Tessera terrain on Venus: A survey of the global distribution, characteristics, and relation to surrounding units from Magellan data

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Abstract. The tessera terrain on Venus, comprised of areas of high radar backscatter, complex deformation patterns relative to other units, and topography standing higher than surrounding plains, covers -35.3 x 10^6 km^2, about 8% of the surface of Venus, and is nonrandomly distributed, being preferentially located at equatorial and higher northern latitudes with a distinct paucity below about 30°S. Individual tessera occurrences range in area from the lower limits of our measurements (about 200 km^2) up to the largest tessera, Ovda, with an area of about 8.6 x 10^6 km^2, or about 2% of the surface area of Venus. The size-frequency distribution of tessera patches is strongly unimodal and skewed toward smaller sizes, reflecting the great abundance of small tessera fragments. Modes of occurrence include (1) large clusters (e.g., Aphrodite Terra and Ishtar Terra); (2) arc-like segments which may extend for thousands of kilometers and are either concave inward toward the major tessera cluster development or away from it; (3) areas where tesserae are rare or absent which occur both as low-lying plains (e.g., Guinevere Planitia), and as elevated regions (e.g., Atla Regio). Tessera terrain has a bimodal elevation-frequency distribution, with the main peak at about 0-1 km and an additional peak at about 3 km above mean planetary radius. In terms of number of occurrences, however, tesserae do not display a correlation with elevation at the global scale, since small tessera patches commonly occupy low-lying regions. Although tesserae exhibit a range of gravity signatures, many occurrences are interpreted to represent relatively shallow (crustal) levels of compensation. Tessera boundaries include Type I (sinuous/embayed, dominated by adjacent lava plains embaying tessera massifs; 73% of total tesserae boundaries) and Type II (linear/tectonic). Only a small percentage of the length of all boundary types show no lava embayment and could be interpreted as tectonically active for long periods subsequent to initial tessera formation. Occurrence of broad slopes of post-tessera embayed plains away from tessera boundaries suggests that regional tilting occurred subsequent to final tessera deformation in some places. Several lines of evidence suggest the possibility that a widespread tessera-like basement, comprising at least 55% of the surface of Venus, is buried under a cover of lava plains a few hundred meters to as much as 2-4 km thick. A wide variety of deformational structures and patterns is observed within the tessera including those representing extension, compression, shear, and transpression; in some cases the apparently complex patterns can be resolved into single-event kinematic interpretations involving noncoaxial deformation (e.g., Itzpapalotl), while in other cases, polyphase deformation is more likely (e.g., central Ovda and Thetis). Where relations can be determined stratigraphically, earliest deformation within the tessera is primarily related to crustal shortening and compression (Phase I), followed by pervasive extensional deformation commonly oriented normal to the strike of Phase I features, generally along the same principal stress direction (Phase II). Evidence also exists for the contemporaneous formation of these distinctive deformation patterns. Lava plains within and adjacent to the tessera embay both of these fabrics but sometimes overlap in time with Phase II extensional deformation and with regional tilting. Tessera terrain as a geologic unit occupies the lowest portion of the stratigraphic column in all areas that we have observed, an observation consistent with many other mapping studies. We see no evidence for transitional stages between tessera and volcanic rises and/or lowlands, that might represent a long-term sequence of upwelling or downwelling followed by crustal deformation and tessera formation. No impact craters deformed by Phase I deformation

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have yet been observed on tessera, suggesting that Phase I tessera deformation sufficiently intense to eradicate earlier impact craters ceased relatively abruptly somewhat before -300-500 m.y. ago; however, the starting time, and thus duration of tessera formation, is unknown. On the basis of the very small number of on-tessera craters deformed by Phase II extensional deformation, this period probably did not last more than several tens of millions of years after the cessation of Phase I. Little observable deformation of the tessera terrain appears to have taken place in the last several hundred million years, during which time the vast volcanic plains were emplaced, although tilting of early plains along some tessera margins is observed. Building on the global synthesis presented here, future analyses of individual tessera occurrences will provide the detailed descriptions, kinematic interpretations, and strain histories necessary to assess and distinguish between the several catastrophic and uniformitarian models for tessera formation.

1. Introduction

Tessera terrain was discovered and named during the Venera 15/16 mission [Barsukov et al., 1986] and represents the most deformed regions on the surface of Venus. Tessera terrain is defined as radar bright (high radar backscatter indicating centimeter- to meter-scale roughness), topographically elevated regions of equidimensional or sometimes elongated shape possessing complex patterns of deformation relative to surrounding terrain [Barsukov et al., 1986; Sukhanov, 1986, 1992; Bindschadler and Head, 1989], consisting of at least two sets of coupled ridges and grooves intersecting at high angles. Such radar, elevation, and morphological characteristics of tesserae make them very distinctive from the other units and terrain on Venus. Tessera terrain has practically no morphological analogs on the terrestrial planets except for...
Figure 1b. Map of the global distribution of tessera compiled in this study on the basis of Magellan Cycle I-III data. Tessera occurrences (black spots and dots) are widespread and nonrandomly distributed features. The nonrandomness is shown by the existence of several clusters of tesserae and areas where tesserae are rare or absent. The densely stippled pattern represents those areas of Venus not covered by Magellan during Cycles I-III.

locally densely developed graben formations in the western United States [McGill and Stromquist, 1979] and some highly deformed and eroded regions of ancient shields on Earth, and the Olympus Mons aureole on Mars [Francis and Wadge, 1983].

Within the area surveyed by Venera 15/16 (Figure 1a), large (up to thousands of kilometers across) and small (up to hundreds of kilometers across) occurrences of tesserae comprise about 10-15% of the surface [Sukhanov, 1986]. The surfaces in intervening areas between tesserae are dominated by smooth and rolling lava plains [Sukhanov, 1986, 1992; Sukhanov et al., 1989; Bindschadler and Head, 1989; Janle et al., 1992]. Tesserae within the northern high latitudes covered by Venera 15/16 are distributed nonrandomly and show a tendency to be clustered. For instance, large tesserae such as Fortuna, Laima, and Tellus are concentrated between 0° and 150°E. In contrast, areas like Sedna and Atalanta planitia and the fan of ridge belts between 150° and 210° (Figure 1f) have only a few occurrences of tesserae. The nonrandomness of tessera distribution and typical associations of terrains within the Venera 15/16 area provided the possibility to subdivide the mapped area into several regional geological unit assemblages [Head, 1990b; Basilevsky, 1992].

Venera 15/16 mapped the Venus surface only above about 30°N (Figure 1a), and thus the distribution of tesserae was not known below this latitude from these data. However, the prediction of tessera distribution based on typical radar properties of the tessera surface derived from Pioneer Venus data [Kreslavsky et al., 1988; Bindschadler et al., 1990] yielded an estimation of 10-20% of tessera within the whole area mapped by Pioneer Venus. This distribution suggested that tesserae tended to be nonrandomly distributed and clustered there also. Besides these predictions, direct observations of the Venus surface made from Arecibo Observatory and interpretation of these data [Campbell et al., 1991; Senske et al., 1991] showed that Alpha Regio and parts of Beta Regio also represent tessera terrain (Figure 1a).

As shown by Venera 15/16 data, tesserae are characterized by basically two types of boundaries with surrounding plains: sinuous boundaries and boundaries that are more linear at the scale of a hundred kilometers [Bindschadler and Head, 1991; Sukhanov, 1992]. The first type of boundary is the most common and is associated with all tesserae. Small patches of tessera are usually completely encircled by this type of boundary, and most of the boundaries of larger tesserae also have this sinuous contact with the surrounding plains. The sinuous
contact is interpreted as representing the embayment of surrounding plains onto the tesserae, and thus in terms of stratigraphy, this suggests that tesserae are usually relatively older than the adjacent plains. The second type occurs less frequently and often coincides with some margins of large and high-standing tessera such as Fortuna and Ovda.

Nonetheless, due to the relatively low resolution of the Pioneer Venus data and the restricted areas mapped by Venera 15/16 and Arecibo (Figure 1a), the actual global distribution and characteristics of tesserae, as well as their origin and evolution were not well understood. Some investigators considered tesserae as areas of thickened basaltic crust [e.g., Sharpton and Head, 1986; Vorder Bruegge and Head, 1989; Head, 1990a], while others considered tesserae as outcrops of nonbasaltic crust [e.g., Nikolayeva et al., 1988, 1992]. In addition, numerous hypothesis were proposed to account for the distinctive surface texture of the tesserae and their mode of formation [see review by Bindschadler and Head, 1991]. The Magellan mission global coverage and very high resolution data provide the possibility to obtain an overview of the global distribution of tesserae, to establish their stratigraphic position in more detail, to characterize and compare the deformational styles in different tessera occurrences, and to attempt to understand the place and role of tesserae in the geologic history of Venus [e.g., Solomon et al., 1992; Bindschadler et al., 1992a].

In this study we first present the global distribution of tesserae mapped using Magellan data and the standard definition of typical tessera terrains: high radar backscatter; distinctive deformational patterns (at least two intersecting trends); and standing higher than surrounding plains. We then discuss the dimensions and shapes of the tesserae occurrences and describe in detail the types of tesserae boundaries and outline the potential implications of their characteristics and distribution. We examine the nature of deformational features and the sequence of deformation in several examples of tesserae terrain as seen in the Magellan data, and conclude by reexamining hypotheses for the origin and evolution of tesserae on the basis of these new data, and the relationship of these findings to general models for the evolution of Venus.
2. Tesserae Global Areal, Size-Frequency, and Shape Distribution

Abundance and areal distribution. In order to characterize the abundance of tessera terrain we have mapped the distribution of all tesserae detected on 20 x 24 inch C1-mosaicicked image data recorder (MIDR) (~1:4,000,000) and F-MIDR (full resolution) prints available through the end of Magellan Cycle III. Where necessary, we have filled the Magellan image gaps with Venera 15/16 data. This differs from the approach of Price [1995], who compiled a global map of tesserae using only the lower resolution C2-MIDRs, and from the approach of Senske et al. [1994], who produced a geologic map from a global image at a scale of 1:50,000,000. In order to calculate the percentage of the planet covered by tesserae, we used two grids on the detailed maps consisting of either 9 x 9 or 45 x 45 km² cells. The smaller grid was used if a tessera covered less than five 45 x 45 km² cells. We used the larger grid if a tessera occurrence covered more than five 45 x 45 km² cells (about 10,000 km²). In both cases we counted all cells which were completely inside a tessera outline, added to this the half-number of cells which included a tessera boundary, and multiplied the total number of the cells by its unit area. Using this technique we measured the areas of 637 individual tessera patches over a range of individual tessera occurrences from about 200 km² up to the largest tessera, Ovda, which has an area about 9 x 10⁶ km² (about 2.5% of the mapped surface area of Venus) (Table 1). The combined area of all tessera occurrences measured is about 35.33 x 10⁶ km². Thus the total tessera area comprises about 7.7% of the surface area of Venus mapped after the Magellan Cycles I-III. This number is less than the 10-15% given by Sukhanov [1986], owing to the fact that his estimates were based on the Venera 15/16 data (the northern hemisphere of Venus above about 30°N) while our estimate is based on global Magellan mapping which reveals a global asymmetry in the tessera areal distribution (Figures 1 and 2).

The global distribution of tesserae over the surface of Venus visible after Magellan Cycle III (Figures 1b and 2) shows that tessera occurrences of different size and shape are widespread.
and nonrandomly distributed. A major discrepancy exists in the distribution of tesserae in the southern high latitudes (Figure 2b) relative to the north (compare Figures 2c and 2d); there is no equivalent in the south of the extensive large tessera blocks associated with Ishtar Terra, thus accounting for the lower global abundance of tesserae (about 8%) relative to that mapped for the Venera 15/16 area (10-15%). Peaks in the tessera distribution occur at 0° to 135° longitude and +10° to -15°, and +60° to +75° latitude (Figures 2a and 2b).

Size Distribution. The size of individual tessera occurrences varies over a wide range from the limit of resolution to a few thousands of kilometers. The smallest tessera measured is about 14 km long and 9 km wide, while the largest tessera, Ovda, has dimensions of about 5700 by 2100 km. The size distribution of tessera patches over the whole range of tessera areas is strongly unimodal and skewed toward smaller areas (Figure 3a). The mean tessera fragment size is 209 km x 93 km and the median is 99 km x 45 km. The unimodal distribution reflects the great abundance in the tessera population of small tessera fragments with areas less than about 10,000 km² and typical dimensions about 80 x 40 km. However, the plot of area fraction of tesserae binned by factor 2 intervals versus tessera area (Figure 3b) demonstrates two recognizable breaks of slope at about 30,000 km² and 500,000 km², suggesting three subdivisions of tessera massifs. Accordingly, we have subdivided the population of tesserae into the following groups (Table 1). Large tesserae (Ovda, Fortuna, Tellus, etc.) are regions with a typical area of about 2 million km², a typical length and width about 2600 by 1300 km, and aspect ratios averaging about 2.1. Eleven tesserae belong to the large tessera class. This number makes only 1.8% of all tessera occurrences, but the total area of the large tesserae comprises about 68% of the tessera terrain on Venus and about 5.5% of the surface of the planet. Medium-sized tesserae (Kutue, Shimti, Moira, etc.) are represented by about 60 occurrences with a typical area of about 140,000 km²;
and characteristic lengths and widths of about 720 by 370 km. Average aspect ratios of the medium-sized tesserae are about 2.6. About 10% of all tesserae belong to this class, and the class makes up about 23% of the tessera terrain surface. Small tesserae (individual parts of Manzan-Gurme tesserae, Nemesis, etc.) are the most numerous tesserae occurrences and have typical areas of about 5500 km², typical aspect ratios of about 2.6, and typical dimensions of about 130 by 90 km. Although about 88% of all tesserae occurrences are in this size class, the total area of the small tesserae comprises only about 9% of the whole tessera population.

