Geology of a rift zone on Venus: Beta Regio and Devana Chasma

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ABSTRACT

Beta Regio is a region of rifting and volcanism on Venus. The nature of Beta, a major topographic rise and rift zone, is herein characterized using Pioneer Venus, Arecibo, and Venera 15/16 data. High-resolution (1–2 km) Arecibo and Venera radar images reveal details of faulting and volcanism, and Pioneer Venus altimetry illustrates the density and location of faults in relation to topography. Faults are distributed throughout Beta but are concentrated in Devana Chasma, where they are spaced 5–20 km apart. The pattern of faulting and distribution and sequence of volcanic activity in Beta can be used to help understand how the rift has evolved, including the origin of the high topography of Beta and the origin and nature of Devana Chasma. On the basis of geologic mapping relations and map patterns, Beta appears to have formed as a result of doming in response to a mantle anomaly. At the same time, Rhea Mons, a major shield volcano, was formed. Formation of Devana Chasma followed, with extensive faulting in the rift trough. Geometry of the trough and fault patterns suggests that some degree of lithospheric stretching has occurred. Later volcanism produced a second major shield volcano, Theia Mons, which is superimposed on the western bounding fault of the rift zone. Both uplift and extension have been involved in forming Devana Chasma and Beta Regio and may be important in the formation of other equatorial highland regions with systems of chasmata on Venus, such as Aphrodite Terra. The bifurcation of Devana Chasma in the vicinity of Theia Mons, and the extension of the rift system south to Phoebe Regio and west toward Aphrodite Terra, suggest that their origins may be linked.

INTRODUCTION

The nature and distribution of tectonic structures on terrestrial planets is closely linked to the major mechanisms of lithospheric heat transfer (Solomon and Head, 1982). On Venus, some of the most topographically distinctive and areally extensive tectonic features are the deep linear valleys known as “chasmata,” which are interpreted by most workers to be the result of lithospheric extension and rifting (Pettengill and others, 1980; Masursky and others, 1980; McGill and others, 1981; Schaber, 1982; Campbell and others, 1984). Schaber (1982) has shown that systems of chasmata define tectonic zones as much as 20,000 km in linear extent.

One of the most distinctive occurrences of chasmata is in Beta Regio, a 2,300 × 2,000 km highland region rising >5 km above mean planetary radius and cut by a north-south–trending linear trough (Devana Chasma) in excess of 1 km deep (Figs. 1a and 1b). Recently obtained high-resolution radar images of central Beta Regio (Fig. 2) show details of the tectonic structure and associated volcanic deposits (Campbell and others, 1984). Two scales of tectonic features are seen: (1) major faults, which generally define the edges of the 300-km-wide rift zone, and (2) abundant minor faults, spaced 10–20 km apart and concentrated in the central part of the rift zone. The faults lie in and on the flanks of the central trough, Devana Chasma, which has an average width of 160 km. Beta Regio is also one of the most prominent features in gravity data of Venus, with a strong positive anomaly highly correlated with the topography (Sjogren and others, 1983). The anomaly suggests a compensation depth of 330 km for Beta or dynamic support for the topography (Esposto and others, 1982).

This preliminary information on the characteristics and distribution of chasmata on Venus and the nature of Beta Regio raises several significant questions concerning their origin and evolution. Is the topography associated with the rift zones (both the broad topographic rises and the narrow flanks of the riffs) due to uplift or volcanic construction? Are these rift-like structures of active or passive origin (Sengor and Burke, 1978)? The association of Devana Chasma with the broad topographic rise of Beta would seem to argue for localized uplift and faulting (McGill and others, 1981) and an active origin, whereas the major global-scale extensional zones defined by Schaber (1982) suggest large-scale horizontal extension and the possibility of passive rifting. If the elastic lithosphere of Venus is thin (in the 1–10 km range), as suggested by thermal-gradient estimates, by laboratory data for the behavior of materials, and by the characteristics of deformation in Isthmar Terra (Solomon and Head, 1984a), then why are the chasmata so wide and deep? Is lithospheric stretching an important process in the formation of rifts on Venus (Solomon and Head, 1984b; Zuber and Parmentier, 1986)? What is the explanation for the two scales of faulting observed in Beta Regio (Campbell and others, 1984)? Are the two scales related to different scales of extension or differential-strength layering in the lithosphere (Zuber and Parmentier, 1986; Zuber, 1987)?

The purpose of this study is to examine the nature of Beta Regio as an example of a major topographic rise and rift zone on Venus, utilizing a variety of data sets. We examine the questions of the origin of the high topography and the

active versus passive nature of the rift. We also examine the significance of volcanism associated with the rift to determine the sequence of tectonic and volcanic activity in Beta Regio.

METHODS AND RESULTS

Three sets of data were used in examining the Beta region. (1) Pioneer Venus roughness and reflectivity data (resolution about 100 km) were used to characterize the general surface properties of the region, whereas Pioneer Venus altimetry profiles across the rift allowed examination of detailed relations between radar brightness patterns and topography (Figs. 3 and 4). (2) High-resolution (approximately 2 km) images of the Beta region obtained at the Arecibo radar facility in Puerto Rico in 1983 were also studied (Fig. 2). The incidence angle of the Arecibo radar varies approximately with the latitude, from about 30°-45°, with the look direction of the radar oriented approximately perpendicular to the curved image edge seen in Figure 2. Surface roughness variations were used to produce maps of central Beta Regio (Fig. 5) (Campbell and others, 1984), as well as a general unit map (Fig. 6). Arecibo data of northern Beta Regio were also mapped (Figs. 7 and 8) and compared to radar images of the same region obtained by the Venera 15 and 16 orbiters. (3) The Venera radar images (resolution 1-2 km), with an incidence angle of 10° and a look direction to the west (Fig. 9), were used to map brightness patterns associated with surface slopes (Figs. 10 and 11). Rose diagrams of lineaments mapped from the Arecibo and Venera 15/16 data were produced (Figs. 12 and 13) and compared to theoretical fault patterns. The Venera 15/16 mission mapped Venus from orbit during 1983-1984, obtaining images and altimetry north of 30°N latitude (Kotelnikov and others, 1985). The two radar image sets, Venera 15/16 and Arecibo, provide different information about the venusian surface, although they are of similar resolution. They are complementary because of differences in their viewing geometries (incidence angles and look directions).

The way in which radar interacts with the surface of Venus can be described by radar-scattering models such as that expressed in Hagfors law:

\[ \sigma(\theta) = \left( \frac{\rho}{2} \right) (\cos^4 \theta + \cos^2 \theta)^{1.5} \]

where \( \sigma \) is the radar cross section per unit area at angle of incidence \( \theta \), \( \rho \) is the Fresnel reflection coefficient at normal incidence angle, and C is the Hagfors parameter (Hagfors, 1970) out to 40° and following \( \cos^2 \theta \) beyond 40° (Fig. 14). At incidence angles less than 20° (for example, Venera 15/16), the curve slopes steeply, so that surface-slope changes control the amount of backscatter. Between 20° and 60° (for example, Arecibo data of Beta Regio), the slope of the scattering-law curve is relatively flat, so that changes in small-scale (wavelength-size; 12.6 cm) surface roughness dominate the returned signal, with changes in the dielectric constant (a function of porosity and composition) also contributing to the radar return. At incidence angles greater than 60°, surface slopes again begin to dominate the returned signal (Campbell and others, 1984).
RESULTS

General Setting

Beta Regio is a major highland region on Venus, rising at Theia Mons to a maximum elevation of >5 km above the mean planetary radius. The over-all topography of Beta is that of an elliptical dome, 2,300 × 2,000 km, with its long axis oriented about north-south (Fig. 1a). The dome is cut by a north-south-trending trough, Devana Chasma, which continues south of Beta through Phoebe Regio (Fig. 1b). Beta has regional slope characteristics similar to those of Aphrodite Terra, with steep slopes at low elevations corresponding to chasmata walls, as well as steeply sloping outer margins (Sharpton and Head, 1985). The topography of the Beta dome is approximately symmetrical about its long axis. In Arecibo images of central Beta (Fig. 2), the dome is characterized by a broad zone of roughness (80–300 km wide) with north-south–trending linear features. The linear features occur over both the central trough, which originates to the south of Beta in Phoebe Regio, and the high topography of the dome (Figs. 3 and 4). The trough and faults are not visible in the vicinity of Theia Mons, but reappear to the north of Theia offset to the east (Campbell and others, 1984) (Figs. 2 and 6). Devana Chasma varies in width and depth through Beta, reaching its greatest depth (2.5 km) in the vicinity of Rhea Mons and is shallowest at Theia Mons. North of Rhea, the trough widens and loses its topographic expression in the plains.

Surface Properties

Pioneer Venus data have been used to characterize the surface of Beta Regio (Head and others, 1985). Root mean square (rms) slope data indicate that the region is moderate or transitional in roughness (2.5°–5°), as is most of the surface of Venus (Head and others, 1985). Areas of increased roughness, as much as 10° rms slope, occur on the flanks of Rhea and Theia Mons. Basilevsky and others (1982) found only a weak correlation between altitude and degree of surface roughness at Beta Regio, with no apparent correlation between roughness and regional slope. The Beta region is generally moderate in reflectivity (0.1–0.2), indicating a rock-dominated surface (Head and others, 1985). Venera 9 lander images from the eastern flanks of the Beta dome show a rocky surface

still detected. The look directions of the two data sets are sufficiently different to provide at least some detection at all angles, while mitigating suppression effects.

Figure 2. Arecibo radar image (1–2 km resolution) of central Beta Regio. Relatively rough surface areas are radar-bright, whereas radar-dark areas are smooth. The radar-bright lineaments are interpreted to be faults, concentrated along the rift zone. Rhea and Theia Mons, topographic highs seen in Figure 1a, appear here as radar-bright features with a central radar-dark region. The lineaments appear to be overlain by bright deposits associated with Theia Mons (bottom), whereas bright deposits associated with Rhea Mons (top) are dissected by lineaments. The image is in a Mercator projection, with the scale referenced to the equator.

Burns, 1980). Therefore, Venera 15/16 images predominantly portray surface slope variations, whereas Arecibo images illustrate changes in centimeter- to meter-scale surface roughness. This difference allows lineaments that result both from surface roughness and from slope changes to be studied in the Beta region.

The look directions of Venera 15/16 and Arecibo also differ in the Beta images. The Arecibo data of Beta has a look direction of approximately N60°W, whereas the Venera 15/16 look direction is about east-west (Fig. 13). Lineaments parallel to the look direction of a radar system will be suppressed (McDonald, 1980; Ford, 1980). Ideally, perpendicular look directions would provide the most complete detection of linear features. The Venera and Arecibo data sets each show a suppression of linear features parallel to their look direction (Figs. 12 and 13), but lineaments at these orientations are
ties of the majority of Beta are similar to those of a diffusely scattering surface (Bindschadler, 1986). Reflectivity decreases in the region surrounding Beta, indicating soils or a rough) regions.

Few impact craters are seen in the vicinity of the Beta Regio rift in either Venera 15/16 or Arecibo radar images, but a few impact craters, with diameters of less than 60 km, are recognized several hundred kilometers north (for example, 45.5°N, 282°; 45°N, 283°) and west (for example, 36.5°N, 274°) of the rift. Some of the impact craters have central peaks, but no ejecta patterns or secondary craters have been discerned in this region.

**Lineament Characteristics**

The general characteristics of lineaments in central Beta Regio can be seen in Figures 2 and 5. The linear features are both radar dark and bright and are located in a broad zone of radar brightness in the Arecibo images that varies from 80-300 km across. The lineaments are generally spaced 10-20 km apart, and 5 km apart in the vicinity of Rhea Mons. They are 25 to several hundred kilometers in length, parallel to subparallel, and some occur in en echelon patterns. The lineaments bounding the rift appear wider in the Arecibo image, but all the lineaments are about 1-2 km across, at the limits of resolution. The greater brightness of lineaments bounding the rift may result from increased surface roughness attributable to age, exposure of higher reflectivity (younger?) materials, or multiple fault offsets producing corner reflectors. Campbell and others (1984) defined two scales of lineaments: (1) major bounding lineaments, 160 km apart on average and defining the edge of the flanks of the rift, and (2) minor lineaments, spaced 10-20 km apart and located in the central rift zone. A rose diagram of lineament orientations shows a predominant N15°E trend, paralleling the crest of the dome, which in places also parallels the orientation of the trough of Devana Chasma (Fig. 12).

**Origin of Lineaments**

Detailed characteristics of the lineaments to the north were obtained from the Venera 15/16 radar images. In this data set, the linear features also appear both radar bright and dark (Figs. 9 and 11a). The lineaments correspond to scarps, some with apparent slump blocks (at A, Fig. 11a). Narrow (<5 km) graben can also be observed as the lineaments splay out into the plains to the north (at A, Fig. 11b). A rose diagram combining lineament orientations from both the Arecibo and Venera 15/16 data reveals three dominant orientations: north-south, N15°E, and N20°W (Fig. 13). A group of narrow (<5 km wide) radar-bright lines are seen to the north of the rift zone, separated from it by a 100- to 200-km-wide patch of smooth plains (at A, Fig. 10). This smaller set, spaced 5 km apart, trends north-south and does not appear to be directly related to the rift.

Combining the Arecibo and Venera 15/16 data sets allows the nature and distribution of lineaments in Beta Regio to be determined in more detail because of the different look directions and incidence angles of the two radar systems. All major lineaments can be identified in both data sets by general shape and location, but some minor lineaments are unique to each data set; for example, the abundant narrow (<5 km) radar-bright lines north of the rift in the Venera 15/16 data (Fig. 10, at A) do not appear in the Arecibo data. The low incidence angle and look direction of the Venera data indicate the presence of scarps and their facing direction, whereas higher—incidence-angle Arecibo brightness patterns indicate a high degree of surface roughness associated with the scarps. Individual lineaments may have a different appearance in each radar data set. For example, radar bright in Venera and no change in Arecibo indicates smooth, shallow east-facing slopes (at A, Fig. 5).
Figure 4. Pioneer Venus altimetry profiles from Figure 3 correlated with Arecibo radar-brightness patterns. Profile altitude is in kilometers above 6,051.0 km. The stippled pattern indicates the location of bright deposits associated with Theia or Rhea Mons. The dark lines illustrate the location of radar-bright lineaments in the Arecibo image and do not indicate exact location or dip of a fault. The arrow indicates the position of the western bounding fault of the rift.

Figure 5. Structural map of radar-bright and -dark lineaments in central Beta Regio from the Arecibo image seen in Figure 2, after Campbell and others (1984). The lineaments are spaced 10-20 km apart, 5-10 km apart near Rhea Mons. The map is in a Mercator projection, with the scale corresponding to 30° latitude.

Distribution of Faults

To the south of Beta (Figs. 1a and 1b), the observed faults are concentrated in a zone of lineaments less than 150 km wide, distributed over the relatively low topography of the rift. At Theia Mons, the faults disappear beneath the volcano, which lies on top of the western bounding fault of the rift zone (Campbell and others, 1984) (profile a, Figs. 3 and 4). To the north of Theia, in central Beta Regio, the faults appear to be concentrated on the western rift flank or more on the crest of the dome (profiles b and c, Figs. 3 and 4). The western bounding fault tends to lie along the highest points on the flanks of the trough, whereas the eastern bounding fault appears in some areas to lie along the inner wall of the trough. The trough itself varies in width from 50 to 200 km and depth from 2.5 km to <500 m. The trough takes several steps 20-30 km to the west along strike between Theia and Rhea Mons. The flank heights in this region are generally less than 1 km relative to the surrounding terrain. South of Rhea Mons, the trough narrows and deepens. Here, the faults are concentrated in the trough and spaced only 5 km apart (profile e, Figs. 3 and 4). North of Rhea Mons, the rift broadens and becomes shallower as the topography decreases. The fault patterns splay out, distributed over the flanks and trough of the rift (profiles f-i, Figs. 3 and 4). The trough everywhere appears to have faults on its floor and interior walls, but the faulting extends over a much broader zone corresponding to the rift zone.

On the basis of linearity, continuity, scarp-like nature, and associated roughness, we interpret the lineaments in Beta Regio as faults. The majority are interpreted as normal faults produced by extension because of the close association of the faults with the Beta rift zone. Distinct scarps with high degrees of roughness can be detected, with scarps generally facing toward the central depression. For example, the western bounding fault of the rift (at A, Fig. 8) can be seen to have a relatively steep scarp facing east into the central depression (see arrow, profile g, Figs. 3 and 4), with a high degree of associated roughness. As the fault loses its topographic expression to the north, the associated roughness becomes more diffuse. Scarps with shallower slopes and less associated roughness become more abundant as the rift faults splay to the north. The deformation in Beta Regio occurs on three scales: (1) a zone of faulting and associated roughness 80-300 km wide, (2) characteristic trough width of 160 km, and (3) fault spacings of 10-20 km in the trough and over the dome in central Beta Regio, and 5 km near Rhea Mons.
Figure 6. Unit map of central Beta Regio (see Figs. 2 and 5). Major volcanic units associated with Theia and Rhea Mons are shown, as well as the zone of roughness and lineaments that characterizes the Beta rift zone. Arrow indicates an area where flows from Rhea Mons appear to overlie lineaments associated with the rift zone. The map is in a Mercator projection, with the scale relative to 30° latitude.

Relative Ages

Crosscutting and superposition relations are commonly used to determine relative age relations of geologic features, but in the Arecibo data, crosscutting and superposed radar-brightness (that is, surface roughness) patterns may not necessarily reflect relative age relations. A lineament with enhanced radar brightness may appear to be superposed on another lineament, but the enhanced surface roughness could be attributed either to age or to the alignment of the brighter feature more perpendicular to the look direction of the radar system. Therefore, crosscutting relations of surface roughness patterns have to be interpreted with caution. The major fault trends of the rift appear to cut across a set of east-west-trending linear ridges (at B, Fig. 8) at the northern end of the Beta highland. Some evidence of offset of the rift faults is seen, and because the east-west linear features are at low angles to the look direction of both radar data sets, it seems likely that they represent features earlier than the rift faults which appear to cut them. In Venera 15/16 images, the majority of faults appear to terminate at the ridges, whereas a few faults appear to be offset by the ridges (at B, Fig. 11b), suggesting that some of the ridges formed contemporaneously with rift faulting but most ridges predated rift faulting. The western bounding fault of the rift cuts a northeast-trending group of faults to the north of the rift (at A, Fig. 8; B, Fig. 11a), which are spaced approximately 5 km apart. This relationship can be seen in both Arecibo and Venera 15/16 data and appears to be a relative age relation. These two sets of lineaments (at A and B, Fig. 8) are within the Beta highland and may be associated with rifting and formation of the dome. An east-northeast-trending set of lineaments to the northwest of the rift (at C, Fig. 8) appears to be embayed by plains-forming material in Venera 15/16 data and is apparently cut by the rift faults. On the basis of general morphology, we interpret these lineaments to be compressional ridges that surround the northern end of the Beta dome and that may be related to initial relaxation or elastic flexure.

Fault Patterns

The fault patterns of the rift can be used to help constrain the processes that formed the high topography of Beta. Withjack and Scheiner (1982) experimentally and analytically studied fault patterns associated with circular and elliptical domes. Homogeneous clay models were subjected to doming, with and without simultaneously applied regional horizontal strain. Without regionally applied strain, normal faults formed on the crest and flanks of the dome, with the normal faults on the flanks trending radially to the dome. Under regional extension, the dome developed normal faults perpendicular to the applied extension direction, whereas on the flanks, normal faults trend obliquely to the applied extensional direction. Analytical models predict fault patterns similar to those produced by doming the clay models. The fault patterns associated with the Beta rift (Figs. 12 and 13) were compared to the experimental and analytical results of Withjack and Scheiner (1982). In the central part of the rift (Fig. 12), where the faults have a predominant N15°E trend, the fault pattern most resembles that of doming under limited external regional extension (applied extension rate and uplift rate approximately equal) (Withjack and Scheiner, 1982). The faults trend nearly parallel to the long axis of Beta Regio on the crest of the cen-
Figure 7. Earth-based Arecibo image (1–2 km resolution) of northern Beta Regio. This area was also imaged by the Venera 15 and 16 spacecraft (see Fig. 9). The radar-bright feature at the center bottom of the image is Rhea Mons. The bright-ringed circular feature at 42°N latitude, 272° longitude is the corona Rauni. The image is in a Mercator projection, with the scale corresponding to 30° latitude. A map based on the surface roughness patterns in this image is shown in Figure 8.

