

Evidence for Divergent Plate-Boundary Characteristics and Crustal Spreading on Venus

JAMES W. HEAD, III, AND L. S. CRUMPLER

Detailed examination of the topography and morphology of western Aphrodite Terra reveals numerous features that are similar to terrestrial divergent plate-boundary characteristics. Individual domains between fracture-zone-like discontinuities contain a variety of bilaterally symmetrical topographic elements that suggest that topographic features have been created at rise crests, rifted and separated, and moved laterally to their present symmetrical positions. The topographic and morphologic similarities, together with strikingly similar mirror-image map patterns on both sides of the rise axis, suggest that western Aphrodite Terra shares the characteristics of oceanic divergent plate boundaries, and is the site of crustal spreading on Venus. Topographic profiles are consistent with spreading rates of the order of several centimeters per year.

PLANETARY EXPLORATION DURING THE LAST 25 YEARS HAS revealed a variety of tectonic styles on the planets and satellites. The smaller terrestrial planetary bodies (Moon, Mercury, and Mars) are characterized by a single, global unsegmented lithospheric plate that stabilized very early in solar system history. In contrast, segmented, laterally mobile, and continuously recycling lithospheric plates characterize plate tectonics on Earth. Planetary heat loss on the small one-plate planets is dominated by conduction, whereas most of the heat loss from Earth's interior is associated with plate recycling processes (1). Venus is similar to Earth in size, density, and position in the solar system, but differs in atmospheric density and composition, surface temperature, lack of oceans, unimodal frequency distribution of topography, and the positive correlation of topography and gravity at long wavelengths. A fundamental question in planetary tectonics for the last decade has been the nature of tectonics on Venus, and the implications for mechanisms of lithospheric heat transfer (2). Is Venus, because of its similarities to Earth in major bulk properties, also similar to the present-day Earth in terms of mechanisms of lithospheric heat transfer and the presence of plate recycling? If not, what are the mechanisms, and what are the factors that cause similar planets to have different mechanisms of heat transfer?

Answers to these questions have not been forthcoming because of the difficulty in penetrating through the opaque Venus atmosphere to obtain global high-resolution images that would show the surface and the nature and distribution of tectonic features. The available data include global low-resolution topography and surface property

information (3, 4), gravity and low-resolution images at low latitudes (5, 6), local and regional high-resolution images from Earth-based radar telescopes (7, 8) and orbiting spacecraft (9), equatorial Earth-based high-resolution altimetry (10), and surface observations and measurements from landers (11). On the basis of these data, proposals have been made that Earth-like crustal spreading and plate recycling do not occur, or are not significant on Venus (12–14), that hot spots are the primary mechanism of heat loss (15), and, alternatively, that the primary mechanism has not yet been resolved (2).

There is general agreement that one of the most distinctive low-resolution signatures of crustal spreading and plate recycling on Earth is the presence of the global network of oceanic rises and their thermal boundary-layer topographic character and symmetry. Several previous workers examined global Venus topography to search for such rises and concluded that a global network like that on Earth did not exist and that although some areas met several of the criteria for divergent plate boundaries, plate recycling was not a globally significant process (13), if it existed at all. Building on these initial studies, and focusing on those areas where broad topographic symmetry of segments of the equatorial highlands have been documented (6, 13, 16), we have been impressed with the great linear extent of these highlands, and the global patterns of topography and slope related to the equatorial highlands (6, 17). We have explored the nature of the topography and geologic structure of the extensive linear highland regions on Venus (exemplified by Aphrodite Terra) using a variety of data sets (18–23), and we have found evidence for linear discontinuities very similar to terrestrial oceanic fracture zones and associated broadly bilaterally symmetrical topography and topographic elements (18–21, 23). Many previous studies have emphasized broad geophysical considerations in discussing

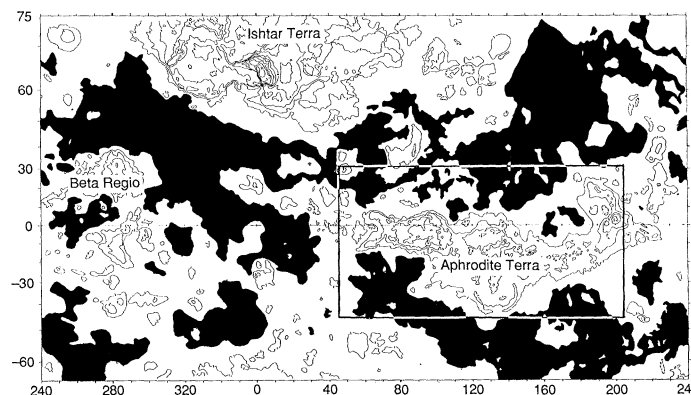


Fig. 1. Global map of Venus, which shows the equatorial highlands, the location of Aphrodite Terra, and the area of more detailed study shown in Figure 3A (3, 6). Areas indicated in black lie below the 0-km datum. Contour interval is 1 kilometer.

J. W. Head is a professor, and L. S. Crumpler is a research associate in the Department of Geological Sciences, Brown University, Providence, RI 02912.

tectonic style on Venus (12–15, 24–26). In this article we adopt a complementary approach and focus on several specific morphological and geological tests for the presence of segmented lithospheric plates and lateral crustal spreading in this area on Venus.

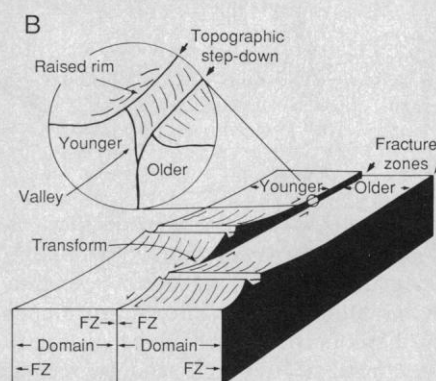
Evidence for the presence of lithospheric plates and crustal spreading at divergent plate boundaries on Earth includes: (i) linear oceanic rises, (ii) the broad bilateral symmetry of topography associated with these rises, (iii) the link of this topography to the evolution of the thermal boundary layer as it moves away from the plate boundary, (iv) median valleys along the crests of many rises, (v) fracture zones that are generally orthogonal to the rises, (vi) lateral offsets of the oceanic rise or ridge at fracture zones, (vii) transform faults located along fracture zones between ridge offsets, (viii) seismic activity localized along transforms, (ix) symmetric magnetic stripes parallel to the rise and their increasing age with distance from the rise crest, (x) volcanism (intrusion and extrusion) concentrated at ridge crests as new crust and lithosphere are created, (xi) localized anomalies in the topography of rises (plateaus) linked to enhanced volcanic activity (for example, Iceland), and (xii) the eventual splitting and separation of such plateaus (27) to produce mirror-image topographic highs away from the ridge crest. Lack of seismic and magnetic data for Venus preclude testing for the presence or absence of localized earthquakes (item viii) or magnetic anomalies (item ix), two very significant indicators of divergent plate boundaries cited above have topographic or morphologic manifestations. Our purpose in this article is to test for the possible presence of such features on Venus. In doing so, we recognize that owing to the distinctive environmental conditions on Venus an exact one-to-one similarity of details of topography may not be expected.

Linear topographic rises. One of the most distinctive characteristics of the topography of Venus is Aphrodite Terra, a broad, linear highland region that stretches for 21,000 km (28) along the equatorial region (Fig. 1). Indeed, the linear topographic belt extends well beyond Aphrodite and it has been named the “equatorial highlands” (14). Aphrodite is characterized over much of its extent by linear troughs along the same trend, which are interpreted to be rifts (28), and by a broad topographic symmetry. In assessing whether linear highland topographic features on Venus could be spreading centers, Kaula and Phillips (13) found that they satisfied two of their proposed tests for seafloor-like spreading: (i) linear highlands are elevated with respect to a broad reference plain that could act as the boundary layer of a mature “ocean” basin, and (ii) the ridge shapes are predominantly concave. Kaula and Phillips further noted, however, that these topographic features failed two other important tests, being unlike the terrestrial ridge system in that the ridge heights do not have a narrow distribution about a mode and that they do not form a global interconnected system. Kaula and Phillips (13) and Phillips and Malin (14) concluded that if plate creation occurs on Venus, only a small amount of heat is transferred to the surface by this process. Thus, on the basis of low-resolution topography and criteria related to the nature of present-day terrestrial divergent plate-boundary topography and map patterns, these prior analyses concluded that there are extensive areas on Venus characterized by a broad, generally symmetrical topographic rise, but that these areas differ from terrestrial oceanic rises in two important ways: rise heights are variable, and there does not appear to be a mosaic of interconnected rises.

We begin with the assumption that broad linear topographic rises are of fundamental significance in understanding the tectonics and heat transfer mechanisms on Venus, and that they are the best candidates for possible divergent plate boundaries, as indicated in previous studies (13, 14). We focus on the nature of the western part of Aphrodite Terra (Ovda and Thetis Regio, Fig. 1) in this context,



Fig. 2. Earth oceanic fracture zones. (A) Map view of the North Atlantic showing offset of rise crests along fracture zones and the differing characteristics of linear rise crests (trough to the south, Icelandic plateau to the north, and the Reykjanes Ridge in between). [Reprinted with permission of the National Geographic Society, copyright 1968]. (B) Generalized block diagram showing topographic and morphologic characteristics of oceanic fracture zones.



using moderate-resolution imaging (6) and high-resolution altimetry data (7), in addition to the low-resolution topographic data discussed above. In particular, we concentrate on the identification of additional geological (topographic and morphologic) features that might reveal the nature of these topographic rises and further test the idea that they might represent lithospheric plate boundaries.

Fracture zones. On Earth, fracture zones are long, narrow linear regions up to about 60 km wide, which consist of irregular ridges and valleys aligned with the overall fracture zone trend, and which cut across both rises and the surrounding abyssal plains for distances up to several thousand kilometers (29). Fracture zones are commonly parallel to each other, ocean floor depth commonly changes across a fracture zone in a step-down fashion, and the crests of oceanic rises are often offset by many hundreds of kilometers at fracture zones (Fig. 2). Fracture zones represent the propagation of an initial stair-step-like boundary between newly formed lithospheric plates along ridges and transform faults. Active horizontal (strike-slip) shearing and deformation is limited to the zone between the two ridge crests (the transform fault) and the fracture zone extending away from each ridge crest in the opposite direction is the scar remaining from the intense shearing activity that takes place between ridge crests.

Crumpler *et al.* (18–20, 23) have recently identified a series of linear discontinuities cutting across the strike of western Aphrodite Terra (Fig. 3A). Using topographic data and images, they documented the presence of numerous parallel linear features defined by linear highland topographic segments, aligned individual topographic features, regional changes in topography in the lowlands, steep gradients in radar backscatter values in images, and linear boundaries in the radar properties of surface materials. Individual

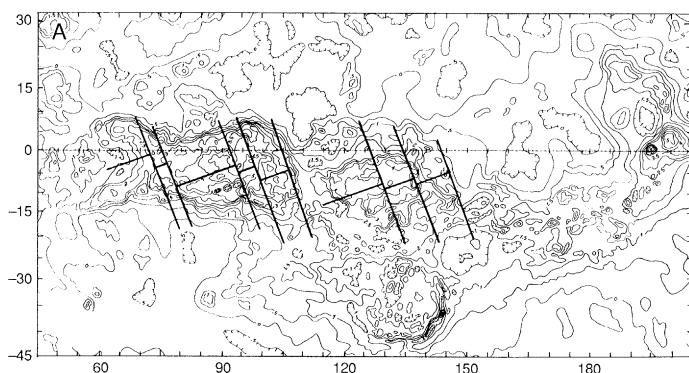
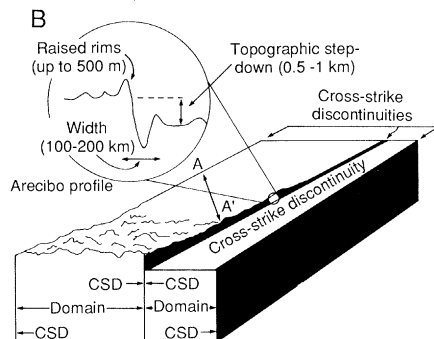


Fig. 3. Cross-strike discontinuities in Aphrodite. (A) Map view (21, 31). Cross-strike discontinuities strike in a north-northwest direction. Lines normal to the cross-strike discontinuities represent the centers of symmetry of topographic profiles shown in Fig. 4. (B) Generalized block diagram showing topographic and morphologic characteristics of cross-strike discontinuities [high-resolution data from (23)].



linear discontinuities extend for several thousand kilometers across Aphrodite Terra and into the surrounding lowlands, trend in a N20°W direction nearly perpendicular to the approximately east-west trend of Aphrodite, and are separated by distances of many hundreds of kilometers (Fig. 3A). Examination of these linear topographic features where they cross near-equatorial high-resolution altimetry tracks (20, 21) reveals that they are characterized by abrupt topographic changes from one side to the other, steep slopes within the zone, and associated central troughs and lateral peaks, all occurring over a distance of 100 to 200 km (Fig. 3B). These linear discontinuities are topographically most distinctive in and at the edge of the central Aphrodite Terra area and become less pronounced as they trend into the surrounding lowlands. The linear discontinuities thus subdivide western Aphrodite into a series of rectangular segments or domains 400 to 500 km wide and several thousand kilometers long, each parallel and striking in a northwest-southeast direction (Fig. 3A). These cross-strike discontinuities clearly share many of the topographic, morphologic, and scale characteristics of fracture zones on Earth (compare Figs. 2B and 3B).

Bilateral topographic symmetry. One fundamental characteristic of topographic rises on Earth is that topography is bilaterally symmetrical across rises in a direction broadly parallel to fracture zones (Fig. 2A) (30), and is less symmetrical in directions more parallel to the general, more sinuous, topographic trend of the rises. Thus, additional tests for the presence of divergent plate characteristics on Venus would be to examine the degree of symmetry of topography across Aphrodite in directions broadly parallel to the fracture zone-like linear cross-strike discontinuities, and to test for potentially rifted and separated topographic elements analogous to oceanic plateaus symmetrically distributed across the rise.

Topographic profiles across Aphrodite Terra that are oriented parallel to the cross-strike discontinuities show bilateral symmetry (21, 31) (Fig. 4B) and are characterized by several components: a broad sweeping bilaterally symmetrical shape extending laterally for several thousand kilometers, a central bilaterally symmetrical steep-

sided plateau approximately 2000 km in width with flanking lows, and individual features 100 to 500 km in width that appear in the same position on both sides of the broadly symmetrical profile. The bilateral nature of the symmetry is illustrated by reversing profiles and then comparing them by centering them on their axis of symmetry (Fig. 4B) and by other quantitative tests (31). Additional characteristics of these profiles are the patterns in which they are arrayed: within a domain between cross-strike discontinuities, parallel profiles are very similar to each other (Fig. 4C), and when topographic profiles are compared between zones, the general bilateral symmetry of each profile is clear, but the details of symmetry differ. When profiles are taken at large angles to the trend of the cross-strike discontinuities, the bilateral symmetry is reduced (31).

Thus, the western Aphrodite region shows bilateral topographic symmetry and symmetry patterns in a manner similar to oceanic rises and divergent plate boundaries on Earth. Examination of the nature of the centers of symmetry of these profiles should provide a further test of the similarity between western Aphrodite and terrestrial divergent plate boundaries.

Nature of axial regions of rises. On Earth, axial regions of rises are highly linear between fracture zones and are offset up to several hundred kilometers at the fracture zone or transform fault (Fig. 2). The detailed structure and morphology of axial regions is linked to spreading rates. On slow spreading ridges such as the mid-Atlantic ridge, the summit is characterized by a median valley or rift a few kilometers wide and several hundred meters deep, extensive intrusions and localized extrusive volcanism, and occasional larger volcanoes on the floor and flanks. On fast-spreading ridges like the East Pacific Rise, there is strong axial symmetry, and local volcanoes, but no median rift valley. In other places (Iceland, for example), greater-than-average rates of volcanic activity independent of spreading rate, perhaps related to hot spots, produce broad plateaus several kilometers higher than typical mid-ocean rises and several hundred kilometers wide, superposed on the divergent boundaries. In general, the average elevation of the rise crest is remarkably uniform throughout the global mid-oceanic rift system on Earth (13). Exceptions include plateau regions such as Iceland; the presence of additional Icelandic-type plateaus on Earth would considerably alter this relationship.

In western Aphrodite Terra, within a domain between cross-strike discontinuities, the centers of symmetry of adjacent topographic profiles define a linear crest of symmetry extending from one cross-strike structure to the next (Fig. 4C) and trending about N70°E. The detailed structure of these linear axial regions is complex and variable. In some zones, the axial region is characterized by a 100- to 300-km wide, 1- to 2-km deep linear trough, with local domical topography on the flanks (Fig. 4B, profiles d and e). On the basis of high-resolution images of central Beta Regio, where the topography is similar, these features are interpreted to be rift zones with associated volcanoes (7). This type of topography is especially well developed in the Dali Chasma area of central Aphrodite (Fig. 4B, profile e). In other zones, the axial region is characterized by a linear topographic crest with no apparent axial trough (Fig. 4B, profile c), and often by a broad plateau (Fig. 4B, profiles b, c, and d). Thus, in terms of their general linearity and range of morphology, the axial ridges in western Aphrodite are comparable to axial regions of divergent plate boundaries on Earth.

Transform faults. On Earth, the region between ridge offsets along the fracture zone is known as a transform fault, and is characterized by ridge crest separation distances of up to 1000 km, intense shear, different age crust on opposite sides of the zone, changes in topography across the zone linked to the difference in ages (young crust is topographically high relative to older crust), and enhanced earthquake activity. Ridge crests can be offset in a left-

or right-lateral sense, but the distribution is not random. One sense or the other usually dominates for about ten ridge segments.

In western Aphrodite, ridge crests representing the center of symmetry of axial regions are offset at cross-strike linear features in a consistent right-lateral sense with offset distances ranging from 200 to 1200 km (Fig. 3A). The age of the crust of Venus is not known in this area and there are no available seismic data, so it is not possible to apply these tests to further the comparison of the intercrest portions of the linear cross-strike structures on Venus and the nature of transform faults on Earth. However, if the ridge crests are the axes of divergent plate boundaries, and the cross-strike structures are fracture zones and transform faults, then the topography on opposite sides of the cross-strike discontinuity should be different. On Earth, this is due to the fact that the topographic changes across transforms are linked to the changing thermal structure of the lithosphere as a function of age (30). Newly formed lithosphere cools and becomes topographically lower as a function of time and distance away from the rise crest. Since rise crests are separated along transform faults and fracture zones, the thermal boundary-layer age relationships predict that if one steps down across a fracture zone, then one should observe offset at the rise crest away

from the observer (Fig. 2B). These step-down relationships are observed in western Aphrodite (Fig. 3, A and B). For example, if cross-strike discontinuities 4 and 5 (Fig. 4A) are projected along their strike into the lowlands they show distinctive topographic step-downs at about 10° to 15° north latitude. Significant right-lateral offset of the ridge crests is observed where these same linear discontinuities cross the highlands.

Discussion of evidence for divergence and crustal spreading.

On the basis of our analysis of the topographic and morphologic data for the western Aphrodite region, and our tests for the presence of analogs to terrestrial divergent plate boundaries and associated features, we conclude that there is abundant evidence for a wide range of features in Aphrodite comparable to those found at terrestrial divergent plate-boundary regions. Specifically, we find evidence in western Aphrodite Terra for (i) the presence of linear topographic rises (Fig. 1), (ii) bilateral symmetry of topography normal to these rises, including small-scale features (Fig. 4), (iii) broad sloping topography suggesting relations like that resulting from a laterally moving and cooling thermal boundary layer (Fig. 5), (iv) the location of median valleys and other analogous features along the crest of rises, (v) the presence of fracture-zone-like

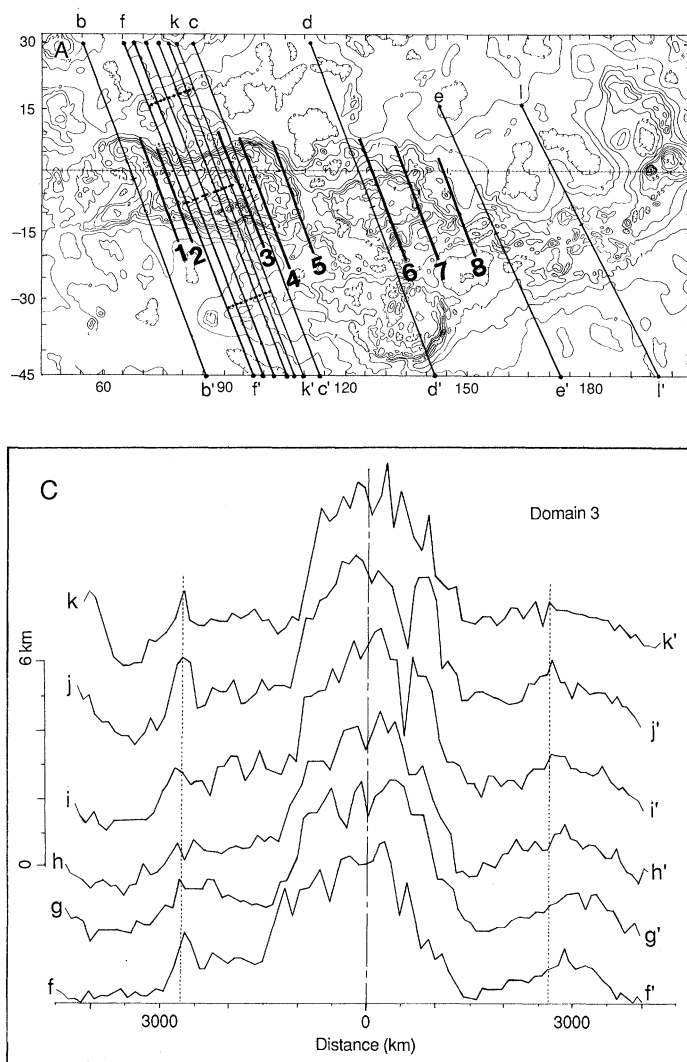
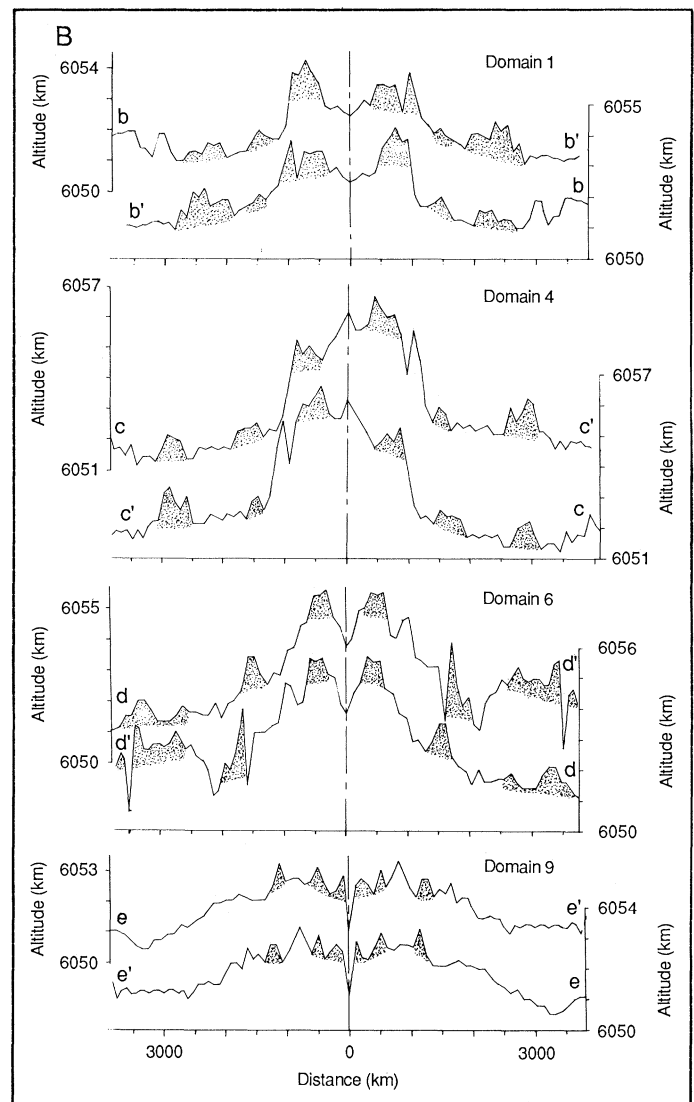