Shape Distribution. In terms of shape, as a population tessera patches are equidimensional to elongated massifs with irregular outlines and length to width ratio (L/W) from 1:1 up to 13:1. The median L/W ratio is 2.1:1 and the mean is 2.6:1. The frequency distribution of the tessera L/W ratio values (Figure 3c) is strongly unimodal and skewed to smaller values, with the peak in the interval from 1:1 to 2.5:1. About 63% of all tessera massifs are within this interval (e.g., Moira (L/W=1.15); Tellus (L/W=1.21); Manzan-Gurme (L/W=1.99)). About 33% of the tessera occurrences have an aspect ratio from 2.5:1 to 6:1 (e.g., Ovda (L/W=2.73); Meshkenet (L/W=4.58); tessera inside the fan of ridge belts (L/W=4.78)). Only 4% of all tessera patches have a ratio higher than 6:1.

3. Modes of Occurrence, Elevation Distribution, and Relation to Other Features and Structures

Modes of occurrence. Three modes of occurrence are observed for tessera patches and these also emphasize the non-randomness of tessera distribution (Figures 1a-1c): clusters, arc-like segments, and tesserae rare or absent.

The first mode of occurrence of tessera terrain is characterized by the existence of several broad clusters. Geographically, the large and medium-sized tesserae which make up the majority of tessera terrain are concentrated in four main clusters. The first one (Figure 1c) is centered at Aphrodite Terra (Ovda, Thetis, two unnamed tesserae northward from Thetis) and it contains about 40% of all tessera terrain area on Venus. The second one is at Ishtar Terra (Fortuna, Laima, Tellus, etc.), and about 30% of the total tessera terrain belongs to this cluster. The third cluster is at Phoebe-Beta Regiones and contains about 10% of the total tessera terrain. The fourth cluster extends southwestward from Alpha Regio along the eastern edge of Lavinia Planitia to the northern edge of Lada Terra. It contains about 5.7% of the total tessera area. The Ishtar and Aphrodite clusters together make a broad band which begins at Atropos Tessera and continues toward the southeast, including the large tessera segments Fortuna, Laima, Tellus, and the
medium-sized Meshkenet and Ananke tesserae, south to Theis Regio. There the band turns to the west, runs along Western Aphrodite and through dispersed small tesserae extending to Alpha Regio, where again the trend changes and continues to the south to Lada Terra at about 65°S, 15°E.

In the second mode of occurrence, tessera appears as arc-like arrangements of equidimensional and elongated patches inside or adjacent to some of the above clusters. These arc-like bands may extend for thousands of kilometers. Examples are (Figure 1c) tesserae bordering Lakshmi Planum, the eastern part of Tellus and Dekla tesserae, Kutue-Ananke tessera chain, the chain including unnamed tessera inside the fan of ridge belts and Nemesis tessera, tesserae at the northern margin of Beta Regio, and at Phoebe Regio. In the case of the first several of these occurrences, the arcs are concave away from the major tessera cluster development (Figure 1c). In other cases, such as at Beta and Phoebe, they are concave toward the area of more abundant tessera patches.

The third mode of occurrence includes areas where tesserae are rare or absent (Figure 1c). These regions consist of two contrasting types with respect to elevation, tectonics, and volcanism. The first type is represented by vast, smooth, low-lying plains like Guinevere, Lavinia, Aino, and Navka planitiae (Figure 1a, 1c, 1d, 1f). The surface of the plains commonly consists of a sequence of lava flows [Solomon et al., 1992; Squyres et al., 1992]. The second type of area where tesserae are scarce is represented by elevated regions like Eastern Aphrodite, Atla, and Ulfrun Regiones (Figures 1a, 1d), where linear graben and fissures (Figure 1g) in association with corona and corona-like features are the most important structures [Senske, 1992; Senske et al., 1992].

**Relationship to elevation.** Tessera hypsometry as a whole (Figure 4a) tends to be bimodal (Figure 4b), with the greatest portion of tesserae concentrated at intermediate elevations (peak between 0 and +1 km), within the topographic province of rolling plains established by Masursky et al. [1980]. There is a general positive correlation between tessera area and mean elevation. The largest of the large tessera massifs (Ovda, Fortuna, Theis) tend to occur at higher elevations (the second peak centered at about 3 km) and to dominate the tessera/altitude correlation (compare Figure 1d and Figures 4a–4c); only Itzpapalotl and Atropos of the intermediate tesserae, both located just outboard of folded mountain belts in Western Ishtar Terra, approach these elevations. These occurrences differ from most other intermediate-sized occurrences (e.g., Tellus, Laima, Alpha, Phoebe, Lada, and Ananke), which all peak between 0 and 2 km elevation. In terms of number of occurrences, however, tesserae do not display a strong correla-
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![Figure 2a](attachment.png)

**Figure 2.** Distribution of tessera terrain. Histograms showing the distribution of tesserae (a) with longitude and (b) latitude. Percentages are the amount of area covered by tessera terrain in each bin relative to the total area of that bin. The location of the hemisphere with most abundant tessera is shown in Figure 2c (centered on 15°N, 60°E) and the hemisphere with the least abundant tessera is shown in Figure 2d (centered on 60°S, 215°E).
Figure 3a. Size-frequency distribution of 637 individual tesserae occurrences.

Figure 3b. Incremental size-frequency distribution of 637 individual tessera areas binned by factor of 2 area bins.

Figure 3c. Frequency distribution of aspect ratios of 637 individual tessera occurrences.

tion with elevation at the global scale, since a large number of small tessera patches commonly occupy low-lying regions (Figure 1d).

Relationship to other features and structures. Comparison of the tessera distribution map and the global contour map of volcanic center spatial density (Figure 1e) shows that there is an anticorrelation between the density of individual volcanic centers [L. S. Crumpler et al., Volcanic and magmatic features on Venus: A global survey, submitted to Special Papers of the Geological Society of America, 1996] and large tesserae occurrences. In addition, broad lowland volcanic plains areas that show very low volcanic center density also show low tessera density, being made up mostly of small tessera patches or no tessera occurrences (Helen-Lavinia, Aino, Atalanta; compare Figures 1c-1e). Comparison of the
global distribution of ridge belts and mountain belts (surrounding Lakshmi Planum) (Figure 1f) shows that large tessera clusters are not correlated with the occurrence of ridge belts, which occur mostly in the lowlands, and that mountain belts are closely related to tessera in western Ishtar Terra. The global distribution of fracture belts (Figure 1g) shows that fracture belts are associated with the high concentration of volcanic features (compare Figures 1e and 1g) [Crumpler et al., 1993], and are associated with some large tesserae occurrences (Aphrodite, Beta-Phoebe) but not with others (Ishtar, Laima, Tellus).

4. Tessera Boundaries

Characterization of the boundaries of the tessera with the adjacent terrain provides important information in establishing the stratigraphic position of tesserae, and in understanding modes of tessera formation and evolution. As the plains and tesserae are the two most widespread units on Venus [Barsukov et al., 1986; Sukhanov, 1986; Bindschadler and Head, 1989; Janle et al., 1992], we have examined closely the types of contacts between these terrains and mapped them globally. As shown by previous work based on Venera 15/16 and Arecibo data [Sukhanov, 1986, 1992; Bindschadler and Head, 1991], tesserae have basically two types of boundaries with surrounding plains and these types of boundaries were found to characterize the global population of tesserae as well (Figure 5). In our analysis, we examined the boundary characteristics of all 637 tessera patches using the two classification categories and also found that we could subdivide the two main types into several distinctive subtypes. For the large- and medium-sized tesserae occurrences, we calculated the lengths of the different types and subtypes characterizing the boundaries and tabulated the results both regionally and globally. Type I (sinuous/embayment) boundaries have very sinuous outlines due to deep embayment of lava plains into tessera massifs along local depressions and troughs between ridges at the tessera edges; this type of boundary is the most common (Figures 5-8; Tables 2a and 2b). About 73% of the large- and medium-sized tesserae are completely encircled by, or have large portions of, Type I boundaries (Figure 5). Type II (linear/tectonic) boundaries are more linear at the tens to hundreds of kilometers scale (Figures 5 and 12) but may demonstrate plains embayment at the finer scale. This type of boundary is less abundant (Tables 2a and 2b) and often associated with large-scale tectonic features within tessera massifs. Examination of the global boundary distribution map (Figure 5) shows that Type II (linear/tectonic) boundaries are often concentrated on one side of a major tessera development (e.g., northern edge of Western Ishtar, northern and western edge of Fortuna Tessera, northern parts of Ovda and Theis regions, western edge of Alpha Regio) and that they are also associated with the arc-like segments of tesserae (compare Figure 5 and Figure 1e).

Examples of Type I (sinuous/embayed) boundaries are numerous, and tesserae of all size classes possess such boundaries; two subtypes of Type I boundaries are recognized. The first one (angular/blocky boundary) shows very sinuous but sharp and continuous boundaries with only a few small tessera fragments within the surrounding plains (Figure 6). The second subtype (diffuse/digitate boundary) is characterized by a relatively wide transition zone between tessera and plains.
Figure 4c. Hypsograms for individual major tessera occurrences.
consisting of a number of small tessera blocks completely separated from the main tessera by lavas (Figure 7). The angular/blocky boundary is usually marked by a low scarp, whereas the diffuse/digitate boundary has no clear topographic signature. For the large tesserae the angular/blocky and diffuse/digitate boundary subtypes comprise about 60% and 40% of the total length of the Type I boundaries, respectively. For the medium-sized tesserae the majority of the Type I boundaries (75%) is of the angular/blocky subtype (Table 2b).

Tessera Ananke represents an example possessing mostly the angular/blocky boundary (Figure 6); here lava plains either penetrate into the tessera massif or separate large tessera blocks from each other. Occasionally the boundary of the tessera becomes angular at the scale of kilometers to tens of kilometers. Apparently, embaying lavas have followed intratessera linear structural trends. The boundary between the plains and tessera is sharp and clearly distinguishable, yet it demonstrates an overall Type I embayment relationship. In many places locally, a low scarp characterizes the transition from the plains to tessera. The lava embayment characteristic of the Ananke boundary provides evidence for the relatively young age of the lava plains, rather than an active tectonic boundary at the edge of the tessera. The sharp contact between the plains and tessera suggests that the topography of this massif originally consisted of blocks a few hundred kilometers across surrounded by low scarps.

The southern flank of Alpha tessera is an example of the diffuse/digitate boundary (Figure 7), where young plains-forming lava flows originating from Eve corona embay deeply into the Alpha tessera massif, leaving only high tessera ridges exposed. Sometimes, lava plains completely separate ridge fragments from the main tessera massif, giving the impression that the fragments are like "islands." The same or similar relationships of tesserae and surrounding plains occur at the other large tesserae (Figure 5, e.g., part of the southern margin of Ovda and Fortuna tesserae, western flank of Laima). As in the case of the angular/blocky boundary, the diffuse/digitate boundary also shows lava flooding of the preexisting tessera. The presence of the diffuse boundary suggests that tessera fragments with such a boundary probably had a more monotonous structure at the scale of several tens to a hundred kilometers but more disrupted at the scale of a few to tens of kilometers. Tessera fragments with both boundary subtypes occur commonly. Although the origin of the different scales is not known, it is possible that tessera blocks possessing a predominance of the diffuse boundary may represent regions of more homogenized relief due to relatively older age and more advanced states of relaxation. However, morphological evidence for post-plains-embayment deformation is not common in either Type I boundary subtype.

Small tessera patches display Type I (sinuous/embayment) boundaries almost everywhere on Venus where small tesserae occur (Figure 8). Type I angular/blocky or diffuse/digitate subtypes usually completely encircle small tessera fragments. Sometimes one can see clusters of closely spaced tessera pieces (Figures 8a-8d). Such clusters of small tesserae strongly resemble the previously described cases either of the angular/blocky boundary where lava plains completely encircle relatively big tessera blocks with recognizable structural pattern or of diffuse/digitate boundary where lava plains separate small blocks of closely spaced tessera ridges into islands. Many of the clusters of small tesserae may represent outcrops of larger tessera massifs almost completely flooded by lava plains, a point we will return to in later discussion.
Figure 5. The global distribution of tessera boundary types. Type I (sinuous/embayed) shows no symbol at the tessera boundary, and Type II (linear/tectonic) is represented by a thick line and teeth at the tessera-plains boundary. The first type, sinuous boundaries, is much more common and usually associated with small tesserae, but a large portion of the large and medium-sized tesserae also have this type of the boundary. The second type, linear boundaries, is less widespread and usually associated with large and medium tesserae.