Figure 8. Lineament map of surface roughness variations, based on Arecibo image of northern Beta Regio (Fig. 7). The letter A indicates the western bounding fault of the rift, which is one of the brightest (roughest) lineaments in the image. The western bounding fault appears to overlie a set of northeast-trending lineaments. At B, the rift faults appear to crosscut a set of northwest-trending lineaments. A set of regional east-west-trending lineaments that appear to predate the rift are indicated at C. The map is in a Mercator projection, with the scale relative to 30° latitude.
Figure 9. Venera 15/16 radar image of northern Beta Regio (quadrangle 19). The region is approximately the same as shown in Figures 8 and 9. The image was digitally mosaicked and has a resolution of 1-2 km. The 10° incidence angle of the Venera radar results in variations in brightness that reflect changes in surface slope.

Figure 10. Structural map of surface slope variations, based on the Venera 15/16 image of northern Beta Regio seen in Figure 9. At A, a group of narrow radar-bright lineaments are mapped that are separated from the rift lineaments by a smooth plains region. These lineaments do not appear to be related to faulting associated with the rift. The letter B indicates the position of crosscutting lineaments arranged in a diagonal pattern, which may be strike-slip in origin. Boxes 1, 2, and 3 indicate the locations of Figures 11a, 11b, and 11c, respectively.
Figure 11. (a) Venera 15/16 radar image of northern Devana Chasma. Faults associated with the rift splay outward as the topography of Beta Regio decreases to the north. At A, a possible slumped block associated with a west-facing scarp can be seen. The letter B illustrates a group of northeast-trending lineaments that appear to be cut by the rift faults. (b) Venera 15/16 radar image of a region to the northeast of Devana Chasma. Faults associated with the rift are visible in the lower left corner. A narrow (<10 km wide) graben can be seen at A. The letter B indicates a group of northeast-trending faults that appear to be offset by west-northwest-trending ridges. A small dome, possibly of volcanic origin, is seen at C. (c) Venera 15/16 radar image of the central portion of the Beta dome, illustrating hummocky terrain (arrow) composed of intersecting trends of lineaments.
Faults, but no evidence of strike-slip motion is predicted by analytical models (Withjack and Cook, 1976). These theoretical fault patterns do not produce the characteristic splaying of faults seen at Beta Regio. The look direction of the radar is approximately perpendicular to the largest peak in the rose diagram.

The structural evidence in Beta Regio thus suggests that uplift or doming has been a predominant process. Lithospheric stretching has also affected the rift, especially in the central region, and probably also to the south, where the trough and zone of faulting continue into Phoebe Regio in a linear pattern (Fig. 1) without exhibiting the splaying of faults seen at the northern termination of the rift.

**Associated Volcanic and Tectonic Features**

Various features of apparent volcanic origin can be identified both within Beta Regio and in the surrounding plains, with some features clearly linked to the rift. The evidence for volcanism includes volcanic plains, domes, and shield-like structures, with distinct flows mapped in the vicinity of the shield volcanoes. The plains surrounding Beta Regio are characterized by moderate roughness and reflectivity, and very low regional slopes. The plains in the northern quarter of Venus have been interpreted by Barsukov and others (1986) to be volcanic in origin, on the basis of general morphology and compositional measurements from the Venera landing sites. No clear sources for the volcanism or flow features can be identified in Arecibo or Venera images of the plains in the Beta region. In the Venera 15/16 image (Fig. 10), two major terrain units can be identified within the northern part of the Beta upland: (1) hummocky terrain and (2) smooth terrain (Fig. 10) (Basilevsky, 1988). The hummocky terrain is characterized by subdued small ridges and hummocks in subparallel, crosscutting, and circular patterns (Fig. 11c). The terrain is mostly localized in the summit region of the dome and in some areas resembles regions of finely patterned parquet (for example, Lakeshside Tessera), indicating that the terrain is the result of earlier tectonic deformation of the surface of the dome.

The areas of hummocky terrain correspond to relatively high Pioneer Venus roughness (Head and others, 1985). The hummocky terrain is crosscut by the major rift faults, indicating that the dome underwent an earlier stage of deformation prior to rift formation. Smooth terrain is localized on the lower slopes of the dome and merges into the smooth plains of adjacent Guinevere Planitia. Domes are frequently found in Arecibo or Venera images of the plains in the Beta region. In the Venera 15/16 image (Fig. 10), which may be strike-slip faults formed as a result of east-west extension.

**Figure 12. Rose diagram of lineament orientations in central Beta Regio south of Rhea Mons.** The lineaments were digitized from Figure 2, then plotted in arbitrary 5° bins to illustrate the general trends of lineaments. The region south of Rhea Mons is covered only in the Arecibo data. The predominant lineament orientation in this region is approximately N15°E. The look direction of the radar is approximately perpendicular to the largest peak in the rose diagram.

**Figure 13. Rose diagram of lineament orientations in northern Beta Regio (north of Rhea Mons), based on Arecibo and Venera 15/16 data.** The lineaments were digitized from Figures 3 and 9, and the rose diagrams were constructed as in Figure 12. Both the Arecibo and Venera 15/16 data sets show a look-direction enhancement of lineaments approximately perpendicular to look direction. Combining the patterns from each data set gives a more accurate set of lineament trends that are associated with the Beta rift.
Abundant domes, 10–15 km in diameter, are located north and northeast of the rift zone (at C, Fig. 11b), and Barsukov and others (1986), noting the presence of summit craters on some of the domes, interpreted them to be of volcanic origin. The high surface pressure and lower subsurface pressure gradient on Venus suppress exsolution of volatiles from a magma and thus inhibit large-scale explosive eruptions (Garvin and others, 1982), but the domes may form by smaller strombolian-type eruptions (Head and Wilson, 1986) or may be analogous to some terrestrial oceanic edifices (Slyuta and others, 1988; Aubele and others, 1988). No flow features are observed around the domes, but they may be undetectable at the resolution of the images. The Venera 9 spacecraft landed to the northeast of the rift in a region that contains many domes. Venera 9 detected a surface composition similar to tholeiitic basalt (Surkov and others, 1976; Vinogradov and others, 1976; Florensky and others, 1977) in a region of moderate reflectivity and roughness in Pioneer Venus data (Head and others, 1985).

FIGURE 14. Scattering-law curve for Venus, based on the Hagfors relationship. Incidence angles of Arecibo data (30°–45°) are in the flat part of the scattering-law curve, where changes in surface roughness will dominate the returned signal. Venera 15/16 data, at 10°–15° incidence angles, are in the steep portion of the curve where changes in surface slope dominate the returned signal. The vertical axis indicates the relative power returned for a cross section I', in decibels (db).

Shield Volcanoes

Two shield volcanoes with diameters >250 km have been identified, Theia and Rhea Mons, both located south of the Venera 15/16 coverage. Theia Mons is at 23°N latitude, 281° longitude, where it forms a radar-bright circular area 350 km across with an irregularly shaped radar-dark central region over its highest point (Fig. 2). Theia is surrounded by lobate flow-like radar-bright features that trend radially down regional slopes from the central topographic high (Figs. 2 and 6). Campbell and others (1984) interpreted these characteristics as supporting the hypothesis of a volcanic origin for Theia. Theia is superposed on the rift (Fig. 6 and profile a, Figs. 3 and 4, illustrate that the trough and zone of faulting are visible to the north and south of the structure), indicating that the construction of Theia postdated formation of the rift.

The other shield-like structure in Beta Regio is Rhea Mons, at 33°N, 283°. Rhea is a 4.7-km-high broad dome interrupted in the center by Devana Chasma. In the Arecibo image, Rhea appears as an irregular radar-bright patch, 230 × 270 km, with the radar-bright areas overlaying the abnormally high rift rims (profile e, Figs. 3 and 4, Fig. 6). The radar-bright area is dissected by a radar-bright stripe (80 km across) overlying the trough, which contains radar-bright faults (spaced 5 km apart) parallel to the trough walls. Flow-like radar-bright and -dark features trending down regional slopes are common on the eastern outer flank of the rift; some of these flows overlie faults on the dome (see arrow, Fig. 6). Rhea Mons is interpreted to be a large volcanic shield on the basis of its dome-like topography, flow-like features, association with the rift, and similarity (both topographically and morphologically) to Theia Mons.

Rhea and Theia are similar in size and morphology, as well as general radar properties. Both have high rms slope values on the flanks (Head and others, 1985), possibly corresponding to rough lava flows, and a dark patch at the highest point on the structure, possibly indicating smooth volcanic deposits and perhaps a central caldera. Flows surrounding both volcanoes trend down regional slopes of the dome, indicating that shield-forming volcanism postdated formation of the high topography. Flows from both features also overlie faults on the dome (Fig. 6), indicating that faulting was earlier than at least some eruption. Both volcanoes have reflectivity values >0.2 near their summits, indicating the presence of high dielectric materials (Head and others, 1985). Theia and Rhea have different relations to the rift. Theia is clearly superposed on the rift, whereas Rhea is interrupted by it. Devana Chasma is very deep (>2 km) in the vicinity of Rhea Mons, and distinct faults can be mapped in the trough, but this is not the case at Theia. From this relationship, we can conclude that flooding and construction of Rhea largely predated the formation of Devana Chasma. In addition, the presence of the hummocky terrain, with evidence of deformation in the vicinity of Rhea Mons, indicates that construction of Rhea may have largely predated this early stage of tectonic deformation of the Beta dome.

FIGURE 15. Effects of differing incidence angles on detection of surface slope and roughness variations. The Arecibo system has high incidence angles (>30°) and is more sensitive to variations in surface roughness, whereas the Venera system (incidence angle of about 10°) is more sensitive to changes in surface slope. The letters A and B represent two hypothetical situations to illustrate the differences in the radar systems. At A, a smooth, shallow slope facing the radar beam will appear bright in the Venera image but will not be detected in the Arecibo image. In contrast, a relatively rough region, as seen at B, will be detected by Arecibo but not by Venera 15/16.
In Arecibo radar images of the Beta region, volcanic flow features are seen only around Theia and Rhea Mons. No flows are visible in the plains or in the vicinity of the small domes. The flows around the shield structures are both radial dark and bright, indicating varying degrees of surface roughness, and are as much as hundreds of kilometers long. Flows are consistently associated both with large calderas and shield volcanoes on Venus, and with smaller (<100 km diameter) shields elsewhere on the planet (Stofan and others, 1987).

