Crustal spreading on Venus: evidence from topography, morphology, symmetry, and map patterns

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ABSTRACT

Evidence for numerous features similar to terrestrial divergent plate boundaries and spreading centers are present in the topography and morphology of Western Aphrodite Terra, Venus (Head and Crumpler, 1987). Linear discontinuities cutting across the strike of Western Aphrodite Terra (Cross-Strike Discontinuities or CSDs) were examined in further detail. It was found that: (1) They represent the most prominent regional structural trend in Western Aphrodite and are readily distinguishable from linear patterns caused by ground tracks in the Pioneer-Venus orbiter data; (2) individual CSDs are either deep troughs or steep regional scarps and steps; (3) the spacing between the more prominent CSDs ranges from about 500 to 1500 km (average spacing is 850 km); and (4) there is a distinctive structural trend orthogonal to the strike of the CSDs. Additional smaller scarps and slopes with characteristics of known CSDs occur in the Arecibo altimetric profiles at spacings of as little as 50 km, in agreement with previous suggestions of Sotin et al. (1989) that other smaller CSDs with less offset may occur in domains between the more prominent ones previously mapped. The detailed characteristics of the CSDs (detailed trough and scarp-like form, association with ridge offsets, linear terminations, linear slope traces, parallelism, great length) are all very similar to the characteristics of transform faults and fracture zones on the Earth's seafloor, and this additional analysis supports the earlier interpretation that CSDs represent analogs to terrestrial oceanic fracture zones.

Assessment of bilateral symmetry of topography and other elements across Western Aphrodite Terra indicate that: (1) an accurate prediction of the large and small-scale symmetrical elements in both the altimetry data and radar images within each domain on one flank of the highlands may be made by substitution of a mirror image of the opposite flank, and (2) smaller wavelength symmetrical elements are revealed in the altimetric profiles by subtracting the background regional symmetry and examining the residuals. Residual altimetry profiles obtained in this manner show that individual altimetry features several hundred kilometers wide and several hundred meters high are frequently located at the same distance from the axis of regional symmetry on the north and the south flanks of the highlands.

Topography and geometric features such as ridge crests and transforms have specific predictable relationships in a crustal spreading environment. Tests were made in Western Aphrodite for such organized relationships predicted to occur in association with ridge crest offsets at transform faults and fracture zones. It was found that: (a) topographic stepdowns occur across CSDs in accordance with the general consequences of juxtaposing lithospheres of different relative ages, (b) the correct direction of stepdown (down toward older crust and lithosphere) occurs relative to that predicted from ridge crest offsets, and (c) the observed amount of stepdown is similar in many cases to that predicted from the observed ridge crest offsets. These analyses of cross-strike discontinuities, topographic and image symmetry across Aphrodite, and predictions of topography based on ridge crest and fracture zone geometric relationships further support the earlier interpretation that the 7500 km extent of Western Aphrodite Terra represents the site of crustal spreading and displays many of the characteristics of terrestrial divergent plate boundaries.

1. Introduction

Aphrodite Terra is a topographic ridge extending for up to 21,000 km along the equator of Venus in a generally east–west orientation (Masursky et al., 1980). The great length and relative linearity of Aphrodite Terra stands in contrast to the shape of highlands on other terrestrial planets, such as the Tharsis region of Mars and the continents on Earth which are both nearly
equidimensional. The great length suggests that, whatever its origin, Aphrodite Terra represents a highland differing in several respects from that common elsewhere in the solar system and more akin to the variety of long and linear topographic features occurring on Earth, such as mountain belts, hot spot traces, and oceanic ridges. Therefore, understanding the nature of Aphrodite Terra will provide further insight into the global geology and tectonic style of Venus, and further address the nature of similarities and differences between the geologic and tectonic styles of Venus and Earth.

On the basis of the presence of rift-like topography (Schaber, 1982; McGill et al., 1983), previous studies have suggested that Aphrodite Terra is a zone of relatively recent lithospheric extension and potential volcanism. Large positive correlations of gravity and topography (Sjogren et al., 1983) have similarly suggested to some that the current topography is supported dynamically by mantle convection perhaps with associated volcanism (Morgan and Phillips, 1985; Kiefer et al., 1986; Banerdt, 1986). In many of these models tectonic deformation is mainly vertical and the crustal extension represents rifting of the crust resulting from limited traction by mantle convection underneath (Phillips, 1986) or rifting resulting from gravitational spreading stresses (Banerdt, 1986; Smrekar and Phillips, 1988). On the basis of a variety of geologic and morphometric evidence, the detailed characteristics of Western Aphrodite Terra (60°E to 150°E) have been interpreted recently to be more analogous to divergent plate boundaries and crustal spreading on Earth (Head and Crumpler, 1987; Crumpler and Head, 1988). This interpretation is based on the presence of linear discontinuities having many of the characteristics of oceanic fracture zones, bilateral symmetry similar to that associated with evolving thermal boundary layers, linear features arrayed at equal distances on both sides of the ridge crest suggesting the splitting and separating of features along ridge crests by crustal spreading, and on a variety of topographic and map pattern (Head and Crumpler, 1987) relationships consistent with the presence of features linked to both crustal spreading and the thermal evolution of lithosphere migrating laterally away from a zone of extension and crustal creation.

The purpose of this paper is to evaluate the characteristics of Aphrodite Terra, its morphology, and its map patterns and to test the hypothesis of crustal spreading by analyzing in more detail: (1) the nature of cross-strike discontinuities (CSDs) in Western Aphrodite, (2) the nature of symmetry across Aphrodite Terra in both altimetric data and radar images, and (3) the way in which topography and geometric features in Aphrodite Terra compare to predicted relationships for ridge crest and transform geometry in a crustal spreading environment.

2. The nature of cross-strike discontinuities in Western Aphrodite Terra

Regional discontinuities that cross the nearly east–west strike of Aphrodite Terra between 60°E and 150°E have been identified on the basis of distinctive linear zones in Pioneer-Venus altimetry maps and Pioneer-Venus radar images, and by steep slopes and troughs with linear map traces in high-resolution Arecibo Earth-based radar altimetric profiles (Crumpler et al., 1987; Fig. 1). These features, referred to as cross-strike discontinuities or CSDs are narrow and linear, extend over several thousand kilometers, are generally parallel to one another, and are distinguished by their tendency to disrupt or segment both the altimetric and the radar-backscatter characteristics of Aphrodite Terra. On Earth CSDs are recognized as indicators of major discontinuities in tectonic patterns regardless of the mode of formation (Wheeler, 1980), a characteristic which distinguishes them from simple map lineaments.

Criteria for the identification of CSDs (Crumpler et al., 1987) include: (1) linear discontinuities in elevation (scarps), (2) linear boundaries in radar backscatter properties of surface materials (RMS slopes and reflectivity), (3) long linear topographic ridges and troughs, (4) abrupt termination of axis-parallel long linear ridges or troughs at steep scarps, (5) aligned topographic features, and (6) segmentation of Aphrodite Terra. Large scale topographic characteristics of CSDs include regional offsets of the east–west strike of Aphrodite
Terra, some of which are apparent in global altimetric maps, and distinct elongate co-linear depressions in the lowlands along the projection of large-offset CSDs (Fig. 1). In addition to the abrupt shift in the center of the highland, a distinct change occurs in the nature of smaller elements of topography across CSDs, and in general each pair of CSDs defines a strip or domain in which altimetric characteristics differ in detail from adjacent domains. For example, in the lowlands north and south of Ovda Regio, the regional altimetry is characterized by linear elements paralleling the east-to-northeast local trend of Ovda Regio (Fig. 1, A), but immediately to the east of CSD 5, the detailed elements of lowland altimetry change to circular or non-linear forms (B, Fig. 1).

**TABLE 1**

Characteristics of additional cross-strike discontinuities in Western Aphrodite Terra *

<table>
<thead>
<tr>
<th>CSD</th>
<th>Long. (at eq.)</th>
<th>Strike (W°E)</th>
<th>Length (km)</th>
<th>PV altimetry</th>
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<tr>
<td>12</td>
<td>109</td>
<td>20.4</td>
<td>2100</td>
<td>-9/113 L</td>
<td>0/108 D</td>
<td>2.3/107 t</td>
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* CSDs 1–8 are described in Crumpler et al. (1987). Loc. = location latitude/longitude; L = linear slope or linear boundary; t = trough < 1 km deep; R = truncated trend or truncated ridge form.
Two CSDs (11 and 12) in addition to those previously discussed (Crumpler et al., 1987) have been mapped on the basis of continued analysis using the above criteria (Table 1). Although many potentially more subtle CSDs were identified, they are not mapped in Fig. 1 because they occur only in one or two of the three data sets necessary in our criteria for mapping CSDs. The precision with which the CSDs are defined depends in part on the data resolution, the surface density of observation footprints, and the surface area coverage of the data. We first examine the level of precision of location of CSDs that can be obtained on the basis of the density of Pioneer-Venus data points in order to provide the ability to test for the location of possible Euler pole positions. We then compare the orientations of CSDs to other linear trends in Aphrodite, and finally we examine the detailed topographic characteristics of CSDs using high resolution Earth-based Arecibo range-doppler altimetry profiles.