Type I boundaries show an embayment of tessera by surrounding lava plains; there is strong evidence that tesserae are the older terrains in each case we examined. The predominance of Type I boundaries (Figure 5; Table 2b) suggests that tesserae, taken as a type of terrain, are commonly the relatively older geological complexes on Venus. The sinuosity of Type I tessera boundaries is similar to margins of the lunar highlands (Figure 9), where young mare lavas flood highlands and also embay local crater depressions and troughs [Head, 1982]. By crater density observations and direct measurements of absolute ages, it is well known that the lunar mare material is younger than highlands [e.g., Taylor, 1982]. The sinuous tessera boundaries on Venus also mean that tesserae are at least locally older than surrounding plains. In order to establish whether the tesserae are older than most of the rest of the

Figure 6. Type I (sinuous/embayed) tessera boundary example (blocky/angular subtype): part of Ananke Tessera. Lava plains either penetrate into the tessera massif or separate large fragments of the tessera. Note the blocky and angular edges of some of the fragments. (C1-MIDR.45N138; the image is 960 x 827 km.)
plains of Venus, the relationships between the plains embay
the margins of the tesserae, and those in the large inter-
tesserae areas must first be established by detailed geologic
mapping. Geologic mapping of 36 regions [Basilevsky and
Head, 1995a] and several larger areas [Basilevsky and Head,
1995b] support the older age for the tessera in each case. Data
on impact crater density on tesserae [Ivanov and Basilevsky,
1993] suggest that tessera terrains on the whole are older than
the intervening plains.

In addition to relative age relationships, the sinuosity of the
highland shoreline (Figure 9) and the number of highland
islands (kipukas) flooded by the maria, indicate the
shallow angle of dip of the highland material under the maria
[Head, 1982]. In general, the shallower the angle of dip of
the surface of a preexisting terrain, the deeper the penetration of
a subsequent plains-forming material emplaced as a fluid, and
the higher the sinuosity of the final boundary between the two
terrains. On the basis of the similarity in appearance of the
boundaries of the lunar highlands and Venus tesserae, it ap-
pears likely that the more sinuous Type I boundaries are also
characterized by a shallow angle of dip under the plains. This,
in turn, suggests that in these areas, tessera material may un-
derlie the lava plains between the tesserae massifs. An example
of this relationship is illustrated at the northeast edge of
Alpha Regio tessera where the contact between tessera and sur-
rrounding plains is Type I, sinuous/embayment (Figure 10a).
Alpha tessera is surrounded by vast smooth plains whose sur-
face is made up of lavas formed during several eruption
episodes; their relative ages are firmly established by stratig-
ographic relationships. Within the plains, several small

patches of tesserae are visible, and all of the patches have
Type I boundaries, indicating that tesserae are the older units
(Figure 10b). The topographic profile and geologic cross-
section (Figures 10c and 10d) across the area shows that Alpha
tessera and the small tessera patches are relatively high stand-
ing areas. The sharp breaks in the profile coincide with the
geological contacts of tesserae and lava plains; the plains oc-
cupy gentle depressions between the tessera highs. Such
stratigraphic and topographic relations are interpreted to mean
that tesserae represent outcrops of gently undulating preexist-
ning basement, the majority of which have been buried under
the uppermost thin layered complex of lava plains (Figure
10d). The association of the plains and depressions is quite
natural because fluid products of volcanic eruptions should fill
in the lows of the preexisting terrain.

Topographic profiles across Type I (sinuous/embayment)
boundaries (Figures 11a and 11b) show evidence of shallow
slopes away from the edge of the tessera and of the presence of
tessera massifs in the vicinity of the boundaries, as seen in the
Alpha example (Figure 10). The profile across the south-west-
ern portion of Ovda (Type I boundary, blocky/angular sub-
type) (Figure 11a) shows a gentle stair-like slope of the
tessera surface toward the plains. The tilted edge of the tessera
extends over 160 km at a slope of about 0.7° (1.25 km to
about -0.75 km), providing an estimate of the gentle tilt of at
least some tessera under the surrounding plains. At the contact
with the plains, the tessera is bounded by a low scarp not read-
ibly visible in this profile. The Type I boundary
(diffuse/digitate subtype) is shown at the northeastern edge of
Phoebe (Figure 11b), and as with the previous case, the topog-
raphy slopes gently toward the plains. However, in this case
of a sinuous boundary, the slope is as little as about 0.2°, and
the coherent tessera mass is separated from the plains by
numerous small kipukas of tessera, and there is no boundary
scarp. These relationships add further support to suggestions
that adjacent volcanic plains postdate tesserae in regions with
these boundaries, and that tessera terrain extends underneath
larger portions of the surface of Venus adjacent to the tessera
in the regions characterized by these embayed boundaries.

Type II (linear/tectonic) boundaries are more linear at the
hundreds of kilometers scale but also show plains embayment
at the finer scale. On the basis of our global analysis (Figure 5),
27% of the total boundaries measured are Type II (Tables 2a
and 2b). This type of boundary is often associated with large-
scale tectonic features on tesserae massifs. Examination
of the global boundary distribution map (Figure 5) shows that
Type II boundaries are often concentrated on one side of a ma-
jor tessera development and bordered by steep-sided scarp
(e.g., northern edge of Western Ishtar, northern edge of
Fortuna Tessera, northern parts of Ovda and Theitis regions,
western edge of Alpha Regio) and that they are also associated
with the arc-like segments of tesserae (compare Figure 5 and
Figure 1c). Several typical Type II boundaries are shown in
Figure 12, and an example of a Type II boundary associated
with an arc-like segment in Phoebe Regio is shown in Figure
13. The topographic profiles show that in many cases of the
Type II boundary, tessera terrain is usually on the summit of
high-standing plateaus often surrounded by a scarp, which can
be as high as several kilometers. The most prominent features
in tesserae with a predominance of Type II boundaries are long
ridges, which are subparallel to the boundary. This is charac-
teristic of elevated tessera occurrences like Ovda and
Iztpapalotl tesserae (Figures 12a and 12c) and of less elevated tesserae like those at Beta Regio (Figure 12c).

Another characteristic of tessera boundaries shown by these profiles is the tilting of plains units that embay or abut the tessera boundary (see profiles in Figures 10c, 12b, and 12f). In both Figures 12b (Ovda) and 12f (Beta), for example, the plains decrease in elevation almost 1 km within a distance of about 200 km from the tessera/plains boundary. This is a characteristic that has been noted previously elsewhere (Alpha Regio [Gilmore and Head, 1992]; Ovda and Kutue tesserae [Tormanen, 1995]; Phoebe Regio [Chapman, 1995]; and also inboard of the Western Ishtar Terra mountain belts such as Freyja Montes, see Head [1990c], and Figure 12d); these relationships imply post-plains-emplacement relative movement and tilting (e.g., subsidence of the plains and/or uplift or gravitational relaxation of the tessera) [Head and Ivanov, 1996; Saunders, 1996]. This phenomenon is particularly well-illustrated in perspective views of areas such as northern Ovda Regio (Figure 12g).

On the basis of detailed mapping of Type II boundaries, we recognize four subtypes.

Parallel fabric (PF) subtype. The first subtype is characterized by long ridges and troughs which are oriented subparallel to parallel to the tessera edge and are generally undisturbed by finer-scale features. This is the second most abundant subtype: 29% of the total length of the Type II boundaries of the large tesserae and only about 8% of the linear boundaries of the medium-sized tesserae belong to the PF
Table 2a. Characteristics of Tessera Terrain Boundaries: Length of Boundary Types

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PF, parallel fabric boundary subtype; HAF, high-angle fabric boundary subtype; RD, ridge belt boundary subtype; MT, mountain belt boundary subtype.

Table 2b. Characteristics of Tessera Terrain Boundaries: Percentages of Boundary Types

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PF, parallel fabric boundary subtype; HAF, high-angle fabric boundary subtype; RD, ridge belt boundary subtype; MT, mountain belt boundary subtype.

Figure 9. Contact of the lunar highlands (Apennine Mountains) and mare along southeastern Mare Imbrium. Embayment of highlands by mare lavas is clearly seen and strongly resembles the contact of tessera and lava plains along Type I boundaries on Venus. Archimedes crater at the top of the image is 82 km diameter.

This boundary subtype usually coincides with the high elevated edges of the tessera and regional scarp bounding high-standing tessera plateaus, for example, the north flanks of Ovda (Figures 18a and 12a) and Itzpapalotl (Figures 18c and 12c) tesserae. At the most elevated northern margin of Ovda Regio between about 63°E and 73°E, large-scale features along the margin are more organized and subparallel to the tessera-plains contact (Figure 12a). Elevations across this boundary change about 1.3 km over a lateral distance of about 9.4 km, producing average slopes as high as 8° (Figure 12b). In contrast, the less elevated tessera to the south from the edge shows a more chaotic pattern of deformation and has a diffuse boundary. At some locations inside the zone of subparallel ridges, fragments of chaotically deformed tessera are seen, suggesting that this zone may be younger than the central parts of Ovda. The structural pattern typical of the northern edge of Ovda in combination with its high topography and steep slopes suggest that this portion of the tessera was formed under compressional conditions (Figure 18a). Because of the steep slope at the tessera margin, embayment relationships between tessera and plains are unclear, but the plains, in contrast to the tessera, are smooth with only minor deformation on their surface and on this basis are presumably younger. Clear evidence of lava flooding along the PF subtype is seen along another portion of the Ovda boundary from about 80°E to 90°E. Similar relationships are observed along the northern flanks of Itzpapalotl Tessera (Figures 12c and 12d) [Head, 1990c; Suppe and Connors, 1992]. Thus the PF linear-boundary subtype in these areas and several others we have examined appears to have formed by lava flooding of highly compressed edges of tessera.

High-angle fabric (HAF) subtype. This subtype is characterized by fine-scale internal tessera features oriented at high angles to the tessera linear boundary. About 55% of the total length of the Type II boundaries of the large tesserae and about 86% of the linear boundaries of the medium-sized tesserae belong to the HAF subtype (Tables 2a and 2b).
Figure 10. Geological map and reconstruction of the area at the northeastern edge of Alpha Regio. (a) Magellan image of region, showing location of mapped area (C1-MIDR.15S009). (b) Geological sketch map and legend for the area shown in Figure 10a. (c) Topographic profile extending SW-NE across the mapped area; see Figure 10b for location. Vertical exaggeration is 17x. (d) Interpretative cross-section superposed on topographic profile.
and closely spaced ridges and grooves characteristic of the HAF subtype cross, as a rule, the larger-scale ridges and depressions which are several hundreds of kilometers long and oriented subparallel to the tessera edge. An example of the HAF subtype boundary is illustrated by tessera on the western slope of Beta Regio (Figure 12e). The tessera shows east-west oriented first-order ridges and troughs with spacing of several tens of kilometers, and crossed by north-south-oriented second-order features spaced a few kilometers apart. The westernmost end of the tessera (not shown) and fragments of the southern edge of the tessera where the large E-W features are terminated by lava plains have Type I (sinuous/embayment)
Figure 12a. Type II (linear/tectonic) tessera boundary example: northern margin of Ovda Regio. The elevated tessera edge is terminated by a large steep scarp, and ridges and troughs inside the tessera are oriented subparallel to the margin (C1-MIDR.00N077). Image is 680 x 560 km. Bar shows location of topographic profile in Figure 12b and is 450 km in length.

boundaries caused by penetration of lava plains into tessera either between larger ridges or finer ones. Probably the larger features, remnants of which are seen within the tessera, represent the oldest recognizable stage of tessera deformation disrupted later by the finer features. Here, and in numerous other examples we have examined, both sets of tessera structures have been flooded by lava plains and, depending on the orientation of the large-scale features, one observes either a linear or sinuous boundary. Thus the two most abundant subtypes of

the Type II linear boundary show clear evidence of lava embayment. This, as in the case of the Type I boundary, suggests that tessera terrain is the older geological unit relative to surrounding plains and that tessera material extends underneath the cover of these plains.

Ridge-belt boundary subtype. The third subtype of the Type II linear tessera boundary is seen where ridges and ridge belts on plains surrounding tessera coincide with the tessera margin [Tormanen, 1993, 1995; Gilmore and Head, 1992, 1993]. This boundary subtype is relatively rare and occurs mostly at large tesserae: about 14% of their linear boundaries belongs to this subtype (Tables 2a and 2b). In contrast to the first two tessera boundary subtypes, this one usually does not display lava embayment into tessera massifs. For instance, at the easternmost edge of Ovda tessera the boundary is marked by a low scarp and both the tessera and lava plains appear to be disturbed by a ridge belt which is a relatively younger feature. Similar situations are observed between Laima and Dekla tesserae, along the northeast edge of Laima, at the western boundary of Tellus, and along some portions of the northern margin of Fortuna Tessera (e.g., Semuni Dorsa, Dyan-Mu Dorsa [Vorder Bruegge and Head, 1990]). The western flank of Alpha tessera (Figures 14a and 14b) is bounded by series of west-facing scarps which merge with a belt of sharp-crested ridges at the base of the tessera [Bindschadler et al., 1992a]. Gilmore and Head [1992, 1993] have shown that the plains adjacent to the western margin of Alpha have been sequentially incorporated into the ridge belt-tessera terrain. It is unclear whether tectonic movements within the plains, tessera tectonism, or a combination of both, led to formation of this sort of boundary. However, its scarcity suggests that it is not evidence for extensive ongoing tessera formation, and most evidence points to tesserae as relatively tectonically stable terrains.

Mountain-belt boundary subtype. The fourth subtype of the Type II linear tessera boundary occurs along contacts between tesserae and mountain belts and is observed only at tesserae encircling Lakshmi Planum (Figures 1f, 12c, 12d). The boundary extends along a break in topography between the relatively flat tessera plateau and the highly elevated mountain range (e.g., Atropos Tessera and Akna Montes;
14,882 IVANOV AND HEAD: TESSERA TERRAIN ON VENUS

320øE  330øE  340øE

75øN - 70øN - 75øN -

37øN - 34øN - 31øN -

70øN - 332øE

Figure 12c. Northern flank of western Ishtar Terra with high-standing smooth Lakshmi Planum and heavily deformed belts of Freyja Montes and Itzpalotl tessera surrounded by low-lying Snegurochka Planitia. (C1.MIDRP.75N338;2). Image is 770 x 1073 km. Bar shows location of topographic profile in Figure 12d and is 1025 km in length.