Fig. 4. Bilateral topographic symmetry. (A) Location map of western Aphrodite topographic profiles (thin lines) taken parallel to cross-strike discontinuities (31). CSDs are designated 1 to 8 from left to right. The center of symmetry of these profiles is indicated by a dashed line across the profile tracks. Dotted lines indicate symmetric elements identified in (C). (B) Four typical profiles, which are labeled by the lower-case letter designations



in (A) taken parallel to cross-strike discontinuities. Each profile is reversed and compared to the original to enhance the detection of symmetry. Altitudes are reported as planetary radius. (C) Similar profiles within a single domain between CSD 2 and 3.

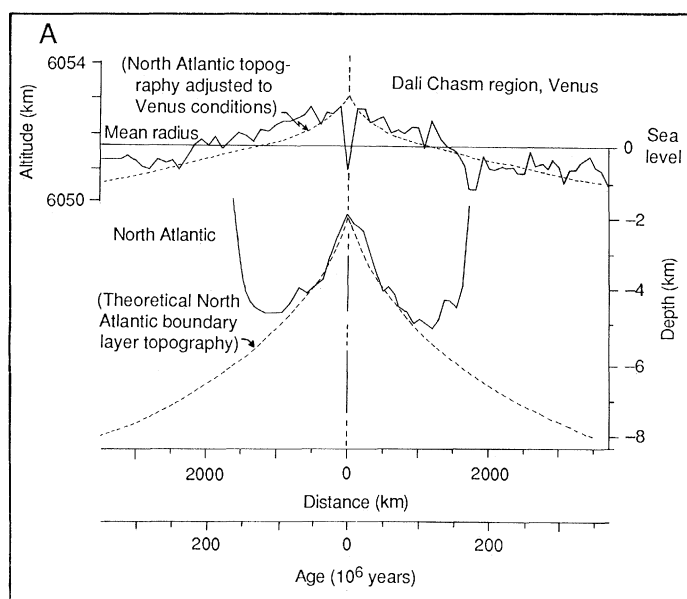
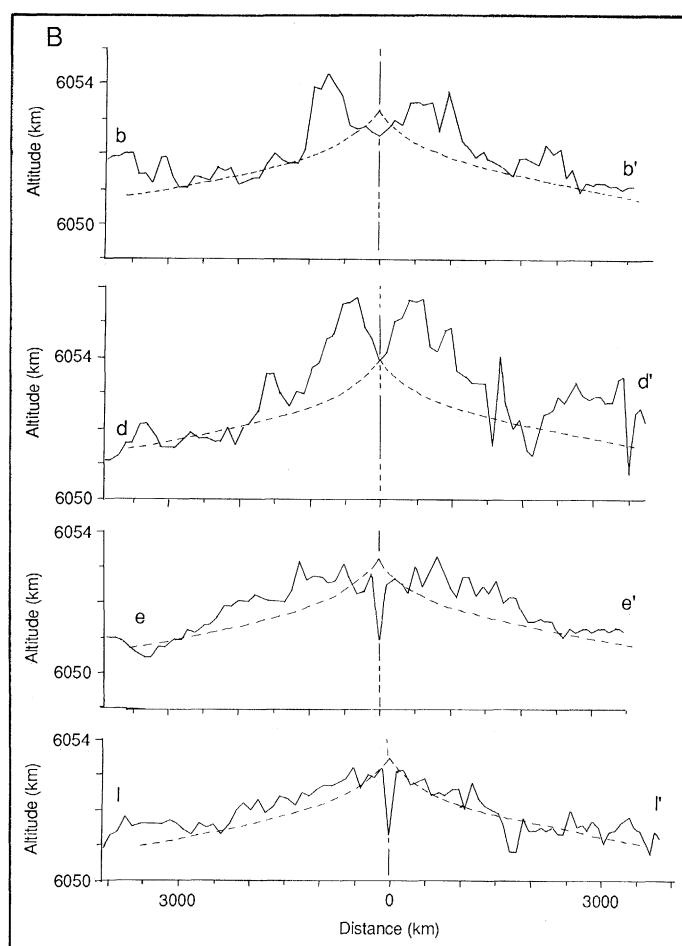


Fig. 5. Idealized divergent plate boundary profiles for Earth (13) and Venus. (A) Comparison of Earth (40) and possible Venus slow-spreading ridges. Solid line is observed profile, and dashed line is predicted profile. Idealized Venus profiles are obtained by boundary-layer theory relations discussed in (14), which take into account the Venus environment. (B) The slow-spreading idealized profile (dashed line) is compared to actual profiles from western Aphrodite Terra taken parallel to cross-strike discontinuities (31). Location of profiles is shown in Fig. 4A.

features oriented generally orthogonally to the rises (Fig. 3) and topographic symmetry in directions parallel to these features, (vi) lateral offset of the topographic rise at the fracture zone-like features (Fig. 3), (vii) topographic relations (step-downs) consistent with predictions for transform faults (Fig. 3), and (viii) probable volcanic features often located at the ridge crest. Given this strong similarity in topography (items i, ii, and iii), morphology (items iv, v, and vii), and configuration (items vi and vii), is there evidence for actual divergence and crustal spreading?

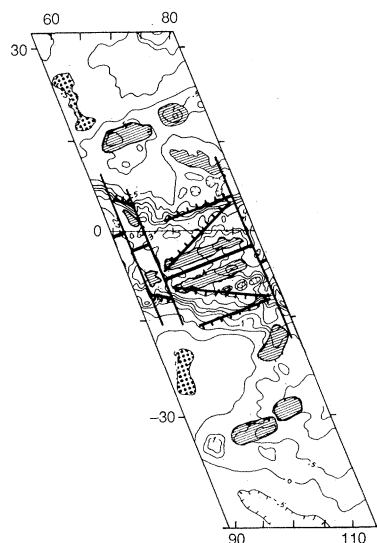
There are no seismic and magnetic data from Venus, and the present weak magnetic field combined with the high surface temperatures probably preclude the formation of detectable magnetic stripes. In addition, there is no direct evidence for the age of the rocks, and sufficient resolution for developing crater-count-related ages is not available in this part of Venus. Three factors, however, seem to provide positive evidence for active divergence and crustal spreading. First, as previously outlined, the magnitude and direction of topographic changes across the fracture zone-like features on Venus are consistent with changes in age implied by the ridge crest offsets (Fig. 3 A and B). Examples of topographic step-downs along the distal portions of fracture zones and cross-strike discontinuities further underline this relationship. Second, the broad aspects of bilateral topographic symmetry of the rises are consistent with a change in altitude as a function of time as newly created crust and lithosphere cools, thickens, and sinks as it moves away from the ridge crest. Comparison of actual profiles on Venus to idealized profiles for Venus and Earth (13, 14) (Fig. 5A) shows that the western Aphrodite region is comparable to slow-spreading centers on Earth, where rates are typically a few centimeters per year. Some aspects of the topography suggest that local accumulations of volcanic deposits such as those responsible for Iceland may be produced in which the plateau-like topography is superposed on the general thermal boundary-layer trends (compare upper and lower two profiles in Fig. 5B). In addition, the offset symmetry of topography in individual domains between fracture zone-like fea-



tures (Fig. 3A) is positive evidence that the topographic symmetry is not simply thermal uplift associated with broad "hot spot" type regional plumes (15), but rather is linked to the properties of narrow individual segments of lithosphere between fracture zones (domains). Third, the nature of one aspect of the bilateral topographic symmetry of rises on Venus (that is, the individual features 100 to 500 km wide that appear in the same position on both sides of the broadly symmetrical profile; see Fig. 4B) could be interpreted as topographic segments that are formed initially at the ridge crest and then rifted and moved laterally apart to their present equidistant from the ridge crest.

Examination of maps and series of profiles within domains (between fracture-zone-like features) in western Aphrodite Terra reveals several types of symmetrical elements or structures (Fig. 6), such as linear ridges 300 to 500 km wide arrayed parallel to the rise crest and normal to the fracture zone-like features, linear troughs 100 to 300 km wide arrayed parallel to the rise crest, linear scarps, and arcuate and circular structures of various sizes located within the domains and equidistant from the ridge crest. Similar features exist in terrestrial divergent zones (27), although they are not commonly studied and documented on Earth for chronological purposes because of the greater simplicity and elegance of the magnetic stripe method of seafloor dating. One common terrestrial type is segments of oceanic rises and plateaus that are created by periods of enhanced volcanism at ridge crests, then rifted apart and spread distally from the ridge crest (32). Another is the creation of individual volcanoes or ridges of volcanoes along the ridge crest and the splitting and lateral migration of these (33). The Venus examples (Fig. 6) are interpreted to be topographic segments that are formed initially at

Fig. 6. Morphology and location of topographic elements symmetrical to the ridge crest within domains between cross-strike discontinuities 1 and 3 (Fig. 4) in the western Aphrodite Terra region, Venus. Solid lines are CSD's and rise-crest axis, linear scarps are shown by hachured lines, positive topography (mountains and linear and arcuate ridges) by a ruled pattern, and negative topography by a stippled pattern. Compare this map with the series of parallel profiles between CSD 2 and 3 in Fig. 4C.



the ridge crest and then rifted and moved laterally apart to their present position equidistant from the ridge crest.

Future tests for divergence and crustal spreading on Venus. Western Aphrodite Terra is characterized by many features that are similar to those present in terrestrial oceanic divergent plate boundary environments. In addition, the Venus data indicate: (i) the existence of bilateral symmetry of topographic elements even at great distances (>1500 km) from the ridge crest, (ii) similarities to terrestrial divergent boundary topography in terms of broad symmetric evolving thermal boundary layer profiles linked to, and consistent within, the individual domains rather than to Aphrodite Terra as a whole, and suggesting spreading rates of several centimeters per year, and (iii) a relationship of topography across transform-like structures (topographic step-down) consistent with spreading age relationships. We thus conclude that fundamental aspects of the plate tectonics process occur on Venus, and that plate creation and divergence is a probable mechanism of lithospheric heat loss. Preliminary assessment indicates that the process is not limited to the western Aphrodite region, and that it occurs elsewhere in the equatorial highlands of Venus (34). The positive correlation of gravity and topography in this area (5) may indicate that large-scale mantle convection processes are more directly linked to divergence on Venus than on Earth.

If divergence and crustal spreading occur in the equatorial regions of Venus, as we suggest, then there are a number of predictions that can be made, and we can propose a number of tests of this hypothesis based on these predictions. First, as a consequence of equatorial divergence in western Aphrodite Terra, we would expect to see evidence for convergence and compressional deformation at higher latitudes. Data for northern mid-to-high latitudes show abundant evidence of compressional and strike-slip deformation (7, 9, 35, 36) and high topography, in contrast to the equatorial regions that appear to be dominated by extensional deformation (37). Second, the age of the surface should increase away from western Aphrodite Terra toward the poles; lower latitudes should be younger on the average than the higher latitudes. At present there is insufficient high-resolution data in the western Aphrodite region to provide crater-count ages. However, if the process is widespread in the equatorial region, and rates of spreading are in the range of a few

centimeters a year, then the average age of the surface of Venus should be relatively young, certainly less than 1.5 billion years. On the basis of crater counts for the northern mid-to-high latitudes, Ivanov *et al.* (38) suggest an age of 0.5 to 1.0 billion years for that region, similar to the average age of the Earth's surface (39). Existing data and global high-resolution data from the upcoming U.S. Magellan mission to Venus can be used to test this hypothesis further, and to determine the extent to which it may be operating on Venus.

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