Other structures in the Beta region linked to tectonic and volcanic processes are coronae, defined by Barsukov and others (1986) as structures 150–600 km in diameter surrounded by concentric ridges and grooves. The corona Rauni can be seen in both Arecibo and Venera images at 42°N, 272° (Figs. 7 and 9). The corona has a diameter of 270 km and is surrounded by concentric ridges spaced approximately 5 km apart. The central region of the corona is slightly raised (<500 m) above the surrounding terrain, as are other coronae in the northern hemisphere (Stofan and Head, 1986). The corona in northern Beta Regio appears to be overlain by volcanic flows and is also cut by a system of grooves, which follow the same orientation of the rift faults, indicating that they may be related to rift deformation. The corona appears to predate formation of some of the plains volcanism as well as the latest rift deformation.

Volcanism has been an important process in the Beta region. Both the dome of Beta and the surrounding plains appear to be composed of volcanic plains material. Several types of volcanism have been identified, from 10- to 15-km-wide domes to shield structures with diameters of >200 km (Rhea and Theia Mons). The shield structures have a complex relationship with the rift, with Rhea Mons predating and Theia Mons postdating its formation. In Beta Regio, shield-like volcanic structures are closely associated in a spatial sense with extensional tectonics.

**CONCLUSIONS**

Beta Regio has had a complex geologic history, with multiple episodes of tectonic and volcanic activity. Analysis of the Beta rift zone indicates the benefits of using multiple radar data sets. The different look directions of the two radar systems result in more complete structural maps, which makes comparisons to theoretical fault patterns easier and has enabled us to address the following questions.

**What Are the Implications of Fault Spacings?**

Scales of deformation may be indicative of the strength and thickness of layers in a planetary lithosphere. The scales of deformation associated with the Beta rift have been used in an attempt to characterize the structure of the Venus lithosphere. Zuber (1987) modeled the lithosphere of Venus as a two strong layers separated by a weak layer, deformed by the growth of small-amplitude perturbations. An upper crust of 2–8 km is underlain by a weaker lower crust, with total crustal thickness not exceeding 30 km, underlain by a strong upper mantle layer of perhaps only a few kilometers in thickness (Zuber, 1987). The model was found capable of explaining the regular spacings of faults and the characteristic rift width in Beta Regio. The 10- to 20-km fault spacing indicates a layer thickness of about 2–8 km, which is comparable to the 1- to 10-km elastic layer thickness predicted by Solomon and Head (1984a). The presence of two wavelengths of deformation in Beta Regio indicates that the upper crust is either weaker or not significantly stronger than the upper mantle. We interpret the closer spacing of the faults in the vicinity of Rhea Mons as indicating a thinner lithosphere at the time of deformation, perhaps linked to volcanism.

**What Is the Origin of the Beta Regio Topographic Rise and Rift Flanks?**

The origin of the high topography of the broad topographic rise of Beta and the narrower flanks of the rift along its strike has been addressed by using a variety of geologic evidence. If the topography resulted only from uplift, faulting would reflect stresses due to doming, and the heights of the rift flanks would not be expected to be higher in the vicinity of volcanic features. On the other hand, if topography resulted solely from volcanic construction, the rift and faults would have formed as a result of lithospheric stretching due to gravity-sliding stresses. The observed fault patterns associated with the rift and dome most resemble theoretical patterns associated with doming under regional tension (Withjack and Scheiner, 1982). The concentration of volcanism at major constructs Rhea and Theia Mons, built coincident with or after the dome had formed, indicates that uplift has dominated over volcanic construction to produce the high topography of the dome. At the major volcanic shields, increased rift-flank heights associated with the topography of the volcanoes indicate that volcanism has contributed at least 1 km of topography. The strong association of updoming and volcanic activity in Beta is interpreted as evidence for a mantle heterogeneity beneath Beta Regio.

**Is the Beta Rift Active or Passive?**

Active rifts originate above a mantle heterogeneity, whereas passive rifts result from lithospheric stretching (Sengor and Burke, 1978). The early-stage uplift and volcanism and broad flank width of the Beta rift are perhaps indicative of an active origin for the rift (Keen, 1985). The geometry of the rift and the fault patterns, however, indicate that some degree of lithospheric stretching has occurred. McGill and others (1981) calculated that bending and an increase in arc length due to uplift can account for only a few kilometers of extension at Beta, indicating that tens of kilometers of crustal extension may have taken place across Devana Chasma. If the rift is a product of active processes, uplift of the rift flanks should follow the formation of a central depression, which would form because of gravity-sliding stresses after domal uplift (Zuber and Parmentier, 1986). Present evidence suggests that the formation of the central depression postdated the formation of at least Rhea Mons, but stratigraphic evidence for an early-stage central depression is not detectable in radar images.

**What Is the Role of Volcanism in Beta Regio?**

Volcanism has also been a major geologic process in the Beta region. Typical Venustus styles of volcanism, volcanic plains and domes, are found in the lowlands surrounding Beta. The volcanism associated with the rift is dominated by two large central volcanoes, Theia and Rhea Mons. The shield-like structures have smooth areas at their highest point and rougher flanks and are both characterized by high-dielectric materials. If high-dielectric materials are associated with relatively recent volcanic activity (Head and others, 1985), the Beta highland may be relatively young. The location of Theia and Rhea Mons is controlled or appears to control structural features. Rhea is dissected by the trough of the rift, whereas Theia is superimposed on the western bounding fault. In the Beta region, shield volcanoes are closely associated with the rift zone, although shields do occur in other tectonic environments on Venus (Stofan,
1985). The concentration of volcanism along the axis of the rift is similar to the situation along terrestrial rifts, where rifts tend to propagate and link up between regions of hot-spot-related volcanism (Dewey and Burke, 1974). At Bell Regio, also an extensional environment, the major volcanic construct is located apart from the zone of faulting (Janle and others, 1987), unlike the nodal arrangement of shield volcanoes at Beta Regio.

**What Is the Sequence of Events in Beta Regio?**

Crosscutting and superpositional relations between volcanic features and faults in Beta Regio allow a sequence of events to be determined (Fig. 16). Flows around Rhea Mons trend down regional slopes of the dome and overlie major faults. We interpret this to indicate that domal uplift was accompanied by faulting, lithospheric extension, volcanic flooding, and formation of Rhea Mons (Fig. 16, stage I). The formation of the trough, Devana Chasma, postdated the formation of Rhea, with continued rift-related faulting in the trough (Fig. 16, stage II). The closer spacing of faults at Rhea Mons may be due simply to crustal thinning or to the existence of layers of differential strength in the lithosphere at the time of deformation. The concentration of faults in the trough at Rhea may indicate that faulting which was originally associated with a broad zone of extension has become progressively localized in the style of behavior predicted by finite-amplitude necking models for the origin of the rift (Parmentier and others, 1987). Lastly, further volcanic activity resulted in the formation of Theia Mons, after the end of the episode of major faulting (Fig. 16, stage III). Some of the events may have overlapped in time. The volcanic activity associated with the rift zone has moved to the south over time, similar to lateral migration of tectonic and volcanic activity at terrestrial rifts (Illies, 1975). The sequence of events at the terrestrial East African rift is similar to the proposed sequence at Beta Regio. In Kenya, faulting was accompanied by doming and stretching of the lithosphere, followed by extensive volcanism (Baker and Wohlenberg, 1971). Trough formation occurred later, with continued faulting within the trough. The similarities in topography (McGill and others, 1981) and evolution to the East African rift indicate that the tectonic style and evolution of the Beta rift is more similar to continental rather than oceanic rifts. The northern segment of Devana Chasma (from Theia Mons to the north) does not appear to be characterized by an active divergent plate boundary.

The crater-retention age of the surface of the northern quarter of Venus has been estimated at 0.5–1.0 b.y. by Ivanov and others (1986). The area of Beta is not large enough to make the paucity of craters in the vicinity of the dome and rift statistically significant. The lack of craters combined with the distinct fault scarps and lack of soils (Head and others, 1985), however, indicates a relatively young age for the surface of Beta. It is possible, however, that the dome itself may be older, with impact craters on the dome covered by a thin veneer of volcanic deposits. The sequence of events outlined above may have occurred over an extensive period of time.

In summary, current data suggest that Beta Regio formed as a result of doming attributable to a mantle heterogeneity which also produced a major shield volcano, Rhea Mons. The doming was accompanied and followed by rifting and faulting to form Devana Chasma, indicating a migration in volcanic, and probably tectonic, activity to the south over time. Later volcanism occurred at Theia Mons. Chasmata similar to Devana have been recognized in Aphrodite Terra and are also likely to be sites of major crustal uplift and extension. Isolated topographic highs identified along those chasmata may be shield structures comparable to Theia and Rhea Mons. Recent regional studies have led to the hypothesis that chasmata in the Aphrodite region may be the sites of crustal divergence and spreading (Head and Crumpler, 1987) and that crustal divergence may be widespread in the equatorial highlands. We find no specific evidence for crustal spreading in northern Beta Regio but, as shown in Figure 1, Devana Chasma bifurcates at Theia Mons and appears to be connected to a chasmata system extending to the west in Aphrodite and toward the south in Phoebe Regio, perhaps indicating that the Beta rift may be linked to other styles of tectonic activity in the equatorial highlands (Head and Crumpler, 1987). The area of rifting north of this bifurcation splays out into the northern lowlands (Fig. 1) and does not appear to be linked.

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**Figure 16. Sequence of events in Beta Regio.** I. Formation of Rhea Mons after initial uplift, probably accompanied by some faulting. II. Formation of Devana Chasma and associated faults. III. Rifting and faulting was then followed by the formation of Theia Mons.
to the more regionally extensive extensional deformation in Phoebe Regio and westward toward Aphrodite Terra. The pattern associated with Beta/Phoebe (convergence of three arms of rift zones) is very similar to that seen in terrestrial triple junctions.

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