Itzpapalotl Tessera and Freyja Montes; Fortuna Tessera and Maxwell Montes). This type of boundary, as the previous one, displays almost no lava embayment and is due to tectonics at tessera edges and also is very rare; only 2% of the total length of large tesserae linear boundaries and 4% of the medium-sized tesserae linear boundaries are of this subtype (Tables 2a and 2b).

The total length of the boundaries of the large and medium-sized tessera that show flooding and embayment relationships (Type I boundary, angular and diffuse subtypes; Type II boundary, PF and HAF subtypes) is 311,900 km. This is 97% of the total length of large and medium-sized tessera (321,980 km). Addition of the small-sized tessera patches would increase this percentage, since virtually all of these show embayment relationships. In summary, detailed study of the tessera boundaries reveals that more than 97% of the total tessera boundary length shows evidence of lava flooding and only a negligible part (<3%) of tesserae boundaries could be interpreted as tectonically active during the emplacement of the plains (primarily the ridge-belt and mountain-belt boundary subtypes, and possibly a small percentage of the HAF subtype) (Table 3). This analysis suggests that tessera is the oldest terrain on Venus and has been relatively stable tectonically (from the standpoint of observable deformational structures) since near the time of its formation, an interpretation consistent with other stratigraphic relationships [Basilevsky and Head, 1995a, b]. Broad tilting of volcanic plains adjacent to some large and medium tessera occurrences occurs after their emplacement, however [e.g., Head and Ivanov, 1996; Saunders, 1996].

5. Deformation Patterns Within Tessera

In order to assess the relationship between tessera aspect ratios, structural characteristics at and adjacent to tessera boundaries, the internal fabric of deformational patterns within the tessera, and the relationships between tessera occurrences, we individually mapped the main structural trends within each of the major tessera patches using C2-MIDRs as a base. Major features mapped included linear and arcuate ridges, troughs, and chevron-like structures. A summary of these maps was compiled and is displayed in Figure 15, and only features and structures visible at the scale of this figure are shown.

As seen in Figure 15, major tessera features inside large tessera regions usually have different orientations and do not form a single trend either inside one tessera or between them. Examples of this are seen in the Aphrodite and Ishtar tessera clusters. For instance, Ovda tessera consists of three parts: western, with an arc-like northern margin displaying sets of ridges parallel to the tessera edge and a chaotically organized central area where, nevertheless, ridges and troughs of finer scale (below the scale of Figure 15) are mostly oriented in a NE direction; central, where deep narrow troughs cut the tessera fabric and have an EW orientation; and eastern, where arc-like

70øN, 332øE  79.5øN, 340øE

Figure 12d. Topographic profile across the northern portion of western Ishtar showing that Ishtar Terra, like Ovda Regio, is bounded by a steep scarp which is close to the edge of Itzpalotl tessera. Vertical exaggeration is 21x.
Figure 12e. Portion of a tessera block located on the western slope of Beta Regio. There are two main sets of tectonic features in this tessera: long ridges which run parallel to the tessera margin, and relatively short narrow graben oriented perpendicular to the longer ridges (F.MIDRP.30N256;1). Bar shows location of topographic profile in Figure 12f and is 300 km in length. Image is 364 x 509 km.

Figure 12f. Topographic profile across the northern boundary of the Beta Regio tessera fragment (Figure 12e). Tessera/plains contact is marked by a 500-m scarp. Note that the surface of the plains is tilted up toward the tessera, which is typical of many zones of plains at tessera boundaries. Vertical exaggeration is 35x.
Figure 12g. Perspective views of the northern border of Ovda Regio and the adjacent plains in Niobe Planitia looking N-S, S-N, W-E, and E-W. Area viewed is approximately 745 km wide in latitude and 745 km wide in longitude. Post-tessera volcanic plains (dark) are clearly tilted [see Head and Ivanov, 1996]. Compare to topographic profiles in Figure 12b.
and chevron-like major features are mostly in the NS and NW directions. Thetis tessera, which is a continuation of the Ovda tessera trend, has a central region with chaotically oriented fine-scale ridges and troughs (below the scale of Figure 15). The Thetis region seems to be enclosed by three elongated marginal areas where the large-scale features are parallel to the general elongation of the area and run in EW, WNW, and NE directions, respectively. Fortuna tessera, as it had been mapped based on Venera 15/16 data by Sukhanov [1986], Vorder Bruegge and Head [1990], and Grosfils and Head [1990], can be divided into several large fragments with specific orientation of their first-order features. Large tesserae near Fortuna, as in the case of the Aphrodite cluster, also possess internal domain-like structure consisting of blocks with different major structural trends. For instance, Laima tessera in its western part consists of short ridges and troughs of NE and NW orientation (too fine-scale to be shown in Figure 15) which are cut by EW to WNW long narrow troughs in the south-eastern part of the tessera. Tellus Regio is divided into west, central and east domains where the major features are oriented NS, NW, and again NS, respectively.

Thus the major feature orientation varies both inside large tessera regions and between them, suggesting that the large tesserae may be mosaics of fragments or tectonic domains several hundreds of kilometers across. Tessera domains are

Figure 13. Type I and II tessera boundary example: arc-like tessera at Phoebe Regio demonstrating both types of boundaries. Northern flank of the tessera shows sinuous, embayed contact with surrounding plains, while the southern boundary is linear at the scale of hundreds of kilometers and is a Type II boundary (C1-MIDR.00N266). Image is 636 x 745 km.

Figure 14a. Western flank of Alpha Regio, where the tessera terrain typical of this highland is in contact with a belt of parallel ridges and grooves (C1.MIDRP.30S351;1). Bar shows location of topographic profile in Figure 14b and is 550 km in length. Image is 673 x 946 km.
merged with each other and usually have no distinct boundaries other than the contrast in orientation of the structural fabric. It may be that these large tessera fragments with their distinctive orientation of major features represent intratessera blocks of different age and deformational style. Such a patch-like structure of the large tessera regions could be explained by lateral accretion of independent preexisting blocks into a single tessera massif [e.g., Vorder Bruegge and Head, 1990; Chadwick and Schaber, 1994], by tectonic activity within more or less independent areas of coherent tessera [Sukhanov, 1986], or by both. Alternatively, various orientations could be due to different manifestations of tectonic deformation in a single event, either through contemporaneous tectonic facies (Figure 18) [e.g., Vorder Bruegge and Head, 1989; Hansen, 1992] or through variation in the evolution of different parts of contemporaneously deformed material (e.g., responses to variations in the brittle-ductile transition [Suppe and Connors, 1992], higher altitude terrain undergoing synorogenic collapse [Bindschadler and Head, 1989; Solomon et al., 1992]).

In a manner similar to the patch-like internal pattern of large tesserae, smaller isolated tessera patches often display trends of their major features which are common for several tesserae; these usually form tessera arc-like bands (Figure 15). These arcs are formed of individual linear occurrences making up linear tessera chains from hundreds of kilometers up to a few thousands of kilometers long. Along-strike dimensions of the arcs are roughly comparable with the size of the domains inside the largest tessera Ovda but several times larger than blocks inside other tesserae. As a rule, tessera arc-like bands consist of tesserae which are elongated and slightly elevated above the surrounding plains. An exception to this is the high-standing Itzpapalotl, part of the mountain-tessera complex surrounding the northern flank of Lakshmi Planum.

At least six tessera arcs showing common trends of their major features are seen on Venus (Figures 1c and 15): sickle-like Phoebe tessera, tesserae along the northern flank of Beta Regio, tesserae surrounding Lakshmi Planum, Dekla-Tellus tessera complex, Kutue-Ananke tessera chain, and the tessera chain which begins at unnamed tessera inside the fan of ridge belts and includes Nemesis tesserae. Linear boundaries embayed by lava plains are characteristic of tesserae making up these arcs. If these tessera terrains are placed in order starting from the single continuous Phoebe tessera and going through the tessera surrounding Lakshmi, the Dekla-Tellus tesserae, to the Nemesis tessera chain, it is noted that their appearance changes continuously from a single coherent massif (Phoebe) to a set of small pieces arranged along a single structural trend (Nemesis chain). It is possible that these arcs could represent different degrees of lava flooding of large tessera blocks (compare Figures 15 and 17) or a range of stages in tessera evolution with arcs representing older, more gravitationally relaxed tessera blocks. Detailed geologic and stratigraphic mapping of tessera and intertessera plains is necessary to assess these possibilities.

In summary, several striking observations and correlations emerge from examination of these deformation patterns. First, for tessera fragments with high aspect ratios, internal structural trends tend to be parallel or subparallel to the long axis, particularly along the outer portions of the tessera occurrences. Second, these internal structural trends are also often coincident with Type II (linear/tectonic) tessera boundaries (for example, at northern Ovda and eastern Tellus). Third, regions of arc-like tesserae, such as those in Beta-Phoebe and

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#### Table 3. Length and Percentages of Flooded and Unflooded Tessera Boundaries

<table>
<thead>
<tr>
<th>Tessera Size Class</th>
<th>Flooded Boundary</th>
<th>Unflooded Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length, km</td>
<td>%</td>
</tr>
<tr>
<td>Large</td>
<td>151,355</td>
<td>47</td>
</tr>
<tr>
<td>Medium-sized</td>
<td>160,120</td>
<td>50</td>
</tr>
<tr>
<td>All</td>
<td>311,475</td>
<td>97</td>
</tr>
</tbody>
</table>
Figure 15. Map illustrating the major structural and tectonic trends within the larger blocks of tessera terrain. Smaller structures (see Figure 18) are not portrayed. Central parts of some larger tessera (e.g., Ovda, Thetis) are often characterized by chaotic patterns. Compare this map to the characteristics of tessera terrain boundaries in Figure 5.

along the northern edge of Lakshmi Planum, commonly are characterized by an internal fabric that is closely parallel to the arc-like segments themselves (compare Figure 1c and 15). Fourth, structures within the innermost cores of several of the large tesserae (Fortuna, Tellus, Ovda) have trends oriented differently than their outer parts; these are often contorted into chevron-like patterns [see also Vorder Bruegge and Head, 1990; Bindschadler et al., 1992a; Sukhanov, 1986]. Finally, the large tessera regions consist of several blocks or domains each with their specific internal orientation of major features; this could be interpreted as the consequence of independent tectonic phases within different areas of the large tesserae, as contemporaneous deformation with different structural styles, as the result of lateral accretion of independent blocks into one large tessera region, or a combination of these. The patterns of deformation within the tessera often bear a strong resemblance to the structure of terrestrial continental cratons with central highly deformed cores fringed by broad deformation belts oriented generally parallel to the continental margin. In addition, the structural patterns of the arc-like tesserae bear planimetric similarities to the arc structures of terrestrial oceanic trenches. Indeed, McKenzie et al. [1992] have described widespread trench-like structures on Venus that they claim have the same curvature and asymmetry as on Earth. Thus the patterns of deformation suggest the possibility of accretion of material around central cores for the larger tessera (Fortuna, Ovda, Tellus, Western Ishtar), and possible regional downwarping and underthrusting at the arc-like tessera boundaries. On the basis of the observed embayment relationships at tessera borders and the lack of evidence for active boundaries, this deformation apparently largely dates from an earlier period in the history of Venus, primarily prior to the formation of the majority of the plains.

6. Distribution of Tesserae in the Subsurface

Although tesserae observed in Magellan Cycles I-III data comprise only about 8% of the surface of Venus, they are widespread and show a tendency to be clustered (Figure 1b and 1c). Global mapping of tesserae shows that the number of small tessera patches far exceeds those of medium and large size, although small tessera patches make up only a small part of the total tessera population by area. Type I sinuous tessera boundaries are observed at places where lava plains flood and embay tessera massifs and make up 73% of the total tesserae boundaries. This type of boundary provides evidence that tesserae are relatively older than adjacent lava plains and that they probably have a shallow dip beneath the adjacent lava
cover between tessera islands (e.g., Figure 10). The majority of the Type II linear boundaries (PF and HAF subtypes) also bear clear evidence of lava embayment, and only about 3% of the length of all boundary types show no lava embayment and could be interpreted as tectonically active. The similarity of embayed boundaries with the mare/highland contacts on the Moon, the abundance of this type of boundary, and the large number of tessera patches peppered regionally over the Venus surface (Figure 1b) all suggest the possibility that there may be a larger area of tessera-like basement buried under the mantle of lava plains. The tendency for tesserae to be clustered and the existence of areas where tesserae are scarce may reveal areas where tesserae do, and do not, form such a basement.

In order to explore this, we compiled a map which extended the boundary of the tessera occurrences to include into the contour all large, medium, and small tessera occurrences, and left outside of the regions areas of tessera scarcity (Figure 16). A large spot with little to no tessera at about 67°N, 330°E corresponds to Lakshmi Planum. We included this feature into the contour of the tesserae basement keeping in mind that tesserae tend to be at intermediate to higher elevation and that tesserae occur inside the plateau and outside as well [Pronin, 1986; Roberts and Head, 1990; Kaula et al., 1992]. On the basis of this map, and the assumption that the outliers of small tessera represent kipukas of underlying tesserae protruding through later plains, we estimate that the total area of relatively shallow flooded tesserae basement may be of the order of ~250 x 10^6 km^2, or about 55% of the surface of Venus. Of course, thicker lava plains could obscure evidence for buried tesserae over the remaining surface of Venus.

7. Flooding of Tesserae Terrain and Estimates of Plains Thicknesses

If tesserae indeed make up a larger portion of the subsurface basement than that revealed by their surface outcrop (compare Figures 1b and 16), then the patterns of presently outcropping tesserae may hold important information about the thickness of superposed plains. In order to test this hypothesis and to assess quantitatively the amount of volcanic cover that may overlie such a tesserae basement, we developed a series of volcanic flooding models [Head and Haggerty, 1994] to study volumes, thicknesses, and outcrop patterns of tesserae flooded by volcanic deposits. We report here on the first stage of this analysis, in which we have taken known major areas of presently exposed tesserae (Alpha, Tellus, Laima, Fortuna, Theis, and Ovda), flooded them evenly to specific contours...
above mean planetary radius (MPR), and tracked the relationship between lava thickness and changing outcrop patterns (Figure 17). In this exercise, we are operating on the assumption that there is an elevation-independent self-similarity between tessera topography in the highlands and below the plains. The bimodal elevation distribution of tessera (Figure 4b) may suggest that other processes are operating, a possibility that will be discussed later. In any case, the exercise provides a first-order estimate of plains thicknesses.

**Alpha Regio Tessera.** Flooding of the Alpha region to 0.5 km above MPR removes almost all outliers of tessera and reduces the area of the main occurrence by less than about 20% but does not modify its coherence. Flooding an additional 1 km to 1.5 km reduces the outcrop area by more than 50% and results in a cluster of islands, each with a different shape and orientation and less than about 100 km in mean width, replacing the coherent Alpha tessera (Figure 17). Flooding to 2.5 km removes all trace of Alpha tessera.

**Laima Tessera.** Flooding to 0.5 km removes outliers and begins to embay the southern and eastern margin of Laima. Because Laima is on a regional slope tilting up northwestward toward Ishtar Terra, flooding to 1.5 km causes systematic embayment for 500-1000 km in a NW direction, forming a series of islands of tessera SE of the main occurrence, which has now been reduced to less than 50% of its original extent. Flooding to 2.5 km reduces the total tessera outcrop to several small patches.

**Tellus Regio Tessera.** Flooding to 0.5 km results in loss of virtually all outliers, in the reduction of the northern arc and outlier to several small patches, and in the reduction of the main occurrence area by about 10%, although it generally retains its coherence. Flooding to 1.5 km reduces the outcrop pattern by more than 75% and results in a cluster of islands replacing the coherent main Tellus tessera (Figure 17). Flooding to 2.5 km removes all trace of Tellus tessera.

**Thetis Tessera.** Thetis consists of a northern highly embayed and segmented portion, and a southern highly embayed but more coherent portion. Flooding to 0.5 km causes virtually no modification, while flooding to 1.5 km begins to encroach on the boundaries of the tessera. Because of the steep sides of the tessera, flooding to 3.5 is required to seriously alter the outcrop pattern, and even then, the outcrop pattern is still somewhat coherent.

**Fortuna Tessera.** Flooding to 1.5 km causes large-scale
Table 4. Tessera Terrain Subdivisions and Facies

<table>
<thead>
<tr>
<th>Tessera Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type I (regular)</strong></td>
<td>Planimetrically isometric pattern; rhombic and grid-system patterns of mutually intersecting lineament sets.</td>
</tr>
<tr>
<td><strong>Type I (chaotic)</strong></td>
<td>Randomly oriented sinuous broken ridges and grooves.</td>
</tr>
<tr>
<td><strong>Type II</strong></td>
<td>Characterized by chevron-like and arc-in-arc patterns.</td>
</tr>
<tr>
<td><strong>Type III</strong></td>
<td>Characterized by a predominantly orthogonal pattern.</td>
</tr>
</tbody>
</table>

*Sukhanov [1986, 1992], Sukhanov et al. [1989]*

- **Subparallel ridged terrain**
  - Subparallel ridges and troughs; lineations cutting across strike. Interpreted to be ridges formed by compressional deformation and faults formed by penecontemporaneous shear; continued shear and extension may lead to disrupted terrain.

- **Trough and ridge terrain**
  - Subparallel troughs and orthogonal ridges and troughs. Both interpreted to be extensional.

- **Disrupted terrain**
  - More chaotic pattern of generally shorter structural elements.

*Bindschadler and Head [1991]*

- **(TI) Interior block terrain**
  - Interior raised blocks, more or less equidimensional, 15-75 km across, separated by curvilinear troughs; blocks highly fractured by graben.

- **(TR) Linear ridged terrain**
  - Linear rounded ridges cross cut perpendicularly by narrow troughs, probably graben. Generally fold-like appearance. Ridges typically 8-15 km wide and 30-60 km long.

- **(TL) Linear trough terrain**
  - Generally appears cross fractured with at least one well-developed system of straight parallel troughs, tens to hundreds of kilometers long and a few hundred meters to a few kilometers wide, interpreted to be graben.

*Sukhanov [1986, 1992], Sukhanov et al. [1989]*

The embayment and breakup of northern Fortuna. Because of the E-W trending large-scale topographic fabric, flooding to 2.5 km causes systematic breakup of the main tessera body into a highly embayed western block and eastern outliers. Total outcrop is now reduced to less than ~50% of its original extent. Flooding to 3.5 km reduces the total tessera outcrop to small occurrence to the east of Maxwell Montes, and a series of small patches extending in an E-W direction.

**Ovda Tessera.** Flooding to 0.5 km removes a few outliers but has no major effect on the main tessera distribution. Flooding to 1.5 km removes a large portion along the western end (~10-15% of the total), but has little influence elsewhere. Increasing levels of flooding remove portions of the western end and isolate the high region to the east until, at 3.5-km thickness, there is one major (~2000 x 3000 km) cluster that is still relatively coherent.

**Summary.** Flooding of presently exposed tessera terrains such as Alpha and Tellus to 1.5 km above MPR produces outcrop patterns similar to the widely distributed clusters of small tessera patches presently common on Venus (Figures 1b, 8, 10), and flooding to 2.5 km totally obliterates all tessera patches. Flooding of Fortuna to 2.5 km would yield a patchy distribution of tessera similar to the present outcrop patterns of Ananke or Meshkenet tesserae (Figure 1b). Flooding of Ovda and Thetis to 3.5 km would produce tessera outcrops which had an areal extent only 1-2 times that of present-day Alpha tessera. These data thus support the idea that the widespread areas presently characterized by tessera patches and clusters (Figures 1b, 1c, 16) may have tessera terrain underlying the plains at depths of several hundred meters to 1-3 km. It also demonstrates that all traces of tessera terrain for significant regional occurrences (e.g., Alpha, Tellus) can be removed from surface exposure by flooding with as little as 2-4 km thickness of volcanic plains. This then implies that if a widespread tessera basement underlies the plains (Figure 16), it may occur at depths of as little as a few hundred meters to 2-4 km below the present plains surface. It also implies that tessera could also underlie thicker plains in the 40-50% of the surface not included in the tessera basement map of Figure 16.

8. Geological Characteristics and Relationships in Typical Tessera Regions

Although the definition of tessera terrain is generally agreed on (defined as radar bright, elevated regions of equidimensional or sometimes elongated shape possessing complex patterns of deformation on their surface consisting of at least two sets of coupled ridges and grooves intersecting at high angles [Barsukov et al., 1986; Sukhanov, 1986]), there is a wide diversity of facies within tessera terrain which provides clues to its origin and evolution. Early on, Sukhanov [1986, 1992] and Sukhanov et al. [1989] recognized several subdivi-
Figure 18. Tessera terrain subdivisions and potential interpretations. (a) Ridge and valley terrain in northern Ovda Regio (portion of F.MIDRP.00N082;1; 124 x 170 km). (b) Ridge and valley terrain with crosscutting graben in northern Ovda Regio (portion of F.MIDRP.00N082;1; 124 x 170 km). (c) Ridge and trough terrain in Itzpapalotl Tessera between Uorsar Rupes and Freyja Montes (portion of F.MIDRP.75N351;1; 124 x 170 km). (d) Large graben dissecting preexisting tessera pattern in northern Ovda Regio (portion of F.MIDRP.00N082;1; 124 x 170 km). (e) Honeycomb pattern of large graben dissecting preexisting tessera pattern (difficult to discern) in northern Ovda Regio (portion of F.MIDRP.00N065;1; 124 x 170 km). (f) Arc-like or chevron-like patterns in tessera in Aphrodite Terra (portion of F.MIDRP.05S087;1; 124 x 170 km).
Figure 19a. Tectonic structure in Laima Tessera. (top) Image of portion of Laima Tessera (portion of F.MIDRP.50N054;1; dimension is 107 x 170 km). (middle) Sketch map illustrating main trends of features associated with Phase I deformation for area shown in top portion of Figure 19a. Dot-dashed lines represent major trends of broad ridges, and shorter lines with cross-bar delineate location of fold-like structures. Plains are indicated by sinuous solid line with dots on plains side of boundary. (bottom) Sketch map illustrating main trends of features associated with Phase II deformation and subsequent deformation of plains for area shown in top portion of Figure 19a. Wavy lines represent trends of graben. Short sinuous lines with cross-bar in plains represent mare ridge-like features in plains.
Figure 19a. (continued)
of Western Ishtar Terra has created structures interpreted to repre-
sent sinistral transpression. On the basis of terrestrial shear zone tectonite fabrics (S-C fabrics, where S is penetrative schistosity and C is spaced shear planes [Berthe et al., 1979]), Hansen [1992] interpreted the Itzpapalotl fabric (Figure 18c) as forming from material undergoing noncoaxial strain. In this case, the material initially develops a schistosity at an angle to the shear zone and with continued displacement, strain is partitioned into more widely spaced shear planes. Continuing deformation results in synchronous homogenous shortening and extension in the penetrative schistosity zone and more brittle deformation dominated by shear strain in the shear planes. Thus, what appears to be a complex pattern representing a distinct sequence of events may instead be the result of contemporaneous deformation.

In still other cases (Figure 18d), regional crosscutting and throughgoing larger graben appear to postdate a wide range of tectonic structures and in many cases to cut plains units that are superposed on these earlier structures (see also at Alpha Regio [Gilmore and Head, 1993]). These relationships suggest that the latter phase of deformation may be more separated in time than the previous examples. The greater width of the graben, and their often broader distribution and more honeycomb-like patterns, suggest an origin through more general postshortening gravitational collapse of regional tessera occurrences. In some cases (Figure 18e) this honeycomb-like pattern is so extensively developed that preexisting regional structural trends are difficult to discern. Finally, in some re-
gions (Figure 18f), tessera terrain has large arcuate and chevron-like ridges reminiscent of syntaxis structures in ter-

Figure 19b. Tectonic structure in Northern Ovda Regio. (top) Image of portion of Ovda Regio (portion of F.MIDRP.00N082; dimension is 200 x 254 km). (upper middle) Sketch map illustrating main trends of features associated with Phase I deformation for area shown in top portion of Figure 19b. Dot-dashed lines represent major trends of broad ridges, and shorter lines with cross-bar delineate location of fold-like structures. Plains are indicated by sinuous solid line with dots on plains side of boundary. (lower middle) Sketch map illustrating main trends of features associated with Phase II deformation and subsequent deformation of plains for area shown in top portion of Figure 19b. Wavy lines represent trends of graben. Short sinuous lines with cross-bar in plains represent mare ridge-like features in plains. (bottom) Sketch map illustrating main trends of features associated with large-graben Phase II deformation; large graben are shown by thick black lines.
These examples (Table 4, Figure 18) illustrate that complex patterns can result from relatively simple tectonic settings (i.e., transpression, synorogenic collapse), as well as complex sequential polyphase deformation. Detailed structural and stratigraphic mapping must be undertaken to establish the chronologic relationships of apparently distinct deformational phases and to decipher the kinematic evolution of individual occurrences of tessera terrain [e.g., Keep and Hansen, 1994; Parker and Saunders, 1994; Head, 1995a, b; Iranov and Head, 1995; Gilmore and Head, 1995].

In order to establish the range of basic characteristics of tessera occurrences and their relationships both within and between tessera, we chose several areas from within the major tessera terrains to examine and analyze in detail. Although our choices were guided by attempts to show both type examples of particular features and relationships and typical regions, the overall complexity of the tessera terrain (Table 4 and Figure 18) means that these examples should not be considered as illustrating the full range of characteristics or relationships. Here we present detailed maps of two of these tessera areas.

In east-central Laima Tessera, the tessera fabric is dominated by essentially orthogonally oriented structural patterns (Figure 19a). The major large-scale pattern strikes generally NW and consists of parallel to slightly wavy ridges and troughs ranging in width up to several tens of kilometers (Figure 19a (top, middle)). These features often display scarp-like ridges that cut at small angles across the main fabric and extend for tens to hundreds of kilometers. The combination of these characteristics leads us to interpret the broad parallel features as large-scale folds due to shortening generally orthogonal to their strike; the scars are interpreted to be either thrust faults where shortening has caused surface rupture and over-thrusting or fine-scale folds. In some instances, there appear to be a few small graben superposed on these features and oriented parallel to them.

Superposed on the large-scale NW-oriented fabric is a dense series of NE-oriented closely spaced graben. Although very widespread, these differ in density from place to place (Figure 19a (top, bottom)). The extensional graben clearly crosscut and thus appear superposed on the earlier fabric of the large-scale compressional deformation (Figure 19a, middle). The orientation of the principal stress axis (NE-SW) is similar in
both major deformational features. Subsequent to the graben formation, radar-dark plains were emplaced in the low-lying areas; these embay both the long ridges and troughs and the orthogonal graben. Although no individual source regions are observed in this map area, small shield volcanoes and other vent structures are observed elsewhere. On the basis of embayment relationships and topography, these plains are interpreted to be of volcanic origin and are likely to be of the order of up to several hundred meters thick. Although these plains clearly embay graben, some linear graben become less well developed in the vicinity of the margins of the plains. This suggests that there may be several generations of both plains units and linear graben, a phenomenon that has been noted in other tessera regions [Bindschadler et al., 1992a; Gilmore and Head, 1993]. In addition, this relationship strongly suggests that at least part of the period of graben formation postdated the shortening that produced the ridges. The radar-dark plains are interlaced with web-like patterns of bright lines which appear to be similar to mare-like ridges (Figure 19a (top, bottom)) that are common on Venus plains, and are interpreted to be of compressional origin. The presence of these features suggests that the plains units were undergoing minor deformation subsequent to the period of graben formation.

At the northern edge of Ovda Regio, a broad 100 to 200 km-wide zone of parallel ridges and arches strikes generally E-W and then sweeps around to the NE. This border zone separates the relatively smooth plains to the north from more complexly deformed terrain to the south in central Ovda Regio; this latter terrain has many of the same components of structure as that of the northern zone (see Figures 18a and 18b), but in addition, has higher reflectivity and additional structural components, including ovoid-like features and large (several kilometers wide) troughs and graben oriented normal to the strike of the ridge fabric and superposed on this (Figure 19b). This larger graben fabric is more sinuous and honeycomb-like and is in contrast to the widely distributed smaller graben that are superposed on the ridge and trough terrain throughout its occurrence (Figure 18b and 19b (top, upper middle)). Thus, in a manner similar to that observed in Laima Tessera, the earliest deformation is primarily related to crustal shortening and compressional deformation, with apparently superposed pervasive extensional deformation oriented generally along the same principal stress direction (Figure 19b (top, upper middle, lower middle)). In contrast to Laima Tessera, larger graben are also superposed on this fabric (Figure 19b, bottom). Dark plains are superimposed on both of these fabrics and embay...
the youngest graben; however, here too, there is evidence for several generations of plains, the last of which does not appear cut by graben structures. The larger graben, however, appear to cut younger plains than the smaller graben. This provides evidence that although many of the crosscutting patterns may well be contemporaneous, at least in some places and to some degree there are components that also represent sequential deformation, with the large graben being the latest deformational features. Detailed mapping and kinematic interpretation in individual areas will be required to develop a better picture of these relationships [e.g., Ivanov and Head, 1995; Head, 1995b].

In Alpha Regio, Bindschadler et al. [1992a] found evidence for a similar sequence of events throughout this 1300 x 1500 km upland region. The directions of shortening associated with the initial stages of deformation were more irregular than that shown in Laima or Ovda (Figures 18 and 19), and more abundant examples of possible shear deformation associated with this phase are seen in Alpha. The development of extensive small graben and formation of intratessera plains followed this initial tectonic phase in Alpha, as in the other tessera regions discussed in this paper and reviewed by Solomon et al. [1992] (Alpha, Ovda, Thetis, Tellus, and Laima). A wide variety of origins for tessera terrain fabric were proposed prior to the Magellan mission (reviewed by Solomon et al. [1992]); the general characteristics of the fabrics and the sequence of events (initial compression, which we call Phase I deformation, followed by and partly contemporaneous with extension, which we call Phase II deformation) seem most consistent with initial phases of crustal shortening and thickening accompanied and followed by lateral extension most likely caused by synorogenic collapse and gravitational relaxation and spreading of the recently elevated terrain [Bindschadler and Head, 1991].

9. Stratigraphy and Age of Tessera Terrain

The age of the tessera terrain is an important question in establishing the geologic history of Venus. We seek to know when and how it formed, and whether it is actively forming today. There are thus several aspects to age determinations: What is the absolute age of the rocks forming the tessera terrain? What is the relative, or stratigraphic age of the tessera compared to other units? What is the absolute age of the tessera stratigraphic unit? What is the age and duration of the range of deformation characteristic of the tessera? On the basis
of this study and recent analyses, information is available to address the latter three questions.

In our analysis, we found no evidence to contradict the generally accepted conclusion that the tessera terrain commonly represents the stratigraphically oldest unit exposed on Venus today [Sukhanov, 1992; Barsukov et al., 1992; Solomon et al., 1992; Bindschadler et al., 1992a; Herrick, 1994; Price and Suppe, 1994; Raitala, 1994; Basilovsky and Head, 1995a, b]. The very large percentage of tessera boundaries that are embayed by volcanic plains (97%) and the very small percentage (about 3%) that show evidence that they might be tectonically active in the recent geologic past, support the idea that the tessera formed at the base of the stratigraphic column of the presently exposed record, prior to the emplacement of the majority of the presently observable plains. This is consistent with the analysis of the stratigraphy of 36 individual 1000 x 1000 km areas randomly distributed on Venus and several other larger areas [Basilovsky and Head, 1995a, b] where tessera was found to be the oldest unit wherever it was exposed. Consistent with the findings of Bindschadler and Head [1991] and Bindschadler et al. [1992a], we also find that the sequence of deformation within the tessera terrain is initially characterized by deformation involving large-scale shortening, folding, and shear and that this commonly shows superposition by smaller-scale but pervasive extensional deformation; the latter stage overlaps with patchy volcanism in the form of intratessera plains and may represent synorogenic collapse and/or later deformation (Figures 18 and 19). These stages are followed by large-scale embayment by plains material, some of which overlaps with the latest phase of extensional deformation in the tessera [Basilovsky and Head, 1995a, b].

Impact crater size-frequency distributions provide information on terrain and unit ages. To a first order, the spatial distribution of craters on the planet as a whole cannot be distinguished from a completely spatially random population ([Schaber et al., 1992; Phillips et al., 1992]; although variations exist as a function of elevation [Herrick and Phillips, 1994]) and the size-frequency distribution yields an average crater retention age of about 300-500 m.y. [Schaber et al., 1992; Phillips et al., 1992; Strom et al., 1994]. On the basis of the stratigraphic evidence outlined here, the age of the tessera terrain is somewhat prior to this average surface crater retention age. The size-frequency distribution of impact craters on the tessera terrain was studied by Ivanov and Basilovsky [1993], who showed that the density of impact craters larger than 32 km on the tessera was greater than that on the rest of the planet. However, because of the small population of craters and the large error bars in the estimation of a tessera crater retention age, the absolute age of the tessera has a high level of uncertainty, and the age difference between tessera and the rest of the planet could be as large as 40% or as small as 1%, or possibly not statistically distinguishable [e.g., Strom et al., 1994].

The characteristics of individual craters on the tessera provide data on the duration of deformation within the tessera. If all craters were deformed, this would indicate that deformation within the tessera continued until recent geological time; if none were deformed, this would indicate that tessera-forming deformation was complete prior to the accumulation of the superposed population and the subsequent emplacement of the plains. In reference to the timing of the deformation within the tessera, Ivanov and Basilovsky [1993] pointed out that there was an absence of distinctive tectonic deformation for the vast majority of craters on the tessera. They interpreted this to mean that "during the majority of the time period during which the observed on-tessera crater population was emplaced the tessera terrain was already tectonically stabilized and no morphologically noticeable deformation occurred." This is consistent with our morphologic and stratigraphic observations that suggest the vast majority of the tessera deformation occurred before the emplacement of the plains and agrees with Herrick [1994] whose analysis of the on-tessera crater population showed that "some form of modest tectonic deformation, such as gravitational relaxation, may have occurred since plains emplacement."

The characteristics and distribution of individual deformed craters provide evidence for the nature of tessera deformation, and the number provides evidence for timing and duration. Our preliminary analysis reveals no examples of extremely highly deformed impact craters (e.g., those that have been significantly modified from a circular to oval shape). We interpret this to mean that the deformation events responsible for the observed tessera tectonic fabric largely modified any preexisting craters beyond recognition. In addition, of the 81 on-tessera impact craters, only nine (~11%) have been distinctly tectonically deformed by structures attributed to the tessera fabric [see also Gilmore et al., 1996]. Of these deformed impact craters, all appear to be cut by the extensional deformation represented by the extensive narrow graben structures (Phase II). None of the impact craters appear unequivocally to be deformed by the tectonic fabric (broad ridges and troughs) interpreted to represent Phase I crustal shortening.

Several conclusions can be reached from these relationships. (1) The large number of craters on tessera that are undeformed (~90%) and their wide distribution suggest that deformation may have ceased relatively simultaneously over the whole area of presently exposed tessera, and that it did not continue to the present. (2) The small percentage of deformed superposed tessera craters (~11%) suggests that tessera deformation continued for a relatively short period of time (very likely less than 50 Ma) subsequent to the beginning of accumulation of the crater population on the tessera and may have overlapped in part with the emplacement of early plains (Figure 20a) (e.g., the densely fractured plains unit, Pdf of Basilovsky and Head [1995a]). (3) The two types of deformation (Phase I and Phase II) which appear stratigraphically to be superposed on each other (Figures 18 and 19) but could also result from essentially contemporaneous deformation, are in at least nine places separated in time by a post-Phase I impact cratering event. More detailed global analysis of the full range of superposed craters and their tectonic and stratigraphic relationships will permit us to refine these early findings [e.g. Gilmore et al., 1995, 1996].

We interpret these observations to mean that most impact craters were obliterated by the pre-existing deformation event(s) represented by the highly deformed terrain (Period IIA in Figure 20a). In addition, at least part of the extensional deformation must have postdated the Phase I deformation, rather than being contemporaneous with it, because several craters that are superposed on the tessera have been modified by the extensional (small graben) deformation of Phase II.

In summary, the tessera terrain in its presently exposed areas appears to have formed through extensive crustal shortening and compressional deformation the last phase of which ceased just prior to about 300-500 m.y. ago, and underwent a
Venus Stratigraphic Summary

Figure 20a. Generalized Venus geologic time diagram with stratigraphic and geologic units and events. On the left is portrayed Period I, which predates the first preserved surface features presently observed on Venus. Period IIA is the period of time during which the presently observed tessera terrain formed, particularly the Phase I shortening and compressional deformation. Rocks comprising these units may well date from Period I. This activity produces an angular discordance between this terrain and subsequent units. The line is slanted because the end of tessera formation (particularly Phase II deformation) may not be instantaneous over the whole planet. Following this in Period IIB, and commonly overlying tessera terrain with angular unconformity, are widespread volcanic plains units that were deformed subsequent to their emplacement; these are units Pdf (densely fractured plains) and Pwr (plains with wrinkle ridges) of Basilevsky and Head [1995a,b]. Subsequently, smooth and digitate volcanic plains are emplaced interfingering with regional rifting and volcanic edifice formation (Period III). Impact craters formed throughout this history, but most presently observed craters formed subsequent to the widespread deformed volcanic plains (in Period III, shown by the thick line); paraboloid craters represent the youngest craters and are estimated to have formed in the last several tens of millions of years.

10. Gravity Data

Gravity data can provide information on the subsurface distribution of mass and a basis for interpreting the crustal and thermal structure of the interior. On the basis of Pioneer-Venus gravity data, Smrekar and Phillips [1991] examined apparent depths of isostatic compensation and showed that many of the upland regions characterized by tessera tectonic fabric had relatively low ratios of geoid anomaly to topography. They interpreted these observations to mean that the tessera regions had shallow (crustal level) compensation depths and did not require dynamic support, in contrast to broad volcanic rises such as Beta and Atla, which required deeper dynamic compensation more akin to hot spots. Magellan image data permitted in-depth interpretation of Pioneer-Venus gravity data and supported interpretations of tessera terrain as regions of highly deformed thickened crust, and broad rises as the surface manifestation (riifting and volcanism) of mantle upwelling [Herrick and Phillips, 1992; Bindschadler et al., 1992b].

Magellan gravity measurements, which provided higher resolution and better quality gravity data as well as more global coverage, confirmed and extended these conclusions [Konopliv and Sjogren, 1994]. Examination of Magellan gravity data for Alpha, Tellus, Ovda, and Thetis regions showed that they were consistent with shallow Airy isostatic compensation at crustal thicknesses of 35-45 km with little contribution from deeper mantle sources, and surrounded regionally by crust of 30-40 km thickness [Grimm, 1994a]. Kucinskas and Turcotte [1994] analyzed Ovda and Thetis and concluded that Airy compensation with a thick crust (~50-60 km) and lithosphere is the dominant support mechanism there. McKenzie [1994] found that many regions of tessera terrain coincided with positive anomalies of residual topography, a relationship to be expected if it is the result of thickened crust in isostatic equilibrium. These results further underlined the differences between tessera regions and volcanic rises. Smrekar [1994] calculated spectral admittance from both local gravity inversions and a spherical harmonic model and concluded that Bell, Atla, Western Eistla, and Beta regions were much more likely to be due to active hotspots than to local compensation or flexure. These results further separate these morphologically distinctive rifted volcanic rises from the highly deformed shallowly compensated tessera plateaus.

Simons et al. [1994] examined global variations in the geoid/topography admittance and showed that the data were
consistent with two models of convection-driven topography. In one model, compressional highland tessera plateaus are due to deformation associated with present mantle downwelling, and broad volcanic rises are linked to present mantle upwelling (steady regime). In the other, mutually exclusive model, tessera plateaus are remnants of a previous period of enhanced crustal strain, and the majority of remaining long-wavelength topographic variations are due to normal basal lithosphere convective tractions (variable regime). On the basis of our data on the stratigraphic relationships, tessera boundary inactivity, on-tessera crater structure, and tessera deformational sequence, we support the variable regime model, in which the tessera formed during an earlier period of enhanced crustal strain and is not presently forming or undergoing significant deformation.

11. Summary of Characteristics of Tessera

On the basis of the global analysis of tessera terrain reported here, we outline a series of characteristics of tessera terrain that should be considered in the formulation of models for the formation and evolution of Venus and the tessera terrain.

Global areal distribution. Tessera terrain occurrences cover a total of $35.33 \times 10^6$ km$^2$, about 8% of the surface of Venus, and are nonrandomly distributed, being preferentially located at equatorial and higher northern latitudes with a distinct paucity below about 30°S.

Size distribution. Tessera occurrences range in area from about 200 km$^2$ up to $9 \times 10^6$ km$^2$ (about 2% of the surface area of Venus) with the size-frequency distribution strongly unimodal at small sizes and skewed to smaller sizes. Small
patches (typical areas of about 5.5 x 10^3 km^2) are the most numerous tesserae occurrences; about 88% of all tesserae occurrences are in this size class, although it comprises only about 8.7% of the tessera population.

Modes of occurrence. There are three modes of occurrence: (1) clusters, characterized by the existence of several broad clusters of tesserae, (2) arc-like segments which may extend for thousands of kilometers and are commonly concave inward or away from the major tessera cluster development, and (3) areas where tesserae are rare or absent which occur both as vast, smooth low-lying plains and as elevated regions.

Distribution with elevation. There is a positive correlation between tessera occurrence and elevation, with the majority of tessera terrain area at high elevations. In terms of number of occurrences, however, tesserae do not display a strong correlation with elevation at the global scale, since a large number of small tessera patches commonly occupy low-lying regions.

Tessera boundaries. The vast majority of tessera boundaries are characterized by lava flooding and embayment of tessera massifs. Only about 3% of the length of all boundary types show no lava embayment and could be interpreted as tectonically active in the recent geological past.

Subsurface distribution. On the basis of the distribution of large, medium, and small tessera occurrences, we estimate that tessera may underlie as much as 55% of the surface of Venus. Flooding experiments indicate that any tessera underlying the plains may occur at depths of as little as a few hundred meters to 2-4 km below the present plains surface. Buried tesserae could be even more widespread if plains thicknesses exceed 3-4 km, or if buried tessera are smoother and not topographically self-similar to exposed large tesserae occurrences.

Sequence of deformation. Earliest deformation within much of the large tessera is primarily related to crustal shortening and compressional deformation (Phase I), apparently followed by pervasive extensional deformation oriented generally along the same principal stress direction (Phase II). Extensional deformation may represent contemporaneous formation (e.g., transpression), synorogenic collapse, and/or later deformation. Lava plains both within and adjacent to the tesserae are superimposed on both of these fabrics, but sometimes late graben of Phase II cut the earliest plains.

Age. The vast majority of tessera deformation largely ceased at some time just prior to about 300-500 m. y. ago [Ivanov and Basilevsky, 1993]. On the basis of the characteristics of deformed on-tesserae craters, it underwent a continuing phase of extensional deformation, partly coincident with the emplacement of the intratesserae plains and the earliest presently exposed exterior plains which embody the tesserae. With the exception of regional throughgoing fracture belts [e.g., Senske et al., 1992], tesserae were tectonically stabilized soon after these phases and suffered no morphologically noticeable deformation throughout the vast majority of the period represented by the crater population. Regional tilting of some tesserae margins continued subsequent to early plains emplacement.

Gravity. Major tesserae occurrences are interpreted to represent relatively shallow (crustal) levels of compensation and contrast with the characteristics of rifted volcanic highlands that appear to represent geologically relatively recent hotspot activity.

12. Discussion of Models of Tessera Origin

Prior to Magellan, proposed models for formation of the distinct tectonic fabric associated with tesserae included large-scale gravitational sliding and glacier-like flow, and gravitational relaxation [Markov et al., 1989; Sukhanov, 1986; Kozyakov and Schuber, 1986; Sukhanov, 1992], deformation associated with horizontal asthenospheric currents [Basilevsky et al., 1986; Sukhanov, 1986], and by plate-tectonic-like crustal formation processes [Head, 1990d] (see reviews in Bindschadler and Head [1991] and Solomon et al. [1992]). In addition, several distinct but general types of models for broad-scale tessera formation were proposed. In the first two models, tessera terrain comes about through the normal evolution of crustal structure formed and modified by mantle convection patterns, but the models differ in the sign of the convection. First, Phillips et al. [1991] and Herrick and Phillips [1990] have proposed that proto-tesserae initially formed above large areas of mantle upwelling (hot spots or plumes) as regions of enhanced volcanism and crustal thickening. Subsequent to their formation, thermal decay and gravitational collapse and spreading converted this distinctive Atla-like volcanic terrain into the highly deformed tessera terrain. Second, Bindschadler and Parmenier [1990] and Bindschadler et al. [1992b] proposed that tessera terrain forms over zones of long-term mantle downwelling, with the characteristic fabric resulting from coupling of mantle flow patterns and crustal deformation. Because Magellan observations indicate that the most likely regions of present downwelling (the lowlands such as Lavinia and Atalanta planitiae) are not regions of tesserae, Bindschadler et al. [1992b] proposed that these lowlands represent an initial evolutionary step in a process that eventually led to crustal thickening and formation of the high-standing, highly deformed tesserae terrain.

On the basis of the characteristics of the tessera terrain outlined above, we do not find strong support for either of these two models in the evolutionary sense. First, there do not appear to be any clearly defined transitional terrains between either the initial upwelling (broad volcanic rises) or downwelling (lowlands) regions, and subsequent tesserae terrain. Rather, they appear to be discrete and different terrain types. Second, the ancient (Figure 20a) and apparently relatively abrupt termination of tesserae formation and its stages of deformation are not consistent with predictions of a range of evolutionary states that should be seen throughout the observed geologic record. One would expect to see more evidence of regions presently deforming to produce tesserae terrain. Finally, the lack of evidence for widespread morphologically visible present deformation in tesserae interiors argues against an ongoing evolutionary process for tesserae formation. Our data do favor, however, models of downwelling [Bindschadler and Parmenier, 1990] over models of upwelling [Phillips et al., 1991], for tesserae formation. Evidence to support downwelling includes high-standing topography (often equal to or higher than volcanic rises), tectonic structures and patterns consistent with marginal underthrusting and accretion, and deformational sequences characterized by initial significant crustal shortening accompanied by and followed by extension and relaxation.

A third type of hypothesis for the evolution of Venus and the origin of tesserae terrain seeks to explain the Magell
observations in the context of uniformitarian thermal evolution and calls on the high surface temperature and the exponential relationship between temperature and strain rate as a major factor in the evolution of the observed surface features (Figure 20b). In this scenario, mantle convection is closely linked to the overlying lithosphere and over most of the history of Venus a weak lower crust deforms readily, resulting in very high levels of surface strain and production of the observed tessera deformation over most of the surface of Venus [Solomon, 1993; see also Nikishin, 1990]. At some point late in the thermal evolution, the heat flux will decline to values that markedly decrease lower crust ductility, and rates of surface strain and deformation will decrease rapidly. This model predicts that the change in strain rate should be sensitive to regional variations in thermal gradients and crustal thickness, with highland regions persisting in deformation long after deformation rates in lowland regions have decreased to modest levels [Solomon, 1993].

On the basis of the characteristics of the tessera outlined above, we do not find extensive support for this model. Although the deformation predicted in this hypothesis would be widespread, consistent with the predicted preplains distribution of tessera (Figure 16), we do not see evidence for continuing deformation in the high-standing tessera beyond the deformation in other tessera regions, as predicted by this model. In addition, areas of thermally enhanced topography (upwellings) are predicted to be the best candidates for continuing deformation, and we see no evidence for associations of recent tessera formation with areas thought to be sites of present upwelling (Figure 11). Finally, the stratiographic, morphologic, and crater size-frequency distribution data [Ivanov and Basilevsky, 1993] that places formation and modification of presently exposed tessera prior to the major volcanic units forming the majority of the plains (Figure 20a) are not consistent with the predictions of this hypothesis, which propose that deformation would continue for a period of time after the general crossover in lower crustal ductility in areas of thicker crust (the present tessera terrain). In addition, quantitative estimates of tectonic strain rates using the observed geologic record have recently been made [Grimm, 1994b] to test the hypothesis that significant decreases in surface strain rates could be caused by a steady decline in heat flow over the last billion years. This analysis indicates that a steady temperature decline is insufficient to cause the observed change in surface strain rate despite the exponential dependence of viscosity on temperature.

Another uniformitarian thermal evolution model predicts evolutionary changes in mantle convection patterns [Arkani-Hamed and Toksoz, 1984; Arkani-Hamed, 1993; Arkani-Hamed et al., 1993; Herrick and Parmentier, 1994]. These models emphasize early very high rates of deformation related to a highly convective interior that has oscillatory properties, resulting in a highly deformable lithosphere capable of being incorporated into the convecting mantle (Figure 20b). After a prolonged period of surface recycling into the mantle, the enhanced cooling results in diminished convective vigor to quasi-steady state, crustal and lithospheric stability, and a one-plate hot-spot-dominated planet about 500 m.y. ago. These models do not make very specific predictions about the nature and evolution of landforms on Venus. Tessera terrain could be the remnants of this earlier phase of prolonged recycling. The vast outpouring of volcanic plains just after the end of tessera formation is, however, not predicted by a model of cooling and stabilization. In our opinion, no evidence in hand can definitively rule out these types of models, although the analysis of Grimm [1994b] favors episodic heat pulses over monotonic thermal evolution to explain the interpreted variations in strain rates in the observed geologic record.

The fourth category of hypothesis involves one or more periods of catastrophic resurfacing in the history of Venus (Figure 20b). The analysis of the nature and distribution of impact craters using the global Magellan database has shown that the crater population [Schaber et al., 1992; Phillips et al., 1992; Strom et al., 1994] represents an average crater retention age of about 300-500 m.y. and that the distribution cannot be distinguished from a completely spatially random population. These data, together with the very small number of craters that appear to be modified by volcanic activity, have led Schaber et al. [1992] (see also Strom et al. [1994], Herrick [1994], and Herrick et al. [1995]) to propose that the surface of Venus underwent a global volcanic resurfacing event about 300-500 m.y. ago, completely eradicating the crater population, and that the present crater population is a production of volcanic activity (Figure 20b). This is in contrast to an equilibrium resurfacing model [e.g. Phillips et al., 1992]. Several mechanisms have been proposed to account for the global resurfacing hypothesized by Schaber et al. [1992], including episodic plate tectonics [Turcotte, 1993] and vertical crustal accretion and periodic overturn of the depleted mantle residuum [Parmentier and Hess, 1992; Head et al., 1994].

On the basis of the characteristics of the tessera outlined above, several of the proposed models are possible. Specifically, we find that a mechanism of tessera formation linked to global and perhaps catastrophic resurfacing at some point in the history of Venus is consistent with the observations (Figure 20b). For example, the near-simultaneous, widespread formation of the tessera (Phase I deformation), accompanied by and followed closely by Phase II extension and gravitational relaxation and subsequent large-scale volcanic flooding and embayment of the tessera, are consistent with a discrete planetwide event. The distinctive difference of styles of compensation between tessera and volcanic rises and the support for a variable regime in the interpretation of the geoid/topography admittance constraints [Simons et al., 1994] also favor an early discrete mode of formation for tessera terrain. In addition, the lack of a preserved geological record for the first 85-90% of the history of Venus, combined with the distinct change in intensity of deformation between the tessera and post-tessera terrains and the apparent low level of geologic activity for the last several hundred million years [Price and Suppe, 1994; Namiki and Solomon, 1994; Phillips and Hansen, 1994], could all be explained by a specific catastrophic event happening in the recent geologic history of Venus (Figure 20). We thus explore this range of hypotheses in more detail.

On the basis of our analysis of tessera terrain and its relation to other characteristics of Venus, what range of mechanisms linked to global resurfacing appear to most plausibly explain the observations and their relation to the geologic and magmatic history of Venus [Head et al., 1992; Crumpler et al., 1993]? In the model of Turcotte [1993] (Figure 20b), heat loss is episodic. Periods of stable conductively thickening litho-
sphere result in small increases in mean interior temperatures, which lead to periods of enhanced mantle convection; these in turn, initiate instabilities that lead to lithospheric foundering, periods of rapid lithospheric recycling and heat loss, and rapid resurfacing rates, prior to a return to stabilization, and another cycle. Although Turcotte [1993] makes few specific predictions relative to the characteristics of terrain on Venus, the tesserae could be remnants of the last episode of plate tectonics, perhaps representing crustal accretion and thickening adjacent to zones of subduction. Arcuate tessera (Figure 1c) could represent ancient subduction zones. McKenzie et al. [1992] cited observations that suggest that there are processes on Venus that produce features similar to terrestrial oceanic crust transform faults, abyssal hills, and trenches, but these occur locally and in terrains of relatively recent age rather than being global and dating from an earlier period coincident with the formation of tesserae. There is little evidence for widespread regions representing remnant divergent plate boundaries and extensive intraplate fabric of the age proposed by Turcotte [1993], or any asymmetries in crater ages that would be manifested in laterally spreading crust. In addition, the extensive plains volcanism following the completion of tessera deformation (Figure 20a) is not specifically predicted by this model. However, insufficient data on the nature of crustal spreading in this environment are available to fully assess this hypothesis.

A variation on this hypothesis (although linear and not episodic) has been proposed by Herrick [1994] in which plate tectonics dominated the surface of Venus prior to about 800 m.y. ago and the highly mobile crust and lithosphere created tessera terrain. General planetary cooling caused thickening of the lithosphere and cessation of plate tectonics, quickly followed by global volcanic flooding (related to heat at the base of the lithosphere from a still rapidly convecting mantle), and then by hot spot volcanism as the planet finalized its evolution from a multiplate to a one-plate planet. This model is consistent with the general geologic history of Venus (Figure 20a) and the major characteristics of the tessera terrain; further investigation is required in terms of geological mapping and the development of specific predictions related to the cratering and geologic record implied by the terminal phase of plate tectonics. For example, if plate tectonics and tessera formation were a normal part of the pre-800 Ma history of Venus, one might expect tesserae regions to have more undeformed craters, more ancient crater ages, and perhaps to show significant differences between different tesserae terrains, rather than the generally similar and young crater retention age observed.

Several other models suggest possible catastrophic global resurfacing/recycling episodes related to changes in mantle convection [Herrick and Parmentier, 1994; Weinstein, 1993; Steinbach and Yuen, 1992] in the history of Earth and Venus due to phase changes, compositional stratification, and thermal evolution. However, none of these models makes predictions sufficiently specific to compare to the Venus record.

Parmentier and Hess [1992] have proposed a model in which vertical crustal accretion on a one-plate planet results in a thickening basaltic crust and residual depleted mantle layer (Figure 20b). Over time, positive compositional buoyancy decreases in significance, and negative thermal buoyancy increases, resulting in net negative buoyancy for the depleted mantle layer. At this point, the depleted mantle layer founders, deforming and delaminating depleted mantle and overlying crustal material, and hot fertile mantle material ascends, undergoing pressure-release melting, resulting in a phase of widespread surface volcanism. Following this overturn event, vertical crustal accretion continues at much reduced rates and the processes repeats itself at intervals of 300-500 m.y. Head et al. [1994] examined the geological consequences of such a model and described how they compared with Magellan observations. On the basis of Head et al. [1994] and our analysis, we find that the following aspects are consistent with the model: (1) lack of preserved surface units from the first 85% of the history of Venus; (2) evidence for a vertically accreting crust over most of observed geologic time; (3) formation of tessera terrain as the first major unit of the present stratigraphic column (Figure 20a); (4) the sequence of deformation in tessera terrain from initial large-scale shortening to partly contemporaneous and subsequent extension related to relaxation; (5) a major change in the style and intensity of deformation (strain rate) following tessera formation; (6) emplacement of widespread regional plains over the vast majority of the surface of Venus closely following the period of tessera formation (Figure 20a); (7) a substantial decrease in volcanic flux and a change from large-scale regional plains emplacement to focused local sources (e.g., individual large volcanic edifices). Thus we conclude that on the basis of available model predictions and information, the predictions of the vertical crustal accretion and depleted mantle layer overturn model of Parmentier and Hess [1992] are compatible with the observations. Although several other models are also consistent with these observations, the Parmentier and Hess [1992] model provides a physical mechanism that includes predictions that can be tested in some detail and is consistent with the recent findings [Grimm, 1994b] on the evolution of surface strain rates; we further pursue these predictions and their relationship to observations.

On the basis of this model and our observations, we visualize the process of tessera formation and its aftermath as shown in Figure 21. Here, vertically accreting crust creates a complementary underlying depleted mantle layer (DML), which thickens until it becomes unstable (Figure 21, top). At this point, instabilities develop and upwelling and downwelling begins; regions of thicker crust (preexisting tessera or old rises?) might serve as focal points for downwelling. As downwelling proceeds (Figure 21, middle), the DML thickens in areas of downwelling, perhaps leading to delamination and loss of parts of the DML into the underlying mantle, while complementary upwelling occurs in regions of thinned DML. The overlying crust is mechanically linked to the unstable depleted mantle layer; shear traction results in crustal thickening and imbrication over areas of downwelling (Phase I-style deformation), and crustal thinning and intensive extensional deformation over upwellings (Figure 21, middle). An angular unconformity is produced at this point (Figure 20a), and virtually all impact craters are deformed beyond recognition by these events. Upwelling of fertile mantle leads to pressure-release melting and the beginning of extensive emplacement of volcanic plains, closely following (but possibly partly contemporaneous with) the deformation of the crust that produced the tesserae terrain. Following this instability event, extensive plains volcanism continues primarily in the plains adjacent to tessera regions of thickened crust, as a result of pressure-release melting of upwelling fertile mantle, largely covering the highly deformed preexisting crust (Figure 21, bottom). The adjacent newly formed tesserae areas of thickened crust have undergone, by this time, gravitational relaxation and exten-
Figure 21. Summary model for the formation of tessera terrain according to the general outlines of the model of Parmentier and Hess [1992]. In this model, the sequence of events interpreted to have occurred during the evolution of a basaltic crust and depleted mantle layer is shown. Following initial vertical buildup of crust and depleted mantle layer (DML), instabilities cause downwelling and ductile crustal thickening (to form tessera) and complementary upwelling and pressure-release melting (to form lowlands and volcanic plains). Subsequent thermal, isostatic, and dynamic readjustments produce the present topography.

sional deformation (Phase II-style deformation); within the tessera, Phase II deformation is followed by the emplacement of small amounts of intratessera plains, possibly caused by negative diapirism at the base of the crust [Head, 1995c]. Continued loading and thermal adjustments cause subsidence in the plains and extensive wrinkle ridge formation (Figure 20a, Period IIb). Finally, following this period, regional volcanic plains give way to smooth and digitate volcanic plains from specific sources and to regional rifting and localized volcanic edifice formation, a style and resurfacing rate quite different from that in earlier times (Figure 20a, Period III).

If large occurrences of exposed tessera (Figure 1c) represent regions of convergence and crustal thickening (Figure 21), what do the small patches of tessera (Figures 1c, 4, 16) in the midlands and lowlands represent, and what is the significance of areas where no tessera patches are preserved (Figure 16)? Clearly, many of the regions surrounding the large tessera occurrences and populated by smaller tessera patches (Figure 16) could be areas of thickened crust covered by subsequent volcanic plains (see Figure 17). However, if large areas of crust are undergoing shortening and thickening, then one would expect the presence of complementary regions that are undergoing crustal thinning and extensional deformation (Figure 21, middle). What would these regions look like? Because of the relatively chaotic nature of any crustal deformation occurring during global overturn, specific predictions about orientation of structures are difficult. It is plausible, however, that the dominant structures might be characterized by complex, perhaps intersecting, graben linked to broader patterns of upwelling and downwelling. Examination of such crosscutting patterns in relatively young rift zones on Venus (e.g., Beta Regio, southwest Atla) and in areas of crosscutting structures in the plains (Figure 22) provides suggestions on the possible appearance of such a terrain.

Much of the terrain undergoing complementary stretching and extensional deformation would also be the regions of thinnest crust, most enhanced fertile mantle upwelling and pressure-release melting, and the site of large-scale volcanic flooding, followed by subsidence due to decay of thermal topography and isostatic adjustment related to thinned crust.
Figure 22. Example of crosscutting graben structures in plains between Tinatin and Aino planitiae. These crosscutting patterns could fit the strict definition of tessera terrain (see text) and suggest that at least some of the low-lying regions of tessera patches could be of extensional origin. Other examples are seen in rift zones in Beta and southwest Atla regiones (F.MIDRP.15S049;201). Image is 121 x 166 km.

Comparison of Figure 1d and Figure 16 shows that much of the region occupied by small tessera patches, or no exposed tessera, occurs in the lowlands or adjacent rolling uplands, an observation consistent with regions of isostatically compensated thinner crust. In addition, tessera formed by stretching (and now largely surrounded by subsequent volcanic plains) might be relatively smoother and not as topographically self-similar to the presently exposed highland tessera topography (Figure 4b). Thus the present distribution of tessera types and associated topography suggest that the variations in distribution and present exposure may mark regions of downwelling and crustal thickening and complementary upwelling and crustal thinning (Figure 21).

Finally, we consider the relation of these patterns to more recent structures and geologic activity (Figure 20a, Period III). Centers of volcanic activity (Figure 1e) and relatively young fracture belts (Figure 1g) are concentrated in the Beta-Atlas-Themis (BAT) region [Crumpler et al., 1993], an area relatively deficient in tessera (Figures 2a, and 2d) and complementary in latitude to the major concentration of tessera (Figures 2a and 2c). We speculate that these relatively recent patterns of upwelling and extension may be related to global mantle circulation patterns set up at the time of the tessera-forming event. Concentration of downwelling in the global area of abundant tessera (Figure 2c) could produce large-scale thermal heterogeneities which would favor subsequent complementary broad thermal upwelling and associated volcanism and rifting (Figures 1e, 1f, 2d). This scenario suggests the presence of global variations in thermal gradients, a prediction that could be tested with further analysis.

On the basis of our analysis of hypotheses of origin, it is clear that the Parmentier and Hess [1992] model for tessera formation can explain many of the characteristics of tessera described in this paper, partly because it makes such specific predictions. Many other models cannot be ruled out, however. One of the major difficulties in distinguishing between models is the fact that the time of onset of tessera deformation is not known. It could have been a specific event just prior to emplacement of the plains, in which case the deformational event obliterated all preexisting craters, or tessera deformation could have been going on continuously throughout the earlier history of Venus, with craters being destroyed almost as quickly as they were formed. In this case, tessera deformation simply ceased rapidly.

13. Outstanding Questions

A number of outstanding questions remain concerning the nature and evolution of tessera [Head, 1995a].

Nature of the tessera terrain. What is its true global
extent? Are the small isolated exposures of tessera that make up the vast number (but not the area) of tessera occurrences linked to an underlying basement of global tessera terrain, with the large continuous exposures simply linked to greater crustal thickness, or do they represent the surface exposures of a different type of deformation? What is the composition of the tessera materials; does the diversity of Venera lander compositions and the relation of steep-sided domes and festoons to tessera mean that they may be compositionally diverse? Can the nature of proto-tessera materials be determined through detailed geologic mapping? What role do the abundant patches of intratessera plains play in the petrogenetic evolution of the tessera? What do the gravity signatures of the different tesserae mean in terms of mode of formation? Can all be explained in terms of different levels of shallow compensation and crustal thickness variations or is there evidence for dynamic support? Why is Western Ishtar Terra so different from other tessera occurrences? Do these different occurrences represent different basic modes of formation of tesserae, or do they simply reflect different aspects of a common origin?

**Processes of tessera formation.** Understanding tessera formation requires consistent interpretation of the nature and sequence of tectonic structures and facies. Because of the demonstrated presence of compression, extension, and shear, and their clear superposition and even contemporaneity, the resulting terrain is often complex relative to surrounding plains. Detailed descriptive and kinematic analyses must be continued to address the following questions: What are isolated examples of individual features making up the complex tessera fabric, and how are they interpreted? What is the relative importance of compressional, shear, and extensional deformation in the formation of these structures and fabrics? How did these vary as a function of time? Is there evidence for interference folding, or do complex structures result largely from extension and shear modification of older terrain? Is there any correlation between intensity of deformation and topography that might be related to crustal thickness differences? How much shortening and extension is involved in tessera formation and how is it accommodated elsewhere? What is the timing and duration of tessera formation; is it fast or slow, sequential or multiple, ongoing or inactive? How do detailed tessera characteristics and individual strain histories more specifically relate to models of upwelling, downwelling, hot spots, cold spots, catastrophic overturn or cyclic plate tectonics?

**Processes of tessera evolution.** Tesserae may be long-lived blocks of thickened crust that have been subject to repeated episodes of tectonic deformation, often external in origin and related to large-scale stresses. If this is true, the level of deformation observed in the highlands would depend in part on its age; for example, differences in tectonic deformation in two tessera occurrences could be due in part to a greater age for a crustal thickening event. Do apparent steps in the tectonic sequence represent sequential or contemporaneous deformation? What are the time scales involved? What is the evidence for multiple deformation phases (e.g., tessera cores representing older events distinctly separated in time from tessera margins, representing later deformation and accretion)? Can these be confidently distinguished from apparently complex non-coaxial patterns? Is there evidence for thickened crust enhancing deformation? Is there evidence of crustal loss during or after tessera formation? What are the latest deformation features and how are they related to the surrounding plains? What is the cause and significance of the broad modification that tessera underwent during and subsequent to plains formation (regional tilting)? What is the role of post-formation surface radar property modification? Can this be used to determine paleo-altitudes?

**Crucial measurements and observations.** Detailed mapping of the structure and stratigraphy of tessera occurrences across Venus is required to address many of these questions. Specifically, detailed analyses of individual occurrences of tessera are necessary to establish strain histories. Stratigraphic analyses of adjacent plains will also provide important evidence for the interaction and chronology of apparently nearly synchronous units. Assessment of high-resolution Magellan gravity data will help to delineate the range of characteristics of tessera and models of tessera evolution, and will sharpen predictions which can be tested with detailed mapping analyses. In the longer term, spacecraft missions to the surface of Venus will be required to address many substantial questions. For example, Venera-like landers in tessera terrain could determine chemical composition, aspects of mineralogy, and reveal detailed structure and morphology in surface panoramas. Balloons with instrumented gondolas could provide chemical measurements in several different places and high resolution images along traverses between touchdown sites, while long-term landers could help determine the levels of present seismic activity on Venus. Together these data could test many of the present hypotheses for the formation and evolution of tessera terrain on Venus.

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