GEOLOGY OF THE SOUTHERN ISHTAR TERRA/GUINEVERE AND SEDNA PLANITAE REGION ON VENUS

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Abstract. Recent high resolution, high incidence angle Arecibo radar images of southern Ishtar Terra and flanking plains of Guinevere and Sedna on Venus reveal details of topographic features resolved by Pioneer Venus. The high incidence angles of Arecibo images favor the detection of surface roughness-related features, and complement recently obtained low incidence angle Venera 15/16 images in which changes in surface topographic slope are well portrayed. Four provinces have been defined on the basis of radar characteristics in Arecibo images and topography. Volcanism and tectonism are the dominant processes in the mapped area, which has an average age of about 0.5–1.0 billion years (Ivanov *et al.*, 1986). These processes vary in relative significance in the mapped provinces and it is likely that geologic activity has occurred simultaneously in all four provinces. On the basis of stratigraphic evidence, however, a general sequence is proposed which represents the major activity in each area. The low predominantly volcanic plains of Guinevere and Sedna Planitiae are the relatively oldest terrain. A major region of complex tectonic deformation, the Southern Ishtar Transition Zone, postdates much of the low plains and delineates the steep-sloped flanks of Ishtar Terra. Lakshmi Planum is characterized by a distinctive volcanic style (large low edifices, calderas, flanking plains) and at least in part postdates the Southern Ishtar Transition Zone. Relatively recent plains-style volcanism occurs locally in Sedna Planitia and embays the Southern Ishtar Transition Zone. Compressional deformation appears to dominate the mountains of the Ishtar plateau, but the nature of the tectonic deformation in the Southern Ishtar Transition Zone is very complex and likely represents a combination of extension, compression and strike-slip deformation. Arecibo data reveal additional coronae in the lowlands, suggesting that corona formation is an even more widespread process than indicated by the Venera data.

1. Introduction

Although Venus is the most Earth-like of the terrestrial planets, little high resolution mapping has been done of the surface due to the dense global cloud cover on the planet. Earlier low resolution altimetry (Pettengill *et al.*, 1980; Masursky *et al.*, 1980) and earth-based radar images (Goldstein *et al.*, 1976; Campbell and Burns, 1980) revealed a number of highland and lowland regions including Ishtar Terra, centered at 65°N latitude, 350° longitude, and flanking linear lowland regions of Guinevere and Sedna Planitiae. Ishtar Terra, approximately the size of Australia, contains the highest elevations on Venus, and consists of a high plateau (Lakshmi Planum) bordered by three groups of mountains (Akna, Freya and Maxwell Montes) and a complex scarp area (Vesta and Ut Rupes) (Masursky *et al.*, 1980) (Figure 1). Sedna Planitia forms an extensive, elongate lowland region along the southern flanks of

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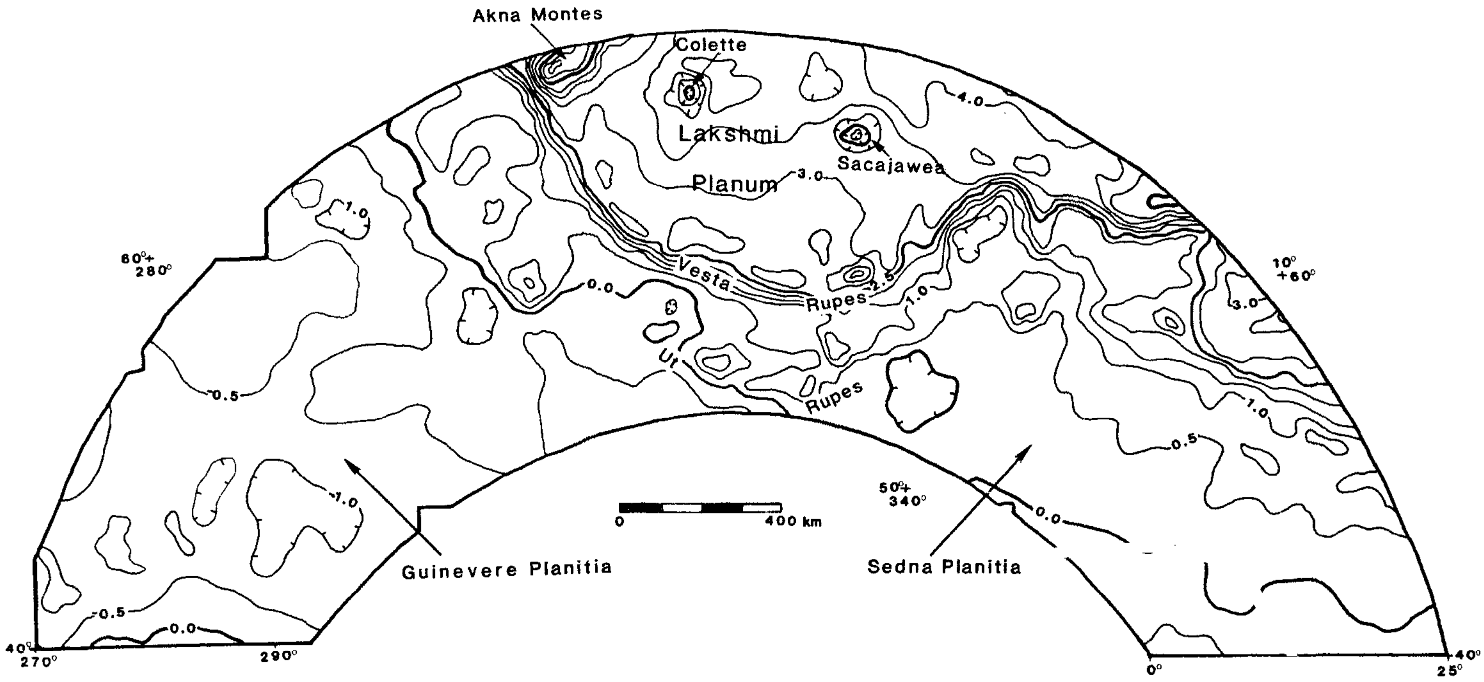


Fig. 1. Topographic map of the southern Ishtar region, based on Pioneer-Venus altimetry (from Topographic map of Venus, V 50M 6/60 RT, USGS, 1984). Scale refers to 60°.

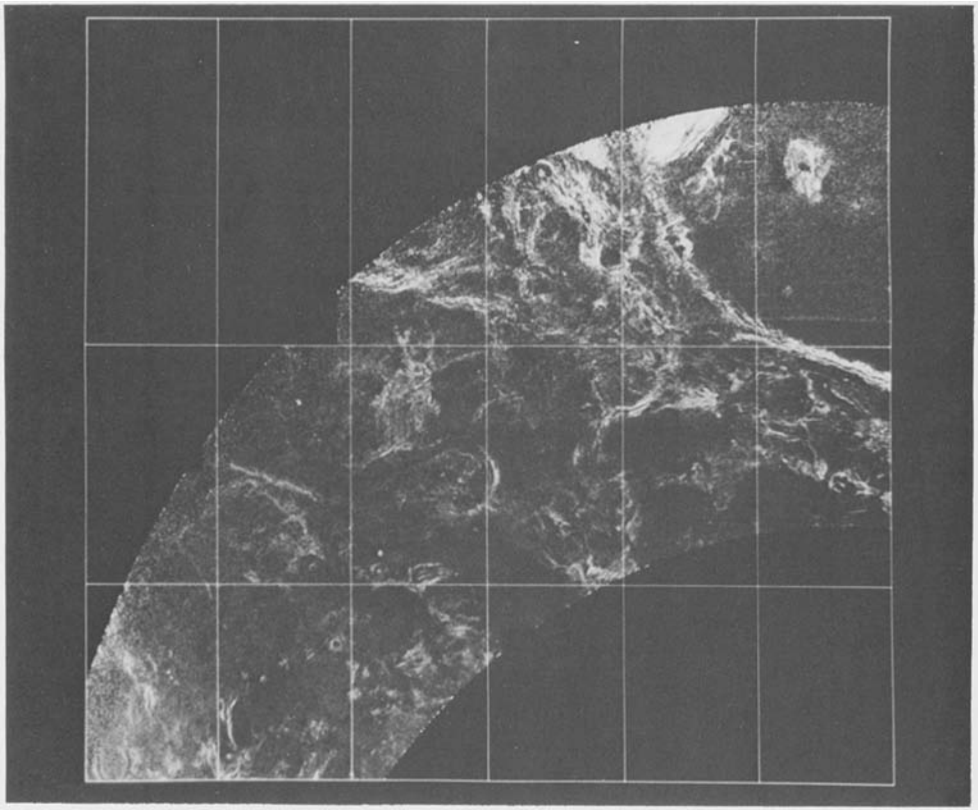


Fig. 2(a). Western half of image swath.

Fig. 2(a)–(b). High resolution Arecibo radar image of the southern Ishtar region. Bright areas are generally rough and dark areas smooth, see text for details. Scale refers to 60° latitude.

Ishtar Terra, striking generally NW–SE and lying from 1–3 km below Lakshmi Planum (Figure 1). The origin of highlands and lowlands on Venus remains one of the most fundamental questions about the planet and is a key to understanding the major mechanisms of lithospheric heat transfer (Solomon and Head, 1982). At the present time, there is an insufficient understanding of the nature of the surface features and their origin and distribution to constrain models for the origin and evolution of the highlands and lowlands. The purpose of this paper is to document the characteristics of the surface of Venus in this important transitional area between highlands and lowlands using new high resolution Arecibo radar images and data from the Pioneer-Venus mission, in order to help establish the geologic processes operating there, and to provide a framework of detailed observations which can be used to assess hypotheses on the geologic evolution of the region.

Phillips *et al.* (1981) and Phillips and Malin (1983) described Ishtar Terra with its flat plateau and mountain belts as different from other Venus highlands regions, and suggested that its origin may be unique. Significant volcanic and tectonic activity in

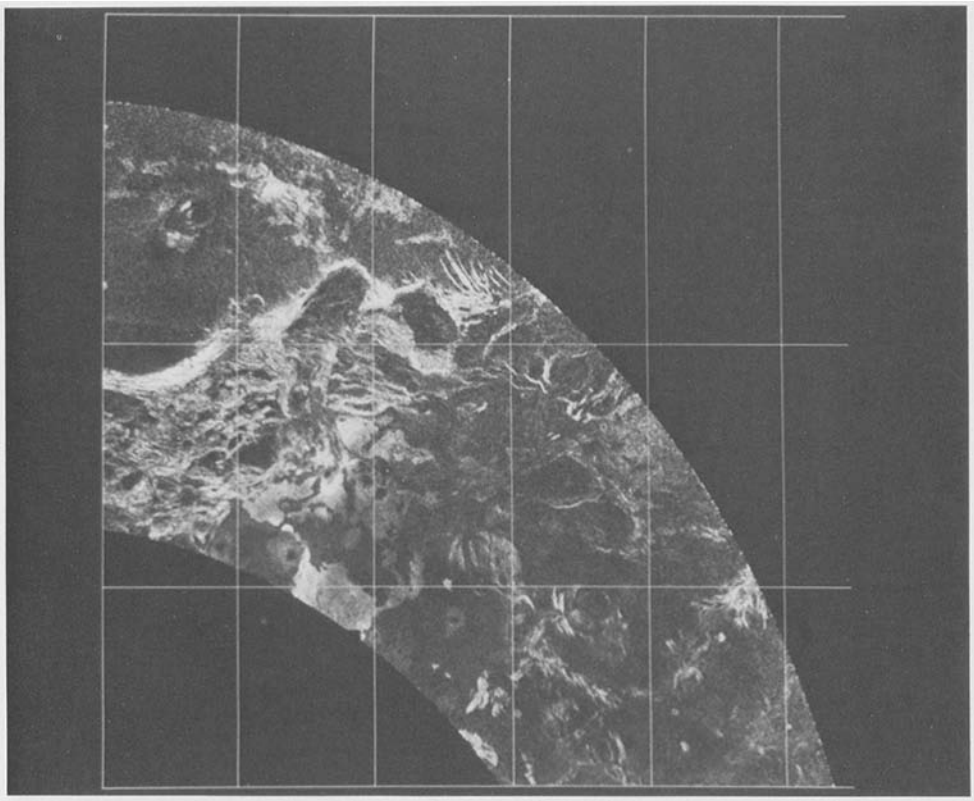


Fig. 2(b). Eastern half of image swath.

the southern Ishtar region have been previously identified, including possible calderas (Masursky *et al.*, 1980) and folded or faulted terrain (Campbell *et al.*, 1983). The banded terrain of the major mountainous regions has been interpreted as compressional in origin (Campbell *et al.*, 1983; Solomon and Head, 1984); however, the relationship between the plateau and the banded terrain is not clearly understood. The origin and nature of the plains surrounding Ishtar Terra (Guinevere, Sedna) and the distinct geomorphologic and topographic transition between the plains and the highlands, as well as the nature of the highland terrain, also remain as key questions in understanding the nature of the surface of Venus.

High resolution (1–3 km) radar images of southern Ishtar Terra and surrounding plains were obtained at the Arecibo Observatory in Puerto Rico in 1983 (Figure 2). Earlier Arecibo images of similar resolution of other regions of Venus have confirmed the presence of volcanism and rifting in Beta Regio (McGill *et al.*, 1981; Campbell *et al.*, 1984) and permitted the characterization of banded terrain of Akna, Freya and Maxwell Montes (Campbell *et al.*, 1983). The images of southern Ishtar and surrounding plains reveal significant details of volcanic and tectonic activity in the region. The sub-Earth point on Venus lies within $\pm 9°$ of the equator, so that incidence angles for the 12.6 cm radar system at Arecibo vary from about 0° near

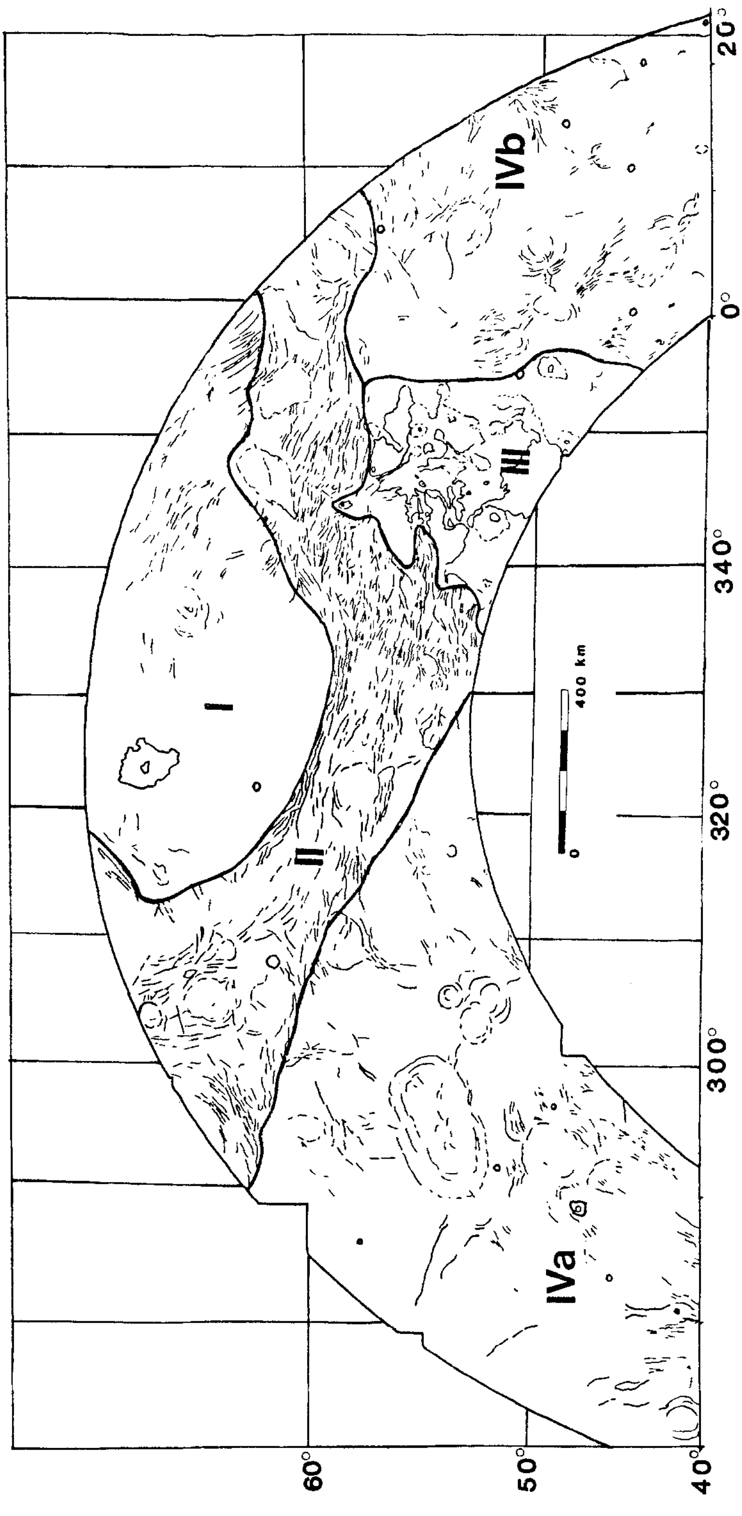


Fig. 3. Province map of the region. Scale refers to 60° latitude. Thick lines represent province boundaries; thin and dashed lines indicate linear or arcuate areas of brightness in the Arecibo image.

the sub-Earth point to values approximately equal to the latitude at high latitudes. The angle of incidence of the image in Figure 2 ranges between 40°–70°, following the increase in latitude. The slope of the scattering law curve for Venus (Campbell and Burns, 1980) in this range is relatively flat; as a result, the returned signal is dominated by diffuse scattering by small-scale, wavelength-size surface roughness. The Arecibo images are complemented by Venera 15/16 images of similar resolution covering the planet north of about 30° latitude (Barsukov *et al.*, 1984). The Venera images have an incidence angle of approximately 10°. At this low incidence angle, the scattering law curve has a steep slope, so that slope effects dominate the returned signal, in contrast to the wavelength-sized surface roughness detected by the Arecibo system. The look directions of the two radar systems also differ. The Venera 15/16 look direction is approximately E–W, while the Arecibo look is perpendicular to the curved image edge (Figure 2) and thus varies from about N75W to N75E. Lineaments parallel to the look direction will tend to be supressed, while lineaments approximately perpendicular to the look direction will be enhanced (Ford, 1980).

Maps of southern Ishtar Terra and the surrounding plains, showing linear and arcuate bright segments and areas of variable brightness, were produced from the high resolution Arecibo images (Figure 3). Brightness variations mainly reflect changes in surface roughness, which may represent a variety of geologic processes and features such as talus associated with slopes or fault scarps, different styles of volcanism, and surface age differences (e.g. increased soil content due to erosion). We first subdivide the mapped area into a series of provinces defined on the basis of the distribution of features seen in the Arecibo images. We then characterize the provinces on the basis of these data and the Pioneer-Venus topography, surface roughness, and reflectivity data (Pettengill *et al.*, 1980). We then examine individual features characterizing them and comparing their roughness properties to the slope-dominated properties observed in the lower incidence angle Venera data (Barsukov *et al.*, 1986). Finally, we outline a preliminary assessment of the major processes operating in each province, discuss the age relationships between provinces, and assess models for the origin of the highlands and lowlands on Venus.

2. Province Descriptions and Interpretations

Province I is a predominantly radar-dark, generally featureless region, covering the area known as Lakshmi Planum. It consists of a high plateau, rising over 3 km above the mean planetary radius (6051.0 km), with distinct, steeply sloping boundaries. To the south, the plateau is bounded by the steep scarp of Vesta, while the mountains of Akna, Freya and Maxwell lie to the west, north and east, respectively (Figure 1). The surface of the plateau rises gently to the north. The major features of the province are two large circular to oval structures and groups of bright lines. The two circular features, Colette and Sacajawea, are irregular depressions located at the summits of broad gently sloping domes. The craters are interpreted to be calderas (Masursky *et al.*, 1980; McGill *et al.*, 1983) (Figure 4). Colette is characterized by an

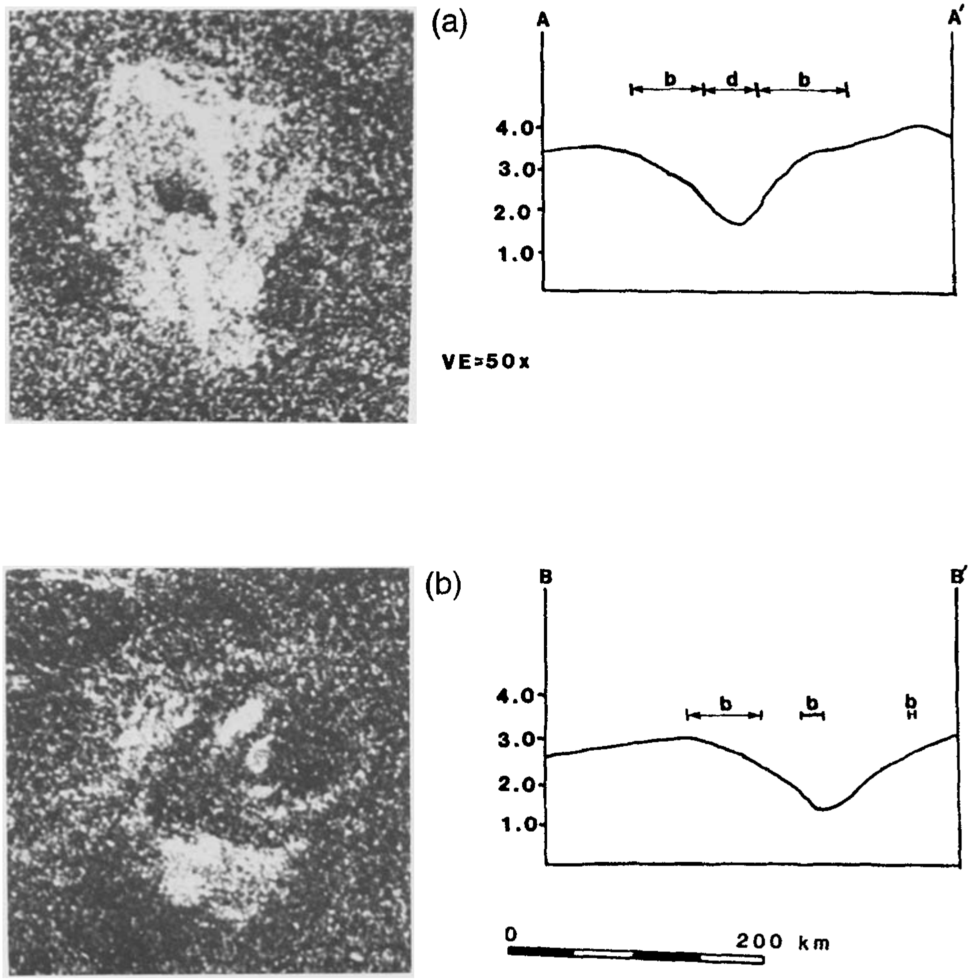


Fig. 4. (a) Arecibo image of the feature Colette (66°N, 323°) and profile across Colette using Pioneer-Venus altimetry data. (b) Arecibo image of Sacajawea and profile across Sacajawea (64°N, 336°) using Pioneer-Venus altimetry data. Relative brightness variations across the structures are indicated (*b* = bright, *d* = dark).

elongated radar-bright patch of about 150 km × 220 km, with a dark quasi-circular center of about 25 km in diameter. The rim of the feature is approximately 1 km above the surrounding plateau (Figure 4a) and the dark spot corresponds to the bottom of the 2 km deep depression. The radar-bright patch coincides with the inner slopes of the depression and the neighboring plateau area, and the concentric ring-like nature of portions of the bright area suggest that it may represent terraces associated with the inner walls of this feature. Sacajawea is less distinct in radar images than Colette, appearing as arcuate radar-bright segments and irregular radar-bright patches rather than a well-defined bright quasi-circular region with a central radar-dark area. The bright segments lie inside a 145 × 190 km depression, again suggesting terraces or slumped material which would produce bands of enhanced roughness. Diffuse bright areas on the edges of the depression indicate areas of enhanced roughness. The brightness variations do not resemble those expected for impact craters, and the polarization ratio for Colette is similar to Theia Mons (a volcanic construct in Beta Regio) (Burns and Campbell, 1985). The general morphology and radar appearance of Colette and Sacajawea are thus consistent with a volcanic origin for these structures (Masursky *et al.*, 1980), an interpretation largely confirmed by Venera 15/16 images (Barsukov *et al.*, 1986). Topography obtained from Pioneer-Venus suggest that the two features are central calderas of large, low volcanic edifices. The shallower topography and irregular, faint radar backscatter appearance of Sacajawea may indicate that it is relatively older than Colette; the arcuate bright segments may be evidence of collapse. Barsukov *et al.* (1984) using Venera 15 and 16 data also interpret Sacajawea to predate Colette, and have identified flow-like features radially surrounding Colette.

The other major features of Lakshmi Planum are groups of bright lines, occurring near the eastern and western margins. The groups are generally less than 100 km wide, and are comprised of narrow (< 5 km) lines that range from less than 50 to 100 km long. The first type occurs in closely spaced groups of parallel straight lines that appear to be embayed in places by the dark plains material (for example, at 66°N, 344°). The second type of line set, located near the easternmost extent of the plateau, consists of parallel, arcuate lines spaced 5–20 km apart (for example, at 63°N, 356°). This type is more distinct, continuous and bright, and does not appear embayed. The lines are most likely to be tectonic in origin; eolian processes, mass wasting and volcanism are not likely to produce such long, continuous linear features on Venus (Campbell *et al.*, 1983). The resolution of Pioneer-Venus altimetry does not permit the determination of positive or negative relief for any individual line or band. In the Venera 15 and 16 images, the second type of lines correspond to a group of graben, indicating that extensional forces have been active in the region (Barsukov *et al.*, 1986). A few small (< 10 km) bright circular features of possible impact origin are also seen in Province I. These features are interpreted to be of impact origin due to their highly circular shape, presence of a central radar-bright feature, and distinct neighboring radar-bright region (interpreted as ejecta). Many features interpreted to be of impact origin in Arecibo images have been similarly interpreted in Venera 15/16 images (Barsukov *et al.*, 1986). However, distinguishing characteristics, such as secondary craters and wall terraces, cannot be identified with either data set in this crater size range. The general characteristics of craters in the southern Ishtar and plains region, most of which are probably of impact origin, are listed in Table I; the diameters given are for the dark interior and most likely represent the diameter of the crater floor rather than a rim-to-rim diameter, since high roughness is most often associated with material on the crater rim and inner slopes of craters (Campbell and Burns, 1980).

On the basis of these combined observations, we interpret the surface of Province

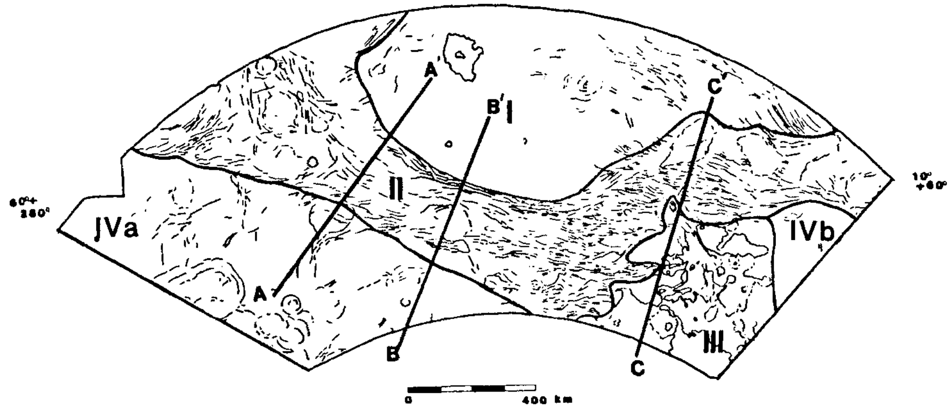


Figure 5a.

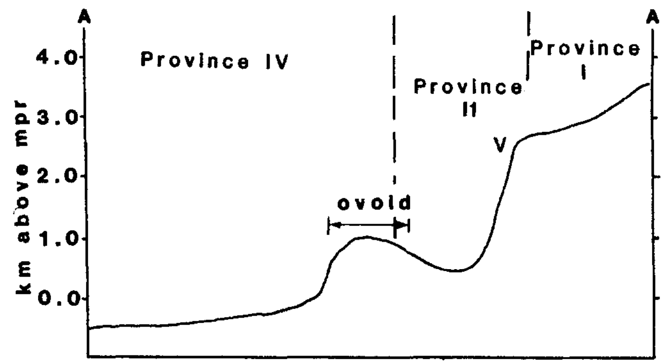


Figure 5b.

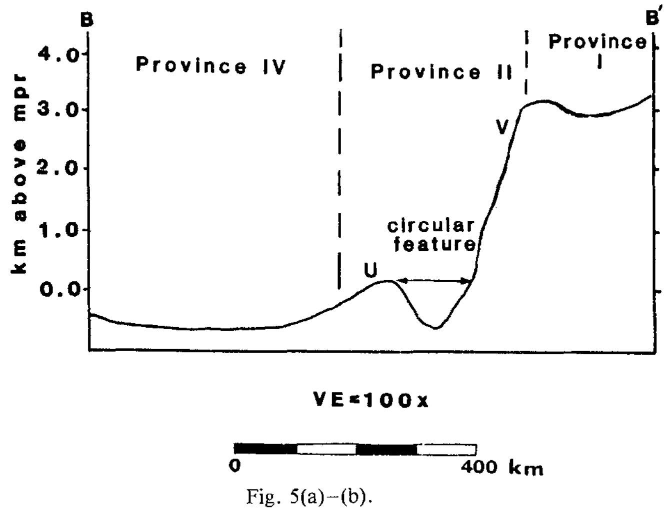


Fig. 5(a)–(b).

Fig. 5(a)–(c). Topographic profiles across southern Ishtar and plains region from Pioneer-Venus altimetry (U = Ut Rupes, V = Vesta Rupes). (a) Profile across Vesta and ovoid on II/IV boundary. (b) Profile across Vesta and Ut Rupes, and a circular depression of Province II. (c) Profile across Provinces II and III showing oval depression in II and topographic low in III.

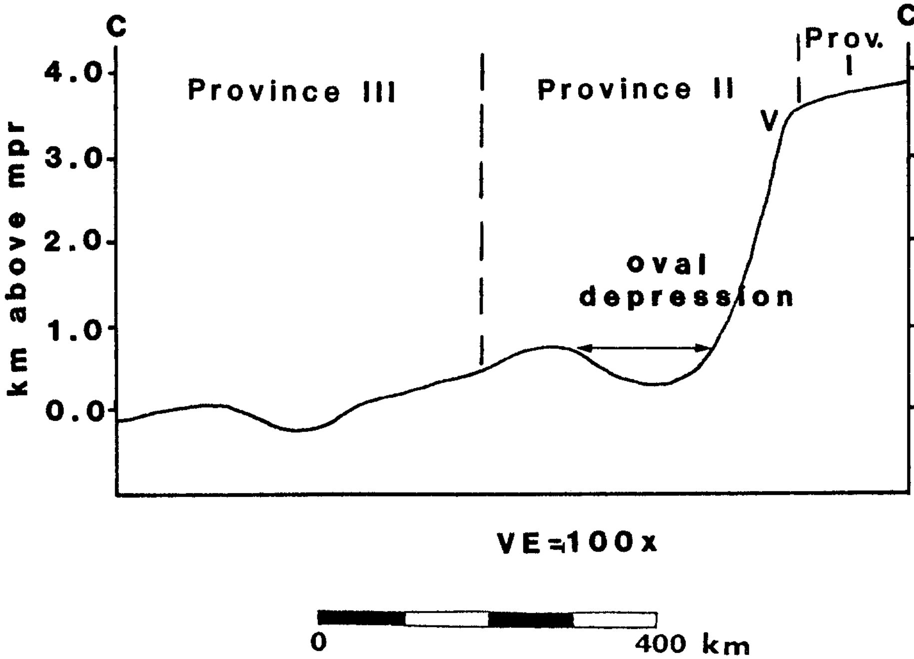


Fig. 5(c).

Sacajawea), and smooth surrounding radar-dark regions that are volcanic plains. The volcanic material embays previous tectonic features near the margins of the plateau. However, at least some of the volcanic activity may have been followed by tectonism, as evidenced by the set of graben (Barsukov *et al.*, 1986) on the eastern border of the province.

Province II is characterized by highly lineated and structurally modified terrain bordering Lakshmi Planum and is a major topographic transition zone from Ishtar Terra (Lakshmi Planum) to the surrounding plains. To the south, Province II is characterized by the steep scarp of Vesta Rupes followed by the gentler slope of Ut Rupes (Figures 1 and 5b), and a linear boundary with Province IV. Akna Montes contains the highest elevations in the province, with maximum altitudes of over 6 km above the mean planetary radius. The eastern and central portions of the province are characterized by several oval to quasi-circular depressions (located at 60.6°N, 347° and 61.2°N, 353°) (see profiles in Figure 5b and 5c). The brightest areas include southern Akna Montes and the mountainous region above Vesta Rupes. Vesta and Ut Rupes appear as darker regions bounded by radar-bright linear features. The linear features may be classified as bands (Campbell *et al.*, 1983) and lines (Head *et al.*, 1985a). Bands are long, very bright, lie in parallel groups, and occur in topographically high terrain. On the border of Lakshmi Planum, the banded region ranges in elevation from 2–6 km above the mean planetary radius (Figure 5a and 5b). The bands appear in the center of the images as a 40 km wide group that trend to the northwest for over 400 km. Continuing to the east, the bands form a narrow bright group that comprise the northern rim of two oval, dark depressed areas (Figure 5c). In the west, they become obscure and then reappear in a northeast-trending coherent group that corresponds to the southern portion of Akna Montes. The bands in Akna are relatively narrow and closely spaced; the banded terrain in Freya, northern Akna and Maxwell Montes (not shown in these images) appear to have wider bands (10–20 km) with band spacings of 15–20 km (Campbell *et al.*, 1983). The bands along the southern edge of the plateau are more linear and continuous than the bands in Akna, Freya and Maxwell. However, the general similarities between the northern and southern banded terrain indicate a similar, probably compressional origin (Campbell *et al.*, 1983; Solomon and Head, 1984). This conclusion is supported by Barsukov *et al.* (1984) who interpreted the banded area as linear structures formed by folding or imbricate faulting in response to horizontal compression. Most of Province II is dominated by lines, which are less bright, narrower, and shorter than bands (Head *et al.*, 1985a). The lines have a dominant trend to the west-northwest. Look direction enhancements are a well-known phenomenon in radar images (Ford, 1980), and a quantitative assessment of structural fabric would require analyses of images with several radar viewing geometries (Stofan *et al.*, 1986; Fisher *et al.*, 1985). Visual inspection of Figure 3 shows evidence of a slight enhancement of linear features in a direction normal to the radar look direction. However, the predominant NNW trend across Province II is clearly a fundamental structural trend because in some areas (e.g. NW section of the province) the linear features are abundant parallel to the look direction, a situation in which linear features are usually suppressed. The lines are more widespread than the bands, corresponding to gentler slopes lying between 2.5 km and the mean planetary radius (Figures 5a and 5b). The lines sometimes appear in pairs 10–20 km apart, separated by a central radar-dark area. The parallel nature and constant separation distance of some of the paired linear zones of enhanced roughness suggest paired ridges which may represent paired faults or graben. Others may represent strike-slip movement (Basilevsky *et al.*, 1986). In the east, the lines appear chaotic and more closely spaced. Barsukov *et al.* (1984) have identified this area as 'parquet' terrain, consisting of orthogonal systems of valleys and ridges produced by complex deformation. Although the orthogonal aspect is visible in Arecibo images, there is a look direction enhancement that favors the linear features arrayed normal to the look direction.

Several probable impact craters (over 30 km in diameter) can also be seen in the zone comprised primarily of lines (Table I). A few large circular structures are also present in Province II, with diameters of over 100 km (two examples are located at 58°N, 323° and 64°N, 305°). The features are defined by arcuate bright segments that rim a mottled, quasi-circular center. The feature at 58°N, 323° corresponds to a slight (< 500 m) depression (Figure 5b). The circular features appear to interrupt

TABLE I
Possible impact craters

Coordinates	Diameter of dark interior (km)	Central peak (Yes/No)
66°N, 304°	99	Y
47°N, 288.9°	40	N
61.2°N, 308.4°	37	Y
50.5°N, 355°	20	Y
45.1°N, 283.5°	19	Y
44.3°N, 359°	19	Y
48.3°N, 297°	18	Y
44.5°N, 10°	17	Y
41.3°N, 280.8°	16	Y
40.3°N, 21.3°	16	Y
43.9°N, 18.3°	11	Y
62°N, 330°	9	?
48.1°N, 13.6°	8	Y
51.3°N, 292.1°	8	N

The bands and lines of Province II indicate that tectonism has been a dominant process. Several episodes of tectonism are indicated; for example, near the western edge of Province II, a northwest-trending set of lines parallel to southern Lakshmi Planum cut northeast-trending lines and bands associated with southern Akna Montes and its extension toward Guinevere Planitia, suggesting that some deformation associated with the southern margin of Ishtar Terra may postdate the northeast-trending Akna Montes deformation, or that there is a major change in tectonic style at this junction. In general, the lines are more chaotic and randomly oriented, while the bands closely parallel the southern border of the plateau indicating a close relationship between band formation and the plateau. Volcanism also appears to postdate tectonic activity in this zone as plains related to Lakshmi Planum (Province I) extend over the edge and down the slope of the plateau (Barsukov *et al.*, 1986) (note area centered at about 63°N, 312° where linear features are low in abundance). The relatively constant width of Province II in the south (about 300 km) suggests that the formation of the plateau has influenced or was influenced by a zone of intense horizontal and vertical deformation, here designated the Southern Ishtar Transition Zone.

Province III is composed of flow-like units, interpreted as volcanic plains (Head *et al.*, 1985a). The province ranges in elevation from 0 to 1 km above the mean planetary radius, 2–3 km below Lakshmi Planum. A broad 140 km diameter depression with a depth of < 500 m relative to the surrounding terrain, lies near the western margin of the province (Figure 5c). The flow-like features (Figure 6) have low to high radar backscatter returns, and frequently have a lobate appearance. Two types of possible flows and vents are seen. The first type is an intermediate to dark area surrounded by dark lobate plains (Arrow A in Figure 6). The flow-like features are 10–30 km wide, and extend over 100 km. Long flow lengths could be explained

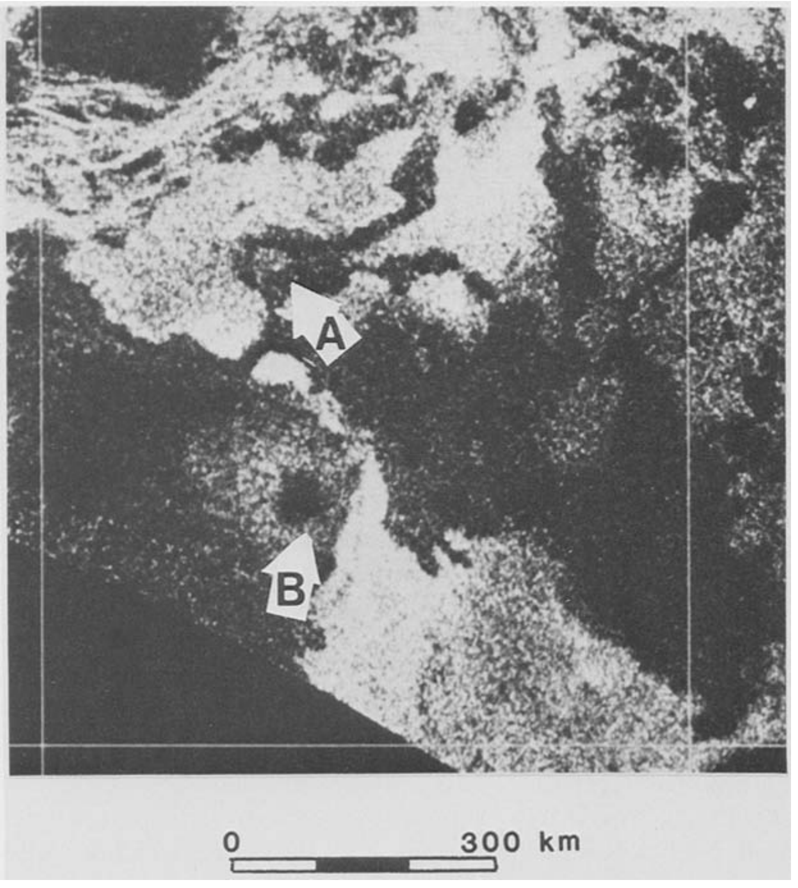


Fig. 6. Bright and dark areas representing volcanic flows in Province III. Arrows indicate two types of features discussed in text.

by high effusion rates (Walker, 1973; Head and Wilson, 1986). The second type has a radar-dark circular center with wide radar-bright surrounding region, resembling the feature Colette (Arrow B in Figure 6). The 50 km radar-dark central area is surrounded by a diffuse bright patch of about 200 km in diameter. The lobate, flow-like boundaries of the features suggest a volcanic origin. Theoretical studies (Head and Wilson, 1986) suggest that lava shields on Venus produced by eruptions from central vents will be topographically low with diameters in this size range, further suggesting that these features may be low volcanic shield-like structures. In contrast to Colette and Sacajawea in Province I, the interpreted centers of volcanic activity are much smaller, more abundant, and are not characterized by large, deep central caldera-like topographic depressions, although the circular to oval features seen at A and B in Figure 6 may be smaller versions of calderas. Similarities between polarized and depolarized images of the Province III structures indicate that surface dielectric properties, and thus flow composition and/or porosity, may vary significantly in this region (Head *et al.*, 1985a). In Venera 15/16 images (Barsukov *et al.*, 1986), the plains appear generally smooth and the detailed flow-like textures are either not visible or locally show a reversal in bright/dark relationships, suggesting a strong influence of illumination conditions on flow detectability and characteristics.

The boundary with Province II is quite distinct. The boundary between Province III and Province II tends to parallel topographic contours and the flows within Province III appear to abruptly truncate the radar bright lines of Province II, suggesting that the flows embay and overlap the tectonic lineaments. The flow units do not appear to have undergone any major deformation, unlike the multiple episodes of deformation seen in Province II. No major structural features (lines, bands) can be seen Province III, indicating that it largely postdates the tectonic activity surrounding Ishtar Terra. The boundary with Province IV is transitional, with the flow units of Province III becoming darker and more diffuse towards the boundary. One small possible impact crater is located on the Province III-Province IVb boundary (at 50.5°N, 355°, see Table I). Province III and Province I have different appearances, although both appear to have undergone volcanic resurfacing, suggesting contrasting styles (major central edifices in Province I; multiple sources and plains volcanism in Province III). If flows become smoother and less distinct with age in radar images, Province III may represent younger volcanic activity. However, the difference in appearance between the two may also be a result of differing compositions and/or eruption styles; the existing data do not support a unique interpretation of the age relationships.

Province IV, characterized by plains, is generally radar-dark like Lakshmi Planum (Province I), but has more abundant bright lines and circular structures. The western (IVa) and eastern (IVb) portions of the image swath are interpreted to be the same province on the basis of similar distributions and abundances of features and similar topography. The province is topographically low, ranging from 1 km above to over 1 km below the mean planetary radius. In the southwestern corner, the gentle rise in slope corresponds to the northern flanks of Beta Regio. The bright lines in Province IV occur in a variety of orientations and types: (1) Single, often arcuate lines – occur predominantly in the western region. Near the southwestern margin, the arcuate lines overlie the northern end of Beta Regio and Devana Chasma. We interpret the lines as fault-related zones of surface roughness associated with rifting in Beta Regio, identified in high resolution Arecibo images by Campbell *et al.* (1984). (2) Paired lines – occur in both IVa and IVb. Paired lines are generally closely spaced and range from straight to arcuate. The pairs are frequently, but not exclusively, associated with circular structures (for example, the paired lines at 50.5°N, 358°). (3) Line groups – occur in closely spaced groups or as arcuate segment groups, most common in IVb. The line groups appear as isolated, very bright groups, as diffuse bright areas, and as arcuate groups of lines (for example, the groups at 46.8°N, 1.5°; 50°N, 15.5°). We interpret the majority of the lines to be of tectonic origin, representing surface roughness associated with fault scarps and ridges.

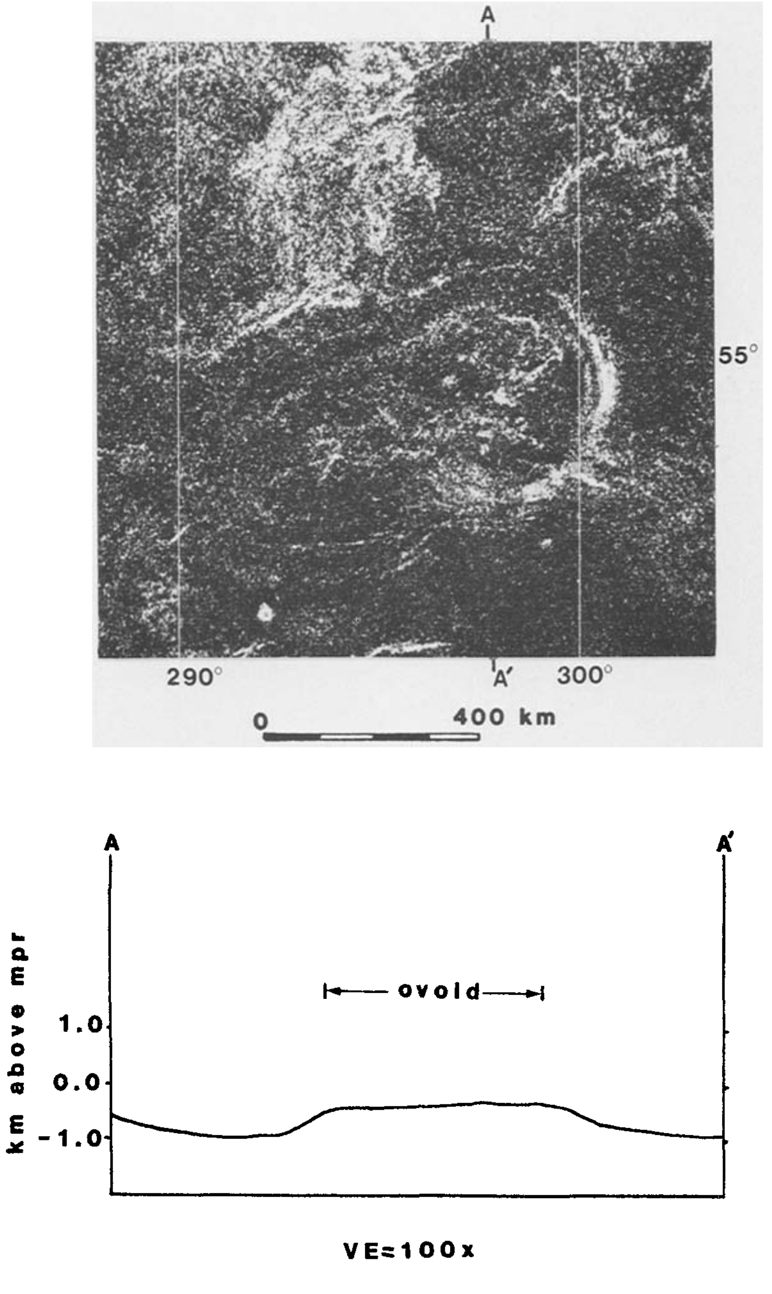


Fig. 7(a).

Fig. 7(a)–(c). Ovoid features. (a) Elongate oval structure from the center of Province IVa and topographic profile. The profile illustrates that the feature is a topographic high that appears to be more degraded to the west. (b) Cluster of ovoid structures from Province IVa. Some of the features appear to overlap, while others are linked. (c) Oval structure and ovoid remnants from IVb, Arecibo image and sketchmap.

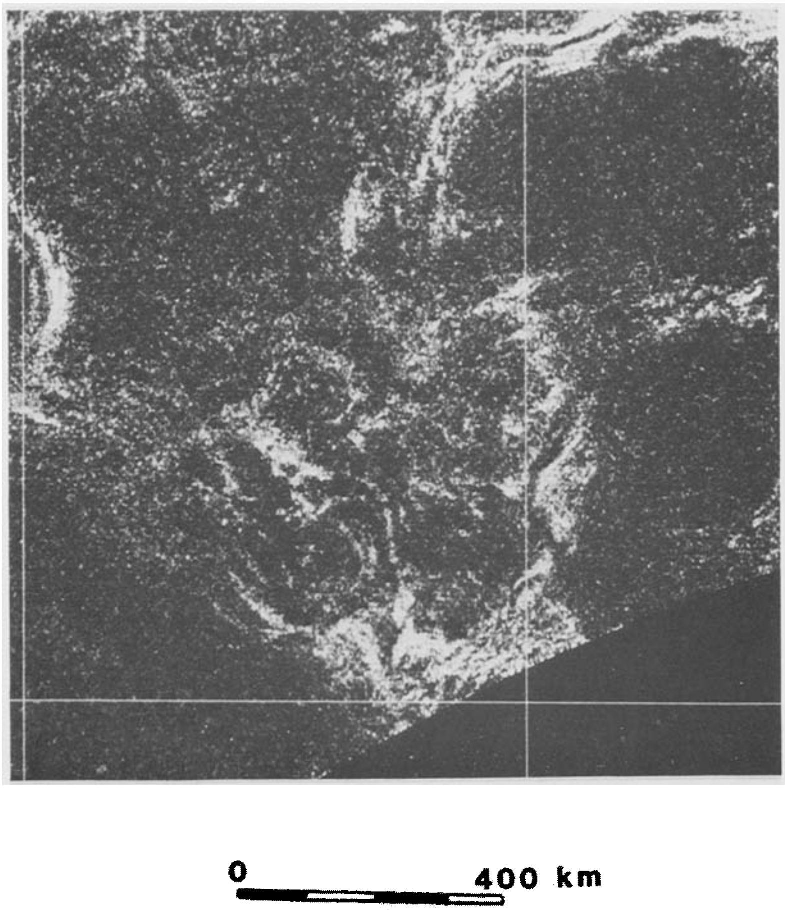
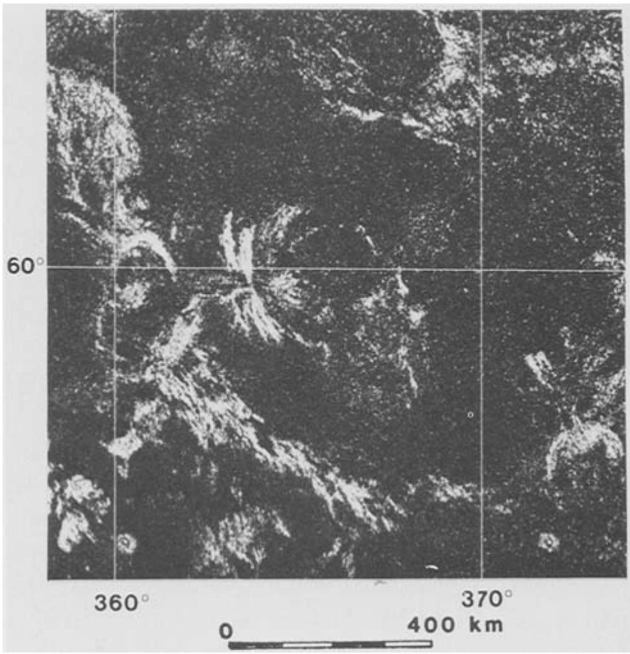


Fig. 7(b).

The province is also characterized by circular and oval structures that range in diameter from 60 to 300 km. They occur in IVa as isolated, generally circular features, elongate structures as can be seen in the center of the plains (Figure 5a, Figure 7a), and in clusters (Figure 7b). In general, the circular structures are topographically raised relative to the surrounding terrain, with contour lines parallel to their boundaries (Figure 7a, profile). Most of the structures have multiple concentric radar-bright rings arranged in an annulus (Figures 7a and 7b). Their interiors range from diffusely bright to dark with some bright interior structure discernible. The rims of the circular structures in IVa range from distinct, bright and continuous to discontinuous and faint, possible representing varying states of degradation and/or flooding by the plains-forming material. The elongate structure in Figure 7a has a less distinct radar signature to the west where it is also topographically lower, suggesting the possibility of flooding in that region. The



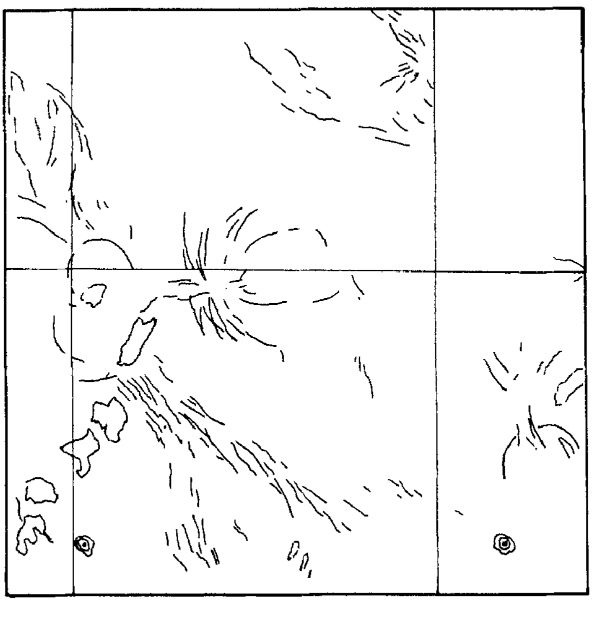


Fig. 7(c).

arcuate segment groups in the center of IVb resemble a group of multiple ring features of possible endogenic origin seen in the southern hemisphere of Venus in Themis Regio. The Themis multiple ring structures have been suggested to be of endogenic origin (e.g. igneous intrusion) because of their chain-like appearance, high topography, and close association with tectonic features (Stofan *et al.*, 1985a). The features in IVb range from circular, concentric ring structures to quasi-circular areas, connected by bright lines often in pairs. Diameters of these features range from 95 to over 200 km. The features in IVb have no resolvable topographic expression at Pioneer-Venus altimetry resolution and are not clearly visible in Venera 15 and 16 images (Barsukov *et al.*, 1986), suggesting that the radar brightness is caused by enhanced surface roughness. The darker interiors of the features in IVb may be a result of more extensive flooding. The easternmost feature, seen in Figure 7c, is characterized by multiple bright arcuate segments on its western side. This structure, as well as the other circular structures described above, resemble ovoids (quasi-circular structures characterized by concentric and radial systems of depressions and ridges) identified in Venera 15 and 16 data (Barsukov *et al.*, 1986). The multiple bright lines of the structure in Figure 7c probably correspond to the concentric ridges characteristic of ovoids. We have identified more ovoids than mapped by Barsukov *et al.* (1986) in this area, indicating that many of the features are defined by changes in roughness as well as topographic slope. Basilevsky *et al.* (1986) have interpreted ovoids to be related to hot spot activity and accompanying gravity tectonics.

Both IVa and IVb have scattered probable impact craters (Table I), with a somewhat higher density in IVb. Most of the craters are < 20 km in diameter. A crater interpreted to be of impact origin from the western boundary of IVb is seen in Figure 8. This feature has a highly circular center, a diameter of approximately 20 km, with a central bright spot possibly corresponding to a central peak. The bright deposit around the crater appears to exhibit approximate bilateral symmetry. In addition, the crater lies in the center of a dark circular area (about 250 km in diameter) that is not bilaterally symmetrical around the crater. Similar dark halos can be seen surrounding a few other probable impact craters in the province, but the halo effect has not been previously identified around Venus impact structures. The halo may have been produced by a seismic shaking effect causing settling and smoothing at centimeter scales, or by the settling out of fine ejecta particles perhaps entrained in the atmosphere.

Province IV has undergone volcanic and tectonic activity, both apparently occurring intermittently in space and time. Flooding has locally postdated formation of the ovoids or circular structures, while later tectonic activity, such as the faulting associated with northern Beta Regio, has postdated plains formation. The boundary of Province IV with Province II is abrupt, and is marked by bright lines trending parallel to the boundary. Between IVa and II, the boundary is highly linear and generally parallels topographic contours. Between IVb and II, the boundary tends to cut across topographic contours. The linearity and distinctness of the boundary

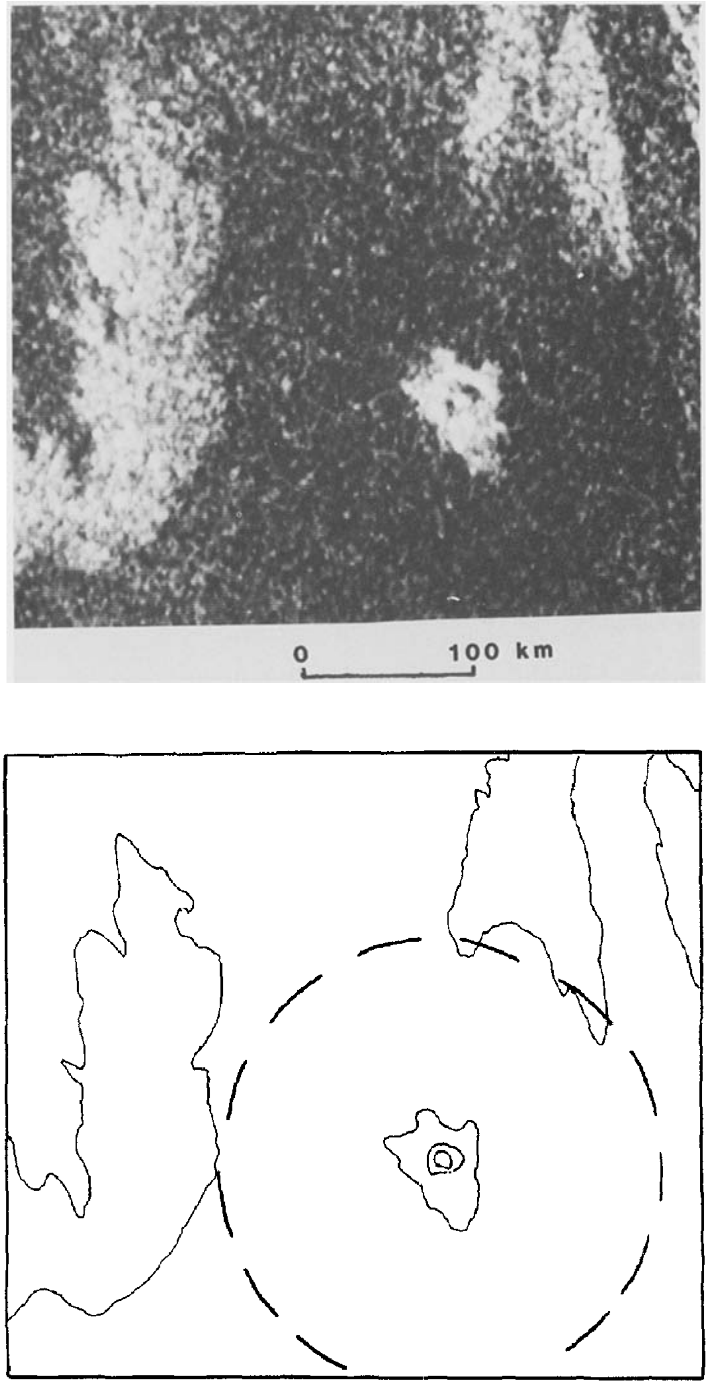


Fig. 8. Probable impact structure from Province IVb. Note the dark halo surrounding the crater, outlined in the sketchmap. Diameter of the dark interior of the crater is 20 km.

boundary, suggest that the major deformation surrounding Ishtar Terra has locally postdated Province IV plains activity. This is in contrast to some of the plains of Provinces I and III which embay the deformed areas indicating that deformation predated this plains activity.

3. Discussion and Conclusions

DEFINITION OF PROVINCES

Analysis of recent high resolution Arecibo images and comparison to Venera 15/16 data suggest that multiple volcanic and tectonic events have occurred in the mapped region. The distribution and extent of the geologic features (e.g., ovoids, flows, bands) have been used to define four distinctive provinces. We suggest that the four defined provinces represent differing styles, sequences, and proportions of tectonic and volcanic activity, rather than geologic provinces formed by distinct, discrete processes. These provinces provide a framework for understanding the characteristics of the lowlands, transition region, and highlands.

NATURE OF LOWLANDS

Guinevere and Sedna Planitiae, the lowland regions in this study, have surfaces that, on the basis of Pioneer-Venus data, are interpreted to be smooth to intermediate in roughness and dominated by rock materials (Pettengill *et al.*, 1980; Head *et al.*, 1985b). The lowlands in the southern Ishtar region are interpreted as volcanic plains, characterized by a complex history of deformation, ovoid formation, and volcanic flooding. No major sources for the flooding have been identified with the possible exception of abundant domes, some with apparent summit pits, seen in Venera 15/16 radar images of the plains (Barsukov *et al.*, 1986). Linear features in the plains are interpreted to represent both extensional and compressional deformation. The linear features extending to the north from Devana Chasma, seen in the southwest corner of Province IVa, provide evidence for extension (Campbell *et al.*, 1984), while the multiple ridges of the ovoid structures indicate another type of tectonic activity in the plains that may be related to vertical tectonics (Basilevsky *et al.*, 1986).

SOUTHERN ISHTAR TRANSITION ZONE

The transition zone between the highlands and the lowlands (predominantly Province II) is characterized by some of the steepest slopes on Venus (Sharpton and Head, 1985) and is dominated by radar-bright linear segments interpreted to be tectonic features, which form a very distinctive 250–500 km wide NW-trending tectonic zone. The Ut-Vesta region has rock-dominated reflectivity values with intermediate to high roughness (Head *et al.*, 1985b). Volcanic deposits also occur in the transition zone (Province II and III) but are subordinate to the predominantly tectonic nature of this zone.

Nature of highlands

The highlands in the mapped area are geologically complex, characterized by compressional deformation (bands) in the mountains, minor extensional features (graben in the southeast corner of Lakshmi Planum) and large areas dominated by volcanism. On Lakshmi Planum, volcanic plains appear to originate from low edifices on which are located large calderas, Colette and Sacajawea. This third type of volcanic structure observed in the southern Ishtar region, large low edifices, is associated with the highlands here, but edifices similar to these do occur in intermediate to low topographic regions on Venus (Stofan *et al.*, 1985b). The surface of the plateau has low roughness and is dