite Terra show (1) a segmented rise crest offset right-laterally along fracture zone-like cross-strike discontinuities (similar to the troughs in Laima Tessera); (2) bilaterally symmetrical topography normal to the rise crest; and (3) a thermal boundary layer topography suggesting spreading rates of about a centimeter a year and Iceland-like plateaus. Also revealed in the moderate resolution images and topography data are patterns of orthogonal elements parallel to the rise crest and in the general direction of the cross-strike discontinuities (Crumpier and Head, Crustal spreading on Venus: Evidence from topography, morphology, symmetry and map patterns, submitted to Tectonophysics, 1989). In addition, the radar properties of the Western Aphrodite Iceland-like plateaus along the rise crest (Ovda and Thetis regions) are very similar to those of the tessera (such as Laima and Tellus) in the regions covered by Venera 15/16. High-resolution Magellan data will permit a comparison between Laima Tessera and the terrain and structure in Aphrodite Terra and the nature and relationship of the intervening region.

The more complex tessera patterns observed by Venera 15/16 (subparallel ridged terrain and disrupted terrain [Bindschadler and Head, 1988b]) are not discussed in this paper but could be due to deformation of the basic trough-and-ridge tessera pattern (analogous to more complex patterns seen on the terrestrial seafloor [Acton et al., 1988; Stoddard, 1987]), or to complex tectonic patterns from other sources of deformation (Bindschadler and Head, Models for the origin and evolution of tessera terrain, Venus, submitted to Journal of Geophysical Research, 1989). Recognition of the key patterns of the trough-and-ridge tessera (long troughs/fractures and short orthogonal corrugated terrain) could provide a "marker" structural type and help in deciphering the origin of the more complex tessera occurrences.

In conclusion, the similarities in morphology, geometry, and spacing of elements of the trough-and-ridge tessera to the terrestrial ocean floor fabric suggest that trough-and-ridge tessera may have formed by similar processes of divergence and crustal spreading on Venus. This hypothesis can be further tested by detailed analyses of the nature of Laima Tessera and other tessera in the northern hemisphere, application of models for the formation of fracture zones and abyssal hills on Earth to the conditions of the Venus environment, and the analysis of global high-resolution imaging, alitmetry, and gravity data from the Magellan mission.

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