A. Pioneer-Venus data density and precision of CSD orientation

Altimetry features on the surface of Aphrodite Terra and in the lowland plains immediately north were measured with a range resolution of approximately 200 m, were sampled with the smallest footprint diameter (40 km), highest data density (> 1 measurement per square degree), and smallest map resolution (\(2\sqrt{2} \times 40 = 100\) km) available in the Pioneer-Venus data set (Pettengill et al., 1980). The areal density of Pioneer-Venus spacecraft data points in Western Aphrodite (Fig. 2) is such that between longitudes 60° and 150° there is more than one altimetry point per square degree (Pettengill et al., 1980) and the spacing between data points is \(-40\) km. The footprint size for each altimetric determination in this area is as small as 40 km, being a function of the low spacecraft periapsis which occurred at a latitude of about 17°N. Pioneer-Venus synthetic aperture radar image (SAR) data show large-scale variations in the radar backscatter (reflectivity and roughness) throughout the low latitudes at resolutions of 20 to 40 km and can also be used for a more detailed characterization of the surface. The
radar images cover areas between about latitudes 8°S to 40°N (Pettengill et al., 1980; Masursky et al., 1980) and record the distribution patterns (images) of relative radar signal backscatter on the surface of Venus acquired through a synthetic aperture radar (SAR) mode.

Linear patterns on a surface can result from both real and artificial causes. Artifacts may arise such as that resulting from orientation of data elements along linear spacecraft mission-tracks (ground traces of orbital path) or if tracking errors result in systematic displacements in along-track location of data points. Because the spacecraft ground tracks are oriented at an angle of approximately 60° to the trend of identified CSDs (N20°W to N30°W) and because the spacing between CSDs is 5 to 10 times greater than the along-track or across-track spacing between data points, the mapped CSDs are unlikely to be the result of serial changes in spacecraft tracking accuracy or limited resolution. In addition, each CSD in Fig. 1 is defined on the basis of between 33 and 90 orbital passes. In the following section, the full range of linear trends in Western Aphrodite Terra is established and their tectonic and geologic significance, as well as the potential for a processing artifact in the production of spurious linear trends, is assessed.

B. Significance of linear trends

The orientation of all linear elements in altimetric maps and SAR images were mapped and these compared to orientations that might result from known data artifacts. Features mapped as lineaments in altimetry data included the margins of the highlands, regional linear slopes, linear troughs, linear ridges, and combinations of these features occurring in linear arrangements at all scales (Fig. 3A). Rose diagrams based on these data (Fig. 3B) record at least four regionally prominent linear trends in the altimetric shape of the highlands. The most prominent is oriented N20°W similar to the orientation of known CSD’s, and a less prominent trend is oriented

Fig. 3. Linear elements in Western Aphrodite Terra. (A) Map of main altimetric lineaments. (B) Orientation of altimetric lineaments showing two orthogonal subsets: One subset is parallel to and at right angles to orbital ground tracks, and the other subset is parallel to and at right angles to CSD orientations. (C) Map of lineaments visible in Pioneer-Venus high-resolution radar backscatter image using a 10° by 10° lineament mapping window. (D) Orientation of lineaments in radar image data divided into four sub areas: two subsets are orthogonal and are similar in orientation to lineaments identified in the altimetric data.
N70°E at approximately right angles to the orientation of CSDs.

The presence of a trend oriented N20°E to N30°E, similar in orientation to spacecraft groundtracks, supports the interpretation that along-track lineation of the altimetric data accounts for most of the lineaments trending in northeasterly orientations. Similarly a fourth trend orthogonal to this (N60°W to N70°W) at nearly right angles to the spacecraft orbital direction could result from along-track digital stepping of topographic slopes. In either case, the two trends that are parallel and at right angles to the orbital tracks cannot be confidently distinguished from artifacts induced by orbital tracks and along-track digital stepping. The CSDs are oriented obliquely to the orbital tracks, and therefore, appear to represent actual linear characteristics of the surface altimetry.

Prominent linear features mapped in the Pioneer-Venus SAR data provide a second, and more detailed assessment of the influence of mission tracks on the visibility of tectonic features, as well as an independent test of the presence of CSDs, their locations, and their orientations. Linear characteristics of the radar image data set were mapped using a non-overlapping 10° mapping cell in an area covering Aphrodite Terra and its surroundings (−15° to 30° in latitude and 50°E to 225°E in longitude). The results (Fig. 3C) show that the lineaments with orientations similar to the known CSDs are most prominent in radar image data throughout much of Aphrodite Terra and that lineament absolute numbers per unit area are greatest within the highlands and become less abundant within the lowlands. The same four directions noted in the altimetric data occur in the radar images. The CSD orientation is the strongest trend (N20°W) and linear features with orientations parallel to the spacecraft mission-tracks (N20°E) are secondary in abundance, whereas two lesser trends (N70°E and N70°W) occur at right angles to each of these.

C. Arecibo high-resolution altimetric profiles of CSDs

The morphological and structural nature of CSDs are resolved in more detail in Arecibo altimetry profiles (Crumpler et al., 1987) than in the

![Fig. 4. High-resolution Earth-based Arecibo range-doppler altimetry profiles across identified CSDs in Western Aphrodite Terra. Along-track (lontudinal) resolution is 10 km and altimetric (range) resolution is approximately 150 m. CSDs 2, 11, 7, and 8 are “scarps” (1° to 2° slope over 100–200 km of longitude), and CSDs 1, 3, 4, 5, and 6 are “troughs” (elongate 1–2 km depression over 100–200 km of longitude). Locations of profile tracks and CSDs with respect to Aphrodite Terra are shown in the inset. Small arrows indicate additional CSDs that are not mapped because of the absence of one of the three criteria for their identification and location, or because they are not resolved in the Pioneer-Venus data. Note that P2 is shifted approximately 3° to 4° of longitude to the left in order to align profile characteristics of CSD 6 vertically.]
Pioneer-Venus data and permit more detailed assessment of altimetric features along approximately east-west oriented tracks across low equatorial latitudes. The resolution of Arecibo altimetry in the along-track (longitudinal) dimension is about 10 km and the vertical (range) resolution is 150 m (Campbell et al., 1984), or between several times to an order of magnitude greater than the Pioneer-Venus altimetry.

These data reveal that several CSDs are trough-like in both the highlands and lowlands (CSD 1, 4, 5, and 6, Fig. 1) and other CSDs are characterized by step-like profiles (CSDs 2 and 5). CSDs 2, 8, and 11 have a distinct scarp-like form (Fig. 4), and examples of trough-shaped profiles include CSDs 3, 4, 5 and 6. The linear trough, illustrated in two parallel Arecibo profiles across CSD 6 in Thetis Regio, is approximately one kilometer deep, 100 to 200 km across, and traverses several thousand kilometers across the equatorial highlands (Fig. 4). Some of the steepest regional slopes on Venus occur across CSDs associated with highland offsets and long troughs (slopes up to 1° to 2° within horizontal distances of up to 200 km). On Earth, slopes this steep occurring over several hundred kilometers are frequently associated with boundaries between major tectonic provinces (Sharpton and Head, 1986), and further suggests that CSDs are important tectonic boundaries on Venus.

In summary, the presence and location of altimetric CSDs is based on a large body of data and from many adjacent orbital passes with relatively high surface data point densities. The fact that the CSD trend is mapped simultaneously in several data sets and is parallel to linear trends along which the large offset and segmentation of Aphrodite Terra occurs supports the suggestion that the CSD trend is a significant tectonic fabric, and related to the segmentation and offset of the equatorial highlands. These orthogonal trends in surface features occur when examined either at a global or at a regional scale in general agreement with the detailed analysis of regional and global slopes performed previously (Sharpton and Head, 1986) and which first suggested the presence within the equatorial highlands of distinct orthogonal trends of regional altimetry and regional slopes.

3. Additional assessment of bilateral symmetry in Western Aphrodite Terra

The symmetry characteristics of Western Aphrodite Terra include symmetry in altimetric profiles and in topographic map patterns (Crumpler and Head, 1988) occurring about axes that lie along the crest of Aphrodite Terra. We have examined symmetry patterns in radar images and in altimetry, including: (1) regional profiles parallel to the CSDs, (2) profiles of the highland surface out to about 500 km from the center of the highlands, and (3) residual topographic features remaining after removal of the broad regional topographic signal in the flanking lowlands. Symmetry in a single domain between two CSDs, based on averaging all altimetry data points lying at the same distance from the highland ridge axis, are discussed elsewhere (Sotin et al., 1989).

A. Bilateral symmetry of Aphrodite Terra in altimetric profiles and maps

The topographic relief associated with Aphrodite Terra is bilaterally symmetric over a variety of scales. The convex-upward profile and ridge-like map shape of Aphrodite Terra (Fig. 5A) is broadly symmetric in profiles at right angles to the long axis of the highland, and the flanking lowlands slope northward and southward at low angles for several thousand kilometers beyond the steep margins of the highland, thus contributing to the broad appearance of symmetry in approximately north–south oriented profiles. These characteristics occur in profiles extending for several thousand kilometers across Aphrodite Terra. The extensive sloping regional flanks of the symmetric ridge-like form, combined with the great length and size of Aphrodite Terra, account for a symmetry in the global shape of Venus in the low to mid-latitudes (Head et al., 1988), and reveal the extent to which Aphrodite Terra and its tectonic features may influence the global topography of Venus.

Short wavelength relief occurs at scales of a few hundred kilometers within both the flanking lowland slopes and the surface of the highland. Multiple profiles constructed parallel to the local orien-
tation of CSDs across the highlands are characterized by linear symmetry axes which are oriented at right angles to each CSD, and terminate and are distinctly offset at each CSD (Fig. 5B). In addition to offsetting and terminating altimetric and radar backscatter features, CSDs also mark zones along which the detailed symmetry is segmented into narrow corridors or domains.

Orthogonal intersection of the symmetry axes and the CSDs is comparable to the orthogonal trends seen in the altimetric and radar image data (Fig. 3). The N70°E orientation, which is orthogonal to the CSD trend, must represent linear elements of altimetry that are parallel to the symmetry axes and implies a certain level of continuity of features across adjacent profiles shown in the discussion of the symmetry axis determination. This implies that there is a family of symmetry features which are parallel to the ridge symmetry axis as well as occurring at right angles to the ridge crest in altimetry profiles.

B. Bilateral symmetry of domain elements

Detailed examination of a series of profiles within separate domains (regions separated by CSDs) shows that at least two scales of symmetry are commonly present. At a scale of several thousand kilometers both highlands and their adjacent lowlands slope symmetrically away from a long
linear axis. This axis is offset at CSDs (Fig. 5A). At a shorter wavelength, between 200 to 500 km, smaller-scale altimetric features within the highland and within the adjacent lowlands appear also symmetrically disposed about the same offset axes of symmetry.

Symmetric features identified on the highland plateau include (Fig. 6): (1) axial troughs or axial ridges, (2) peaks and troughs with relief up to 2 km, and (3) plateau-marginal steep slopes descending to the surrounding lowlands. In the lowlands, although altimetric relief is in general much less than on the central plateau, distinct peaks and troughs occur at the same distance from the symmetry axis across several profiles in adjacent domains. In some cases the symmetric elements within a single domain are linear and parallel to the symmetry axis and, in other domains, the symmetric feature is a diagonal ridge or linear troughs parallel to and lying along discontinuities (Fig. 6).

The domain-to-domain mirror-symmetry was tested by a simple experiment in which one side of the altimetric map of Aphrodite Terra was reflected about the proposed symmetry lines (Crumpler and Head, 1988) in order to simulate what the topography would look like if it was perfectly symmetric (Fig. 7), i.e., if the topography were reflected, as in a mirror, at each symmetry axis. Comparison of the predicted topography with the observed topography reveals a number of similarities in both large and small scale features. For example, both the local width and overall offset shape of Aphrodite Terra are reproduced by the reflection. In the third domain, between CSDs 11 and 3, two nearly linear ridges parallel to the ridge axis are predicted to occur at a distance of several thousand kilometers to the north and south.
of the highlands. Similar features of this orientation and location are identified in the observed altimetry in Fig. 6 and in the left side of Fig. 7. Two ridges are predicted to occur extending obliquely outward from the margins of the plateau between CSDs 11 and 3 in the approximate location where ridges are observed to occur. Using this technique, detailed altimetric characteristics are identified in each domain and further illustrate the detail of the symmetry as well as its relationship to the CSDs.

Departures from the predicted symmetry characteristics occur commonly on the east side of large-offset CSDs (CSD 2 and CSD 5) and imply that over a distance of several hundred kilometers, the symmetry axes near these two CSDs may in detail be displaced by many small and finite offsets unresolved in Pioneer-Venus data. Several unusual small scarp-like features in the Arecibo altimetric profiles across these particular areas supports the suggestion that such additional small CSDs may be present. Similar conclusions about

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**Fig. 6.** Location of bilaterally symmetric smaller-scale altimetric features (dotted lines) on the central plateau and flanking lowland slopes in several domains throughout Western Aphrodite Terra. Individual domains between CSDs 1, 2, 3, 4, 5, and 11 are shown with their centers of symmetry aligned for comparison. Scales determined for great circle oriented N22°W with respect to the equator.

**Fig. 7.** Mirror-image symmetry comparisons. (A) Bilateral symmetry of altimetric map features within individual domains of Western Aphrodite Terra compared with altimetry derived assuming perfect symmetry. The map on the left in each example is the observed altimetry, and the map on the right is modeled assuming perfect mirror symmetry across the proposed symmetry axes (lines between CSDs). Width, length, and domain to domain characteristics of the plateau between CSDs are predicted in the model by a simple transformation in which altimetry on one side of the axis is replaced with a mirror image of the opposite flank. (B) Comparison of observed and modeled symmetry when assembled at regional scale. Basic symmetry is reproduced in the model; significant differences between the observed and modeled width of the plateau occur on the east side of large offset CSDs and suggest that additional small CSDs and incremental north to south-stepping symmetry axes may occur in these areas in order to reproduce the observed altimetry. Differences in length scale between the predicted and observed patterns on the southern flanks also reflect distortions resulting from the Mercator projection and were not adjusted in the reflected altimetry.
large offset zones are reached by Sotin et al. (1989) on the basis of examining symmetry in gravity data. Identification of these and other small CSDs, and the magnitudes of their offsets, may be assessed in altimetric maps and radar images by high-resolution Magellan spacecraft radar imaging of the surface of Venus.

C. Bilateral symmetry in radar images

Figure 8 shows a sketch map of relative radar backscatter based on the SAR radar image data for Western Aphrodite Terra. (The latitudinally limited coverage of SAR mode data restricts the test for image symmetry to those parts of Western Aphrodite Terra lying north of 8° S.) The upper half of the figure shows segments of radar images within Ovda Regio and Thetis Regio. In order to test for symmetry of radar image features, the same technique is adopted that was used above in testing for mirror symmetry in altimetry maps. The proposed symmetry axes based on the altimetric profiles were mapped onto the radar images and the southern half of each domain removed and replaced by a mirror image of the northern half.

Images of the radar pattern predicted on this basis (Fig. 8) suggest a number of comparable

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**Fig. 8. Mirror-image symmetry comparisons.** (A) Bilateral symmetry in radar image features. Symmetry axes and CSDs from altimetric data overlain onto sketch maps based on Pioneer–Venus SAR images of Ovda and Thetis Regio. (B) Predicted radar image pattern if single features south of the altimetric symmetry axis are mirror images of features north of the altimetric symmetry axis. The observed and predicted patterns are similar in terms of regional patterns, local detailed shapes, sense of offset, and location of radar bright elements. Arrows indicate “point-to-point” symmetry features, letters B are oblique and “V”-shaped symmetry elements, and C are symmetrically expressed linear discontinuities. Dimensions: image on the left, 3000 km × 1100 km; image on the right, 2500 km × 880 km.
symmetries in the observed images, including "point-to-point" symmetries, "V"-shaped or "butterfly" symmetry patterns, and several axis-normal discontinuities or offsets in radar bright areas. Linear discontinuities at right angles to the proposed symmetry axes (labelled C in Fig. 8) represent CSDs not resolved in other data sets. Similar results are achieved if the northern half is removed and the southern half reflected at the proposed symmetry axes. These results show that the process responsible for the generation of symmetry in radar backscatter data involves regional material properties at radar wavelengths in addition to the larger scale altimetric properties of the surface.

4. Interpretation of CSDs and bilateral symmetry in Aphrodite

Origins of the CSDs and the offsets of domains in Western Aphrodite Terra considered initially (Crumpler et al., 1987; Head and Crumpler, 1987; Crumpler and Head, 1988) included (1) joint patterns, or a planetary scale "grid", (2) strike-slip faults, and (3) fracture zones analogous to those occurring on the seafloor on Earth. The planetary grid hypothesis was rejected on the basis of the topographic evidence for horizontal as well as vertical offsets in the surface associated with CSDs. Also, unlike previously described planetary grids consisting of local alignments of small features and short length segments of lineaments, the CSD trends are part of global zones of slopes and other topographically distinct surface elements. Many of the CSDs trend along great circles generally oriented at less than 45° to the equator (Sharpton and Head, 1986). The strike-slip hypothesis for the origin of the CSDs was rejected on the basis of misfit of the potential strike-slip separated elements and differences in regional morphology of the offset domain when the proposed offsets between domains are restored to a pre-slip config-
Fig. 9. (A) Bathymetric contour map of the South Pacific seafloor illustrating the characteristics of large-offset transform faults and fracture zones. Contour depth interval in kilometers. (B) Segments of ridge crest axis mapped on the basis of centers of symmetry. Fracture zones and transform faults are mapped as discontinuities in the ridge crest. Fracture zones and transform faults are the single most distinctive characteristic of seafloor bathymetry at these scales.

Fig. 10. (A) Bathymetry of the Quebrada fracture zone (after Searle, 1983). The Quebrada fracture zone is actually a composite of many closely spaced parallel transforms that mark a large offset zone. (B) Profiles P1 and P2 across CSD 6 in Thetis Regio, Aphrodite Terra. Profiles correspond to lines P1 and P2 of Fig. 4, inset.

altimetric profiling, show that in terms of length, width, parallelism, and detailed morphology, CSDs are similar to fracture zones at ridge crest offsets on the seafloor (Fig. 9) (Crumpler et al., 1987; Head and Crumpler, 1987).

A. Interpretation of CSDs and orthogonal pattern

Fracture zones, like CSDs, frequently mark zones across which there are distinct offsets in ridge crests, bathymetric steps in the seafloor (Fig. 9), and changes in a variety of seafloor characteristics, such as bathymetric roughness (short-wavelength relief 0.1 to 1 km scales), tectonic patterns, or the orientation of magnetic lineations. In bathymetric profiles, fracture zones are also frequently characterized as scarps or valleys, similar in morphology to that of many CSDs identified in high resolution Arecibo profiles (Fig. 10). A third characteristic, the step-like form of regional altimetry across CSDs, is discussed in a later section.

Individually, fracture zones are long and narrow valleys often with adjacent ridges, or they may be simply a distinct trough-like valley that extends for several thousand kilometers (Garfunkel, 1986; Collette, 1986). To first order, the trough-like bathymetry of fracture zones is attributed to plate-bending stresses where two plates of differing age (and, therefore, buoyancy) are mechanically coupled, and, secondarily, to thermal contraction (Collette, 1974; Sandwell, 1986). On Earth, the range in detail of morphological styles, and the widths and the depths across fracture zones is a consequence of variations in
spreading rates, magnitude of ridge-crest offset, lithospheric rigidity, the local kinematics, and volcanic style of the transform zone between offset segments of divergent ridge crests (Menard and Atwater, 1969; Sandwell and Schubert, 1982; Sandwell, 1986; Colette, 1986).

Elongate troughs parallel to the orientation of CSDs are one of the few identifiable traces of CSDs where they cross into the lowlands around Aphrodite Terra and generally lie along CSDs where the largest offsets in the highland ridge crest occurs. On Earth troughs along the strike of fracture zones are a large-scale characteristic of many fracture zones in addition to the primary regional altimetric offsets. Trough-like bathymetry is commonly predicted from mechanical behavior expected of juxtaposed segments of lithosphere of differing age, but a larger-scale trough, much wider than the troughs associated with individual fracture zones, can frequently form in areas of large ridge crest offsets as a result of topographic coalescence of several closely-spaced adjacent transform faults (Searle, 1983). The trough-like form occurs due to a variety of reasons, including the additive effects on structure and bathymetry of several closely-spaced transform faults, thermal perturbations and reduction of volcanic crustal production accompanying the intersection of some ridge crests and transform faults (Shouten and White, 1980; Fox and Gallo, 1984; Karson and Elthon, 1987), and kinematic effects such as might occur in transforms where the plate boundary between ridge tips is oblique to the direction of plate motion (Garfunkel, 1986). Some examples of troughs possibly arising from one or more of these influences include the Quebrada fracture zone (East Pacific Rise, 4°N), the 25–30 km wide Tamayo Fracture Zone at the mouth of the Gulf of California (Macdonald et al., 1979), and the Eltanin and Heezen fracture zones (Fig. 9, East Pacific Rise, 55°S). Therefore, in addition to the thermal and mechanical effects related to the interaction of lithospheres of differing age, effects of closely spaced transforms on volcanic production and tectonic features might contribute to the observed depth, and particularity to the observed anomalous widths of many fracture zones in the seafloor at large-offset transforms.

In the lineament analysis, it was shown that CSDs are associated with a distinct orthogonal pattern of topography in Pioneer-Venus and Arecibo data sets and orthogonal trends at moderate (10's to 100's of kilometers scales are known to occur elsewhere on Venus, particularly in distinct complexly disturbed terrain known as “tessera” (Basilevsky et al., 1986). Pioneer-Venus radar properties in areas of tessera covered in Venera images are comparable in roughness characteristics with the Pioneer-Venus radar backscatter character of Aphrodite Terra and suggest that both the tessera and Aphrodite Terra have similar radar-wavelength surface roughness and topographic slope frequency distributions (BINDSCHADLER and Head, 1988a; Bindschadler et al., 1990). Morphological similarity between the orthogonal patterns of the seafloor and equatorial regions of Venus have also been suggested on the basis of a variety of studies. Analysis of trough-and-ridge tessera type (Bindschadler and Head, 1988b) in Laima Tessera, covered by Venera 15/16, shows similarities in morphology between the orthogonal fabric in Laima Tessera and the terrestrial ocean floor (Head, 1990). The simple orthogonal fabric of the seafloor is a result of the production and divergence of new crust along linear ridge axes and the preservation in the form of parallel transforms—fracture zones intersected by abyssal hills. Fracture zones are a part of this orthogonal topographic and tectonic fabric and are oriented at approximately right angles to ridge crests (Lonsdale, 1977). We thus interpret the patterns orthogonal to CSDs seen in topography and radar images to be related to an abyssal hill-type fabric.

The similarities between fracture zones and CSDs can be tested further on the basis of their global kinematic behavior. Fracture zones generally behave according to the geometric constraint that rigid plate motion on a sphere can be described by rotation about a single pole. In this test, if the CSDs are analogous to fracture zones associated with lithospheric divergence at the boundary between two plates, then, like fracture zones, they should essentially lie along arcs of small circles about a single Euler pole of rotation. In current models of rigid plate motion, it is
actually only the transform part of the fracture zone which is constrained to lie along small circles about the Euler pole, but if plate motions are orderly to first order, and if large changes in plate motion do not occur, then the fracture zone traces may closely follow small circles about the Euler pole. Using these broad geometric characteristics of fracture zones, while noting these potential detailed geometric constraints, the fracture-zone model of CSD behavior was tested by Grimm and Solomon (1989). It was found that no single Euler pole may be defined for the observed orientation and distribution of CSDs in the 16,000 km long Aphrodite Terra. This implies that a simple two-plate model does not apply along the total 16,000 km long region and that additional plate boundaries may be present if spreading is occurring. This is not surprising since terrestrial two-plate spreading center boundaries average about 6000 km in length, and nowhere exceed 13,000 km (Forsyth and Uyeda, 1975). These results might suggest that (1) the CSDs are not accurately located in the flanking lowlands because of the low altimetric and radar image contrasts there, (2) that a simple two-plate model does not apply at great distance from the equatorial highlands, (3) that a rigid plate model does not apply, (4) that the mapped CSDs represent complex fracture zone traces originating from multiple closely-spaced fracture zones whose off-axis relationships are not simple, or (5) that one or more of the CSDs acts as a plate boundary along nearly its full length, similar to the Macquarie transform (associated with the Pacific–Antarctic Ridge south of New Zealand) which becomes a subduction zone along much of its length.

The possibility that a rigid plate model does not apply, raises the question of whether true rigid plate-like behavior is a necessary condition for lateral tectonic behavior of the lithosphere on Venus. Because of the higher surface temperature of Venus and the potentially different thickness and intrinsic rheology of its crust, the nature of the lithosphere (its strength, elastic and thermal thickness, and ability to transmit and support tectonic and gravitational stresses over great horizontal distances) are likely to differ from that on Earth. For these reasons the detailed altimetric form of individual fracture zones could differ from that occurring on the seafloor. However, large offsets in altimetry across lithosphere of differing age should occur in either case, but might lack some of the detailed bathymetric behavior of fracture zones that arise from bending stresses in the thicker, cooler, and stronger elastic lithosphere of the terrestrial seafloor. Further theoretical, mechanical, and observational studies are required to assess the potential of these influences on the existence and nature of characteristic fracture zone topography in the Venus environment.

Additional questions that remain to be addressed include: (1) the characteristics of tectonic deformation along CSDs in order to establish if there are compressional or extensional strains associated with CSDs of a non-transform nature, (2) age relations of the surface across CSDs in order to establish potential differences in altitude arising from differences in thermal evolution of the lithosphere across CSDs, (3) presence of deformations characteristic of strike-slip in the individual CSDs lying between the tips of symmetry axes, (4) the origin of trough-like behavior of individual CSDs, and (5) the presence or absence of additional smaller CSDs, domains, and associated highland offsets. Increased precision in the identification and location of CSDs in the lowlands, and detection of the presence and characteristics of CSDs along other parts of the equatorial highlands to the east and west will be possible with the increased resolution of Magellan spacecraft radar images. High-resolution image data planned for the Magellan mission should also help assess whether the orthogonal texture seen in Fig. 3 at a relatively large scale is part of a much finer orthogonal texture similar to that occurring in the tessera.

B. Interpretation of regional bilateral symmetry

Both fracture zones and large-scale symmetry are a predicted general result of thermal boundary layer (TBL) topography (Davis and Lister, 1974) and the bilaterally symmetric nature of the spreading process. Profiles taken parallel to the CSDs throughout Aphrodite Terra are predicted to be symmetric at long wavelengths if the CSDs are
analogous in origin to fracture zones. For these reasons, the presence of TBL behavior associated with divergence in Western Aphrodite is useful as a test and a conditional requirement for the fracture zone interpretation of CSDs.

The physical theory of surface elevation associated with the lateral divergence, cooling, and thermal contraction of a newly created lithosphere is based on the combined effects of isostatic adjustment (density change) and linear (vertical) thermal contraction (Parker and Oldenburg, 1973; Davis and Lister, 1974; Parsons and Sclater, 1977). The change in altitude of the surface from its initial value, $h(x=0)$ at the ridge crest is a function of time since emplacement at the ridge crest ($t$, in millions of years), distance from the ridge crest ($X$, in kilometers), the half-spreading rate ($u$ in centimeters per year), and relative temperature difference between the surface ($T_s$) and the mantle ($T_m$) given by

$$ h = h(x=0) - \left[\frac{2}{\pi^{0.5}}\alpha(T_m - T_s)k^{0.5}\right](X/u)^n $$

where $\alpha = 3.2 \times 10^{-5}/K$ is the thermal expansion coefficient (and is expressed as $a_0[p_o/(p_o - p_w)]$ on Earth, where $p_w$ is the density of water), $k = 10^{-6} \text{ m}^2/\text{s}$ is the thermal diffusivity of the lithosphere, and $n = 0.5$. In general, the quantity in brackets is assumed to define a constant slope, $\beta$, to the functional relationship between altitude and age, and eqn. (1) is expressed simply as a function of the observed age of the lithosphere ($t$) for a relatively uniform half-spreading rate. Based on analysis of the rate of subsidence of the seafloor in several ocean basins, the terrestrial value for $\beta$ is 300 to 350 m/m.y.$^{1/2}$ (Parsons and Sclater, 1977; Hayes, 1988). Results of fitting this function to profiles across the South Atlantic on Earth (Fig. 11A) illustrate that there is a broad correspondence to the theoretical form expected of a TBL in the bathymetry of the seafloor.

In the absence of actual information about ages or spreading rates, the surface elevation may be expressed simply in terms of distance from the ridge crest, in which $\Delta$ is the slope of the best-fitting line to the altimetry data plotted as a function of the square root of distance from the symmetry axis. The equality between the observed value of $\Delta$ and the theoretical value of $\beta$ may be solved for half-spreading velocity ($u$) assuming appropriate thermal constants and values for the mantle temperature

$$ u = (\beta/\Delta)^2 $$

Using the principles outlined above, the altimetry throughout Aphrodite Terra can be assessed for the characteristics of TBL topography, the presence of offsets in TBL topography in association with fracture zones, and estimated rates of crustal spreading. In the following section, we discuss the nature of the evidence for TBL topography. The analysis of the two-dimensional topography alone assesses only the thermal component of the topography which may occur with or without significant horizontal motion of the lithosphere (Morgan and Phillips, 1985). Therefore, in a later section (5), we apply these results to the nature of the evidence for horizontal mobility of the type associated with transform faults.

Kaula and Phillips (1981) examined the altimetric characteristics across linear highlands elements, including Aphrodite Terra, and tested for the presence of a shape that might result from a thermal boundary layer associated with divergence using an upper (appropriately warmer) mantle temperature scaled to Venus ($\sim 480^\circ\text{C}$). Profiles were examined in a variety of directions and the results compared with both the observed altimetry of divergent thermal ridges on Earth and with the results of simple models for the predicted character of the TBL topography as it might occur on Venus. The results of the analysis by Kaula and Phillips (1981) indicated that although some of the profiles, notably in the eastern end of Aphrodite Terra, are close to that predicted for TBL topography, other profiles, particularly in Western Aphrodite, are more plateau-like, have steep non-thermal margins, and do not match overall with the expected form of simple TBL topography (Phillips et al., 1981; Phillips and Malin, 1983; Kaula and Phillips, 1981).

In a more detailed analysis of altimetry across Aphrodite, Grimm and Solomon (1989) concluded that TBL topography of the type identified with
Fig. 11. (A) Bathymetry for a part of the South Atlantic (after Hayes, 1988) showing linear correlation between depth and the square root of age as well as the fundamental difference in depth of the eastern (circles) and western (dots) flanks. Increase in residual bathymetry and absolute differences in altitudes of the western and eastern flanks are among some of the detailed departures that occur from simple symmetric thermal boundary layer type spreading. (B) Location of altimetric profiles across Aphrodite Terra. Profiles shown are plots of nearest-neighbor PV altimetry data for lines shown in Fig. 11B. (C) Altitude as a function of the square root of distance from the center of Aphrodite Terra highlands along profiles parallel to CSDs. Profiles A through F are across Ovda Regio; profiles G through J are from Thetis Regio. The dashed lines represent linear regression of straight lines, by method of least squares, to lowland slopes ($x^{0.5} > 30$). A central plateau, common to the central 2000–3000 km of nearly all profiles, is depressed frequently in the axial region and exhibits greater variations in altimetric relief in single profiles than the lowland slopes. The upper surfaces of at least three of the profiles (C, D, and E) in Ovda Regio appear to fall as the square root of distance and at a similar rate as the surrounding lowlands, but are 3 km higher than the corresponding lowland profiles. Typical errors on the Pioneer Venus altitude determination are shown.
Fig. 11 (continued).
crustal spreading on Earth cannot be unequivocally resolved and that additional processes must contribute to the observed topography. Other factors that may contribute to the altimetry include crustal thickness variations (Sotin et al., 1989; Grimm and Solomon, 1989; Crumpler and Head, 1988), temperature and density anomalies in the mantle beneath a rise axis, or dynamic support of topography by underlying mantle convection. Therefore, important questions are whether there is an Earth seafloor-like TBL component to the observed altimetry, and whether other contributions to the observed topography are present.

Detailed analysis of the nature of altimetry in this area shows that much of the observed altimetry deviating from that predicted on the basis of simple models of TBL topography could result from step-wise crustal thickness variations resulting in isostatic variations in surface altitude. Reid and Jackson (1981) and Sotin et al. (1989) discussed how a divergent boundary overlying anomalously warm mantle material, for example, can result in additional crustal production in excess of that predicted for a typical spreading model. The result is an increase in altitude of the rise heights from localized increases in rates of volcanism, increased crustal thickness resulting from the accumulated volcanic and intrusive materials, and the corresponding isostatically higher-standing seafloor. In this interpretation Western Aphrodite Terra is analogous to some oceanic plateaus on Earth (Ben-Avraham et al., 1981) many of which may have formed where locally enhanced melt production rates are superposed on a spreading center and have created anomalously thick crust and steep-sided plateaus. Detailed ridge crest bathymetric anomalies, oceanic plateaus, and ridge crest hot spots such as Iceland, Jan Mayen, Reunion, Kerguelen Plateau, Hess Rise, Ontong-Java, and Rio Grande Rise are associated with, or have been associated in the past, with divergent plate boundaries (for example, Vallier et al., 1983), and attest to the potential presence and influence on crustal production at ridge crests of local and global variations in mantle temperature, chemical composition, and convective structure on Earth and Venus (Head and Crumpler, 1990).

The abrupt change in altitude at the boundary between the highlands and the lowlands in Western Aphrodite Terra in particular cannot be accommodated by a simple model involving a continuous TBL from highlands to lowlands. If variations in crustal thickness were responsible for the difference in elevation, then the surface of the plateau and the surface of the lowlands lie at a different altitudes only because of differences in crustal thickness (lowlands crust thinner) (Sotin et al., 1989), and to a lesser extent because they might represents different spreading rates.

In order to test this hypothesis further and to isolate any potential isostatic component of abrupt altitude change from a TBL component of topography, if present, the boundary between the highland plateaus and lowlands was established prior to an analysis for TBL topography. This was done by performing a linear fit to the height \( h \) versus square root of distance \( X \) curve independently for altimetric data grouped between \( 0 < X < 1000 \) km and \( X > 1000 \) km. The actual point at which the data were divided between the plateau and the lowlands was measured from the altimetric midpoint of the marginal slopes, and determined the reported plateau width (Table 2). Best-fitting square-root-of-distance curves were determined for each profile from the north and south flanks by method of least-squares (Fig. 11C).

Within the central plateau part of the profiles within Ovda Regio, the surface decreases approximately linearly with with the square root of distance from a point near the symmetry axis out to the margin of the highland (e.g., Fig. 11C, profiles C, D, E). The altitude of the surface descends at the plateau margin 2 to 3 km to the adjacent lowlands with an approximately 0.5° slope over an interval of a few hundred kilometers. From the base of the highlands outward (between 1000 to 4000 km from the symmetry axis), the surface of the lowlands descends linearly as the square root of distance a further 2 km in altitude. In contrast to the variable relief at horizontal scales of 100–200 km in the highlands, the lowland part of the profiles slopes more uniformly away from the highlands throughout Western Aphrodite in accordance with that predicted from TBL theory (e.g., Fig. 11C, profiles A–F, I, J).
TABLE 2

<table>
<thead>
<tr>
<th>Profile</th>
<th>$h_0$</th>
<th>$\Delta$</th>
<th>$r$</th>
<th>$\nu$</th>
<th>Endpoints</th>
<th>Center</th>
<th>Plateau half width (km)</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
<td>S</td>
<td></td>
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<td>0.77</td>
<td>11.0</td>
<td>30/50</td>
<td>-45/85.5</td>
<td>-02/67 1120</td>
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<td>0.033</td>
<td>0.63</td>
<td>4.0</td>
<td>36/61</td>
<td>-45/93</td>
<td>-03/75 900</td>
</tr>
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<td>$B_n$</td>
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<td>0.83</td>
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</tr>
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<td>$B_s$</td>
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<td>0.76</td>
<td>1.7</td>
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<tr>
<td>$C_s$</td>
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<td>0.011</td>
<td>0.22</td>
<td>36.4</td>
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<td></td>
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</tr>
<tr>
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<td>0.035</td>
<td>0.51</td>
<td>3.6</td>
<td>30/75.5</td>
<td>-45/107.5</td>
<td>-04/89 960</td>
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<td>4.9</td>
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<td>$E_n$</td>
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<td>0.021</td>
<td>0.50</td>
<td>10.0</td>
<td>30/82</td>
<td>45/113</td>
<td>-03/95 1080</td>
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<tr>
<td>$E_s$</td>
<td>6054.6</td>
<td>0.045</td>
<td>0.76</td>
<td>2.2</td>
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<tr>
<td>$F_n$</td>
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<td>0.037</td>
<td>0.52</td>
<td>3.2</td>
<td>30/90</td>
<td>-45/122</td>
<td>-06/105 1000</td>
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<td>30/106</td>
<td>-45/137.5</td>
<td>-09/120 675</td>
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<td>-09/126 780</td>
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<td>0.84</td>
<td>1.0</td>
<td>30/119</td>
<td>-45/151</td>
<td>-07/134 520</td>
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<tr>
<td>$I_s$</td>
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<td>0.042</td>
<td>0.78</td>
<td>2.5</td>
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</tr>
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<td>$J_n$</td>
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<td>0.016</td>
<td>0.62</td>
<td>17.2</td>
<td>30/123</td>
<td>-45/157</td>
<td>-06/138 1320</td>
</tr>
<tr>
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<td>0.26</td>
<td>36.4</td>
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<tr>
<td>$K_n$</td>
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<td>0.86</td>
<td>1.8</td>
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<tr>
<td>$K_s$</td>
<td>6053.7</td>
<td>0.041</td>
<td>0.64</td>
<td>2.6</td>
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</table>

* Heights ($h_0$) and widths in kilometers; $\Delta = \text{observed slope, } h/\sqrt{X}$, in eqn. (3), $r = \text{correlation coefficient between } h \text{ and } \sqrt{X}$, $\nu = \text{half-spreading rate in cm yr}^{-1}$, and end and center points of profiles are in degrees latitude/longitude. "n" and "s" subscripts designate north and south profile segments. $\nu$ is calculated as discussed in the text assuming a mantle temperature of 1500°C.
different technique (assessment of averaged profiles) for a portion of Western Aphrodite (Ovda Regio) by Sotin et al., (1989), who determined a value of $A$ of 0.091 and an estimate of the inferred half-spreading rates for the plateau portions of Western Aphrodite Terra of about $0.5 \pm 0.15$ cm/yr. The use of a longer baseline for the lowland slopes and the use of single altimetric profiles in our study, instead of averaged altimetric data as used in Sotin et al. (1989), account for differences in the determined slope of the lowlands and corresponding differences in estimated spreading rates. Additional variations in fitted curves and the determined spreading rate of the highlands may be attributable to tectonic and volcanic altimetric variations on the highland surface, the influence of these variations on the determined location of the break between the highland and lowland portions of the altimetry, and the use of averaged altimetry data as opposed to single altimetric profiles. The perceived flatness of the lowlands beyond about 1600 km in Sotin et al. (1989) results from the fact that they truncated the analysis of altimetry at a distance of 2000 km instead of 4000 km as done in this study. A broad altimetric high occurring symmetrically at a distance of about 2500 km from the symmetry axes in this domain imposes a positive slope to the approximate last few hundred kilometers of their profiles; at distances greater than about 3000 km the surface slope is similar to that in the inner 1000 to 2000 km, or on the order of 0.030 km/(km)$^{0.5}$ and the result is an accordingly steeper inferred slope in profiles analyzed out to 4000 km.

As with the bathymetry of the South Atlantic in Fig. 11A, significant differences in absolute altitude of opposing flanks occurs in many profiles. The origin of such differences on Earth are unknown, but could reflect variations from place to place in the values for $(T_m - T_i)$, $k$, and $a$ (inside the brackets of eqn. 1) due to fundamental inhomogeneities in either the process of lithospheric creation, variations in underlying mantle physical properties, shallow convection, or simply because of changes in plate kinematics (Hayes, 1988). However, the characteristic small range in values of $k$ and $a$ limits the magnitude of altimetric variations that may be attributed to local differences in these quantities. Other possible origins of regional scale altimetric asymmetry include regional variations in shallow mantle temperature and bilateral asymmetry of the crustal thickness (Sotin et al., 1989) about a spreading axis.

5. The relationship between CSDs, bilateral symmetry, regional topography, and map patterns

An interconnected system of spreading and related tectonic elements is predicted to have consistent relationships between topography and tectonic features. The interpretation of CSDs as analogs to oceanic fracture zones and the interpretation of the symmetric shape of the parallel altimetric profiles as evolving TBL topography can be further tested at regional scales by assessing the presence of these integrated relationships. If CSDs are analogs to terrestrial fracture zones, then the observed stair-step offset of ridge crest axes at CSDs (Fig. 1) predicts: (a) topographic stepdowns across transform faults/fracture zones where different ages of lithosphere are juxtaposed, (b) the direction of stepdown (down toward older crust and lithosphere), and (c) the amount of stepdown (related to the amount of lateral offset of the ridge crest along the transform, and spreading rates on either side of the transform). In this section we examine the predictions and test for such relationships. Although typical fracture zones are relatively narrow features on Earth which would not be readily visible at Pioneer-Venus resolution if present on Venus, the altimetric change represented by such topographic stepdowns across fracture zones affects large areas and should be visible at the available resolution (Arvidson and Davies, 1981). In the following section we show that (a) regional topographic stepdowns are observed along the projections of CSDs into the surrounding lowlands, and (b) that the sense of stepdown is generally consistent with the sense of offset of ridge crest segments.

A topographic stepdown occurs across fracture zones because of the difference in age (the amplitude of thermal subsidence) of the two adjacent segments of the seafloor. TBL theory can be used to predict the magnitude of the topographic step
that will occur if the offset of the ridge crest is known. For similar spreading rates and other physical properties on either side of the topographic step the difference in altitude, \( S \), as seen in a direction parallel to and at a distance \( (x) \) from the ridge crest is given by:

\[
S = \pm \left[ h_{(x2)} - \Delta_2 (x_2)^{0.5} \right] - \left[ h_{(x1)} - \Delta_1 (x_1)^{0.5} \right]
\]

(3)

where \( x_1 \) is the distance of the observer from the local ridge crest and \( x_2 \) is the distance of the point immediately across the fracture zone from its corresponding ridge crest of origin; \( h_{(x0)} \) is included in as much as variations in elevation may occur due to variations in crustal thickness, and \( \Delta \) is defined for each domain on the basis of both potential variations in this slope in the presence of large-scale mantle differences, as well as on the basis of the apparent variations in slope throughout Western Aphrodite Terra. The sign of eqn. (3) depends on the sense of offset; the step is down (negative) if the sense of offset is right-lateral as defined with the ridge crest on the right. In map view (Fig. 1), regional downsteps to the east are noted along the northern projection of CSDs 4, 5, 6, and 8. Using the relations above we can test whether the magnitudes of the observed stepdowns are consistent with the ridge crest offsets observed and with the predicted shape of the TBL-like behavior of topography. The value of the surface altitude change, \( S \), was calculated for the line along \( X-X' \) in Fig. 12 using the observed local distance \( (x) \) of line \( X-X' \) from the ridge symmetry axis and using an average of the observed altimetry in each domain listed in Table 2. The observed altimetry (Fig. 12A and B) can be compared with the predicted altimetry stepdown (Fig. 12C) that would occur if the topography originated from simple spreading center offset of the observed magnitude along CSDs. The largest steps are predicted to occur northward of the projected location of the CSDs marking the largest horizontal offsets of the axis of Aphrodite (CSD 5–17). The results also predict that the altitude of the surface for the domains between CSDs 3–7 should lie near the mean planetary radius, and that along the line from \( X \) to \( X' \) the observed elevation should decrease by approximately one kilometer.

The observed domain-averaged topography falls several hundred meters per step between CSDs 11, 4, and 12, and further eastward as predicted from eqn. (3). The predicted altimetric profile and the observed altimetry along the line \( X-X' \) have the following similarities: (1) both the observed and the predicted profiles lie within 1 km of the mean planetary radius, (2) the western half of both the observed and the predicted profiles lie above the mean planetary radius and the eastern half lie near the mean planetary radius, (3) the largest topographic step occurs at CSD 5 and 12, and (4) topographic steps occur at CSDs 11, 3, 4, 12, and 6. These characteristics show that CSDs, which are observed mainly as features in the central plateaus, exert an influence on the regional altimetry at up to four thousand kilometers from the highland. On the basis of these comparisons, we conclude that significant changes in the regional altitude of the surface (topographic stepdowns) occur over short distances across the CSDs, and that as the distance from the highland increases, the altitude of the surface along the profile \( X-X' \) decreases at a non-linear rate, and in a manner and direction generally consistent with that predicted from the sense of ridge crest offsets.

In the western half of the profile, local topographic elements (a linear ridge located primarily between CSDs 2–3; see arrows in Fig. 12) superimposed on the broad regional altimetric profiles may be responsible for the differences between the predicted and observed profiles. As discussed later, many of these altimetric “residuals” (topography in excess of that predicted from TBL) are symmetrically distributed about the ridge axis (see also Fig. 11). If the more distinctive residuals are subtracted from profile \( X-X' \), the resulting profile descends more uniformly from west to east. Other variations that can produce differences in detail between predicted and observed profiles include potential differences in the fundamental nature, rates, and thicknesses of crustal production from that based on simple evolving thermal boundary layers at similar rates.

In summary, tests were made for the presence of the consistent relationships predicted by the
Fig. 12. (A) Observed altimetry across the north flank of Aphrodite Terra and at right angles to the linear projection of several CSDs into the lowland slopes. (B) Same as (A) but with the altimetric data in domains between two CSDs shown as an average altitude in which dashed lines are standard deviation on the average. Dotted line is the average domain altitude that results if the topography corresponding to approximately 0.5 km high dorsa (arrows here and arrows A in Fig. 1) are subtracted from the observed profile (between CSDs I and 2, 2 and II, and II and 3) before calculating the average domain altitude. (C) Predicted altitude of the surface along the profile X--X’ for offset of thermal boundary layer topography by amounts equal to the offset of symmetry axes in Western Aphrodite Terra. MPR = mean planetary radius.
interpretation that bilateral symmetry is analogous to divergent ridge crest symmetry and that the stair-step offset of ridge crest axes and altimetry at CSDs is analogous to fracture zones and transform faults. Consistent relationships observed include (a) topographic stepdowns across CSDs where predicted different ages of lithosphere are juxtaposed, (b) the correct direction of stepdown (downward toward older crust and lithosphere) relative to that predicted from ridge crest offsets, and (c) similarities in the amount of predicted stepdown relative to the distance from the ridge crest. On the basis of these tests, we conclude that these observations support the hypothesis of a consistent regional system of spreading in Western Aphrodite Terra.

6. Presence and interpretation of short wavelength bilateral symmetry elements

The symmetry characteristics of Aphrodite Terra occur at two prominent scales. One scale of symmetry, the broad ridge-like form of the highlands (both the plateau and the flanks) has been shown to behave in accordance with the combined influence of TBL and crustal thickness variations. A second scale of symmetry is proposed in the arrangement of shorter wavelength features in the lowlands on either side of the highlands. In order to detect the presence of these shorter wavelength features and to test for the degree of symmetry, the altimetric $\sqrt{X}$-relation determined from the lowland slopes for two profiles in Western Aphrodite (Fig. 11C) is subtracted from each profile in order to assess the shorter wavelength topography superposed on the much broader TBL topography. The “residual” topography obtained in this way for profiles across Aphrodite Terra (Fig. 13) reveals that there are detailed individual features in the surface altimetry that are superimposed on a broader symmetric form characteristic of the equatorial altimetry. In order to test systematically for symmetry of the observed residuals, the northern and southern halves of the residuals for each of these two example profiles have been plotted along the same axis in order to facilitate qualitative comparisons. By plotting the residuals from the south flanks upside-down beneath the residuals from the north flank, the presence of corresponding altimetric residuals of similar absolute relief on opposite flanks can be easily detected where present. Several positive and negative symmetrically disposed residual topographic elements with differential amplitudes of 500 m to over 2 km are observed separated by distances of up to 6000 km. This simple correlation of residual topography implies that the small altimetric features in the lowlands as well as the highlands are bilaterally symmetric about the same axis, as is the broadly bilateral more regional shape of the profiles. In addition, similar phenomena occur in different domains, but the amplitudes and spacings of the symmetrically disposed residual elements in each domain often differ (compare Fig. 13, profile $E$ and profile $H$) suggesting that whatever the process of formation, the control on symmetry is limited to relatively narrow ribbon-like strips within domains between adjacent CSDs.

Broad symmetry is predicted from the bilateral
form of the thermal boundary layers associated with two diverging plates, but the smaller scale symmetry is not accounted for under general divergent plate boundary theory. A similar analysis of seafloor symmetry on Earth (Vogt, 1979) reveals apparent relatively short wavelength topographic variations symmetrically arranged with respect to the Mid-Atlantic Ridge. Two small symmetrically disposed topographic features can form in a spreading environment if a topographic, geochemical, or magmatic anomaly, such as Iceland or some similar zone of thickened crust at a ridge crest is split apart and spreads away from both flanks of the ridge (Vogt, 1972; Hey, 1979; Lewis, 1979). The two symmetric halves then are a record of a short-lived temporal variation in the crustal production at ridge crests, as well as changes in spreading direction and magnitude. Many of these features originate from along-axis temporal variations in bathymetry, are recognized as important records of variations in plate motions, and have been cited as evidence for the existence of hot spot motions on, near, or relative to ridge crests on Earth (Vogt, 1972; Vink, 1984). The origin of variable crustal productivity of a spreading center may be attributed to variations in mantle temperature (Reid and Jackson, 1981; Sotin et al., 1989). The record of crustal variations that they leave are analogous to symmetric distribution of magnetic anomaly lineations although their occurrence in a variety of orientations, including broad “V”-shaped patterns on the seafloor, may indicate along-axis propagation as well as global variability in magma production and crustal accumulation (Vogt, 1972; Hey, 1979; Lewis, 1979).

Although this and other characteristics of the seafloor have been described as symmetric, quantitative techniques applied to the analysis of topographic profiles imply that there is a relatively modest correlation of these residuals in only a few profiles (Grimm and Solomon, 1989), and that bilateral symmetry at short wavelengths is not expressed, if present, across either the Mid-Atlantic Ridge on Earth or Aphrodite Terra on Venus. Possibly for similar reasons quantitative identification and correlation of patterns of magnetic symmetry in studies of the seafloor on Earth has not been successful. One reason that such an analysis is not generally successful is because it requires near-perfect symmetry (no asymmetrical spreading) and/or that the history of the spreading process leading to phase differences in the symmetry production (e.g., ridge jumps) be taken into account. Such detailed information is available for only a few ridges. However, the presence of a qualitative symmetry of features which are geologically correlated, such as magnetic, chronologic, topographic, and geologic elements, is an important basis for the interpretation of divergence and large-scale horizontal separation at ridge crests on Earth.

Another possible explanation of the smaller-scale symmetry elements is that it represents deformation caused by an axi-symmetric mantle plume, or an elongate bilaterally symmetrical linear zone of upwelling, weakly interacting and deforming the overlying lithosphere (e.g., Phillips, 1986). Ordered convective rolls within narrow ribbon-like domains or spreading corridors oriented at right angles to the ridge crest (Buck and Parmentier, 1986) may be proposed to account for domain to domain variations in the surface altimetry, but detailed small scale symmetry features are not a general result of these models. These ideas may be tested with high-resolution gravity data on the basis of the differences in predicted depths of compensation for convective versus crustal processes.

7. Conclusions

(1) The nature of cross-strike discontinuities (CSDs)

Long, narrow, linear features, described and mapped as “cross-strike discontinuities” or CSDs, have been shown previously to be present and to influence the larger-scale morphology and structure of the equatorial highlands of Western Aphrodite Terra (Crumpler et al., 1987). Additional detailed analyses of the CSDs document their characteristics and permit us to assess further the hypothesis that they represent analogs to fracture zones associated with spreading centers (Head and Crumpler, 1987).

(a) Regional linear trends: Detailed lineament analysis of regional linear trends and surface
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structural fabrics using topographic maps and Pioneer-Venus image data shows that CSDs represent the most prominent regional structural trend both in Western Aphrodite and in its flanking lowland slopes to the north and south. CSDs are readily distinguished and differ both in orientation and in character from linear patterns caused by ground tracks in the Pioneer-Venus orbiter data.

(b) Regional structural fabric: Detailed lineament analysis also reveals the presence of a distinctive structural trend orthogonal to the strike of the CSDs, and different from the Pioneer-Venus groundtrack orientations. This orthogonal fabric is pervasive throughout the region and is seen in both the topography and the image data. It may be related to the orthogonal fabric of abyssal hills and fracture zones seen in terrestrial seafloor, and to the fabric of some types of tessera terrain observed in the Venera 15/16 data (Head, 1990).

(c) Precision of CSD locations: Resolution of the PV data in the low latitudes of the equatorial highlands and the altimetric data density are shown to be sufficient to enable precise CSD locations within less than a few degrees of longitude, particularly where they cross the highlands.

(d) Nature of individual CSDs: High resolution Arecibo altimetric profiles across most of the longitudinal length of Western Aphrodite show that individual CSDs are either deep troughs or regional scarps and steps. Arecibo profiles show that one prominent CSD is a linear 1 km deep trough that extends for more than 1000 km. Slopes associated with these features are typical of major tectonic boundaries on Earth.

(e) Evidence for additional CSDs: Further analysis shows the presence of two additional CSDs with a dominant orientation similar to those previously identified (N20° W).

(f) CSD spacing: The spacing between CSDs mapped in the PV data ranges from about 500 to 1500 km, and the average spacing is 850 km. Additional smaller scarps and slopes with characteristics of known CSDs are seen in the Arecibo profiles and occur at spacings of as little as 50 km, suggesting that other smaller CSDs with less offset may occur in domains between the more prominent ones previously mapped. This observation accords with a similar suggestion by Sotin et al. (1989) based on an analysis of gravity data.

(g) Regional trends and relation to regional slopes: The general trend of CSDs and the linear fabric orthogonal to them is similar to the orientation of the regional and global slopes identified by Sharpton and Head (1986). CSDs in conjunction with their associated orthogonal slopes may therefore exert considerable control on the shape and structure of Aphrodite Terra and the regional altimetry in other parts of the equatorial highlands.

(h) CSDs as analogs to fracture zones: The detailed altimetric trough and regionally steep slopes, association with ridge offsets, linear terminations, linear slope traces, the parallelism, great length, and other detailed features are all similar to the characteristics of transform faults and fracture zones on Earth's seafloor. This more detailed analysis supports the initial interpretation (Head and Crumpler, 1987) that CSDs represent analogs to terrestrial oceanic fracture zones.

(2) Bilateral symmetry of topography and other elements across Western Aphrodite Terra and the nature of domains

Pioneer-Venus altimetric profiles were constructed across Aphrodite Terra parallel to the CSDs, and were shown previously by Crumpler and Head (1988) to have a high degree of symmetry. Multiple profiles parallel to the CSDs show that the center of this symmetry lies along linear trends which are oriented at right angles to, are terminated against, and are offset at, CSDs. Two adjacent CSDs therefore define a "domain" in which the symmetry is internally consistent, but adjacent domains may have different symmetries and surface characteristics, particularly in the details of symmetrical short wavelength topographic and radar image elements.

(a) Mirror image symmetry of domains: Symmetrical elements occur in such detail that a prediction of both large and small scale altimetry within each domain on one flank of the highlands may be made by substitution of a mirror reflection of the opposite flank (Crumpler and Head, 1988). A similar mirror-type symmetry prediction was
performed with the higher-resolution Pioneer-Venus radar images of the highlands and shows that symmetry axes similar to those determined from altimetric profiles apply to SAR data within 1000 km of the symmetry axes as well.

(b) Short wavelength bilateral symmetry elements: Symmetry occurring at smaller wavelengths in the altimetry can be demonstrated by subtracting a TBL curve from the altimetric profiles and examining the residuals. The resulting residual topography shows that individual altimetry features several hundred km wide and several hundred meters high are frequently located at the same distance from the axis of regional symmetry on the north and the south flank of the highlands.

(c) Interpretation of symmetry elements—summary: Symmetry at a large scale and over a great horizontal distance can occur in at least two independent ways: (i) thermal uplift of a broad symmetrical ridge-like ridge associated with a "hot spot" or symmetrical underlying mantle convection, or (ii) from crustal spreading and the symmetrical growth and evolution of new lithosphere by divergent movement of lithosphere at a plate boundary over great distances. The shorter wavelength-type symmetry (the existence of individual symmetrical features) is strong geological evidence for twinning of topographic features as a result of the spreading process. A TBL which thickens and decreases in surface elevation with distance from the center may be associated with either of these processes. The former process may occur in the absence of significant horizontal motion of the surface, and in the latter process large-scale horizontal motion of the surface takes place. Altimetric profiles across Western Aphrodite are symmetrical and decay from the ridge crest as the square root of distance in accordance with that predicted from TBL theory. The slope of the observed thermal boundary-layer-like component of the regional symmetry is in accord with that predicted for the general form of a TBL evolving under the surface conditions of Venus. The detailed level of short wavelength symmetry in addition to the regional symmetry, and the fracture-zone-like characteristics of the CSDs are evidence that the Western Aphrodite equatorial highlands represent TBL topography of the type associated with crustal spreading and large horizontal motions of the surface.

(3) Regional relationships and map patterns

Tests were made for the presence of predicted consistent topographic and map relationships implied by the interpretation of CSDs and bilateral symmetry, and the stair-step offset of ridge crest axes at CSDs, as indicating an integrated system of spreading. Consistent relationships were found as follows: (a) topographic stepdowns across CSDs where predicted different ages of lithosphere are juxtaposed, (b) the correct direction of stepdown (down toward older crust and lithosphere) relative to that predicted from ridge crest offsets, and (c) similarities in the amount of predicted stepdown predicted from the relative offset of the ridge crest.

(4) Crustal spreading and divergent plate boundary characteristics in Western Aphrodite Terra

Zones of crustal spreading and divergent plate boundary characteristics display organized relationships, many of which may be predicted on the basis of the existence of ridge crest offsets at transform faults and fracture zones, in the presence of horizontal divergent motions of a TBL. If Western Aphrodite Terra represented processes similar to a spreading center and divergent plate boundary, we would expect to see (i) a broad symmetric altimetry associated with a TBL, (ii) offset of this symmetry at nearly right angles along linear fracture zones, (iii) regional step up or down in altimetry of the surface across the CSDs depending on the sense of the ridge crest offset, and (iv) differences between the detailed features of the surfaces in adjacent ridge crest segments which are individually symmetric about the ridge crest and result from splitting and drifting apart of topography associated with anomalous crustal production.

These predicted characteristics of the organized relationship between divergent plate boundaries processes may be compared with observed altimetric characteristics in Western Aphrodite Terra which include a broad symmetry which is quanti-
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This tendency to that predicted for TBL topography diverging at rates of a few centimeters per year. This symmetry is frequently offset at right angles to the symmetry along through-going and nearly linear discontinuities (CSDs) which can be traced for several thousand kilometers across the highlands and into the surrounding lowlands much like fracture zones extending on either side of a ridge crest along the trace of a transform fault. Altimetric profiles in the lowlands across the CSDs show that there is frequently a regional altimetric step up or down across the CSDs depending on whether the horizontal sense of offset across the CSD moves the ridge crest closer or farther away respectively. Removal of the broad symmetry of a TBL from the altimetric profiles across Aphrodite Terra results in a residual short-wavelength topography which is shown to be symmetric about the same symmetry axis, and which differs in character from one domain to the next.

This range of characteristics, their detailed relationships, and their predictable behavior throughout Western Aphrodite Terra are similar to those features known to occur in association with the terrestrial seafloor and at spreading centers and divergent plate boundaries. We conclude that the detailed analyses outlined in this paper support the earlier interpretation that Western Aphrodite Terra represents the site of crustal spreading and displays many of the characteristics of divergent plate boundaries (Head and Crumpler, 1987). The extent of similar characteristics and processes elsewhere on Venus outside of the 7500 km long Western Aphrodite Terra ridge is unknown at the present, but recent analyses suggest that Eastern Aphrodite Terra, extending some 5500 km to the east, displays similar characteristics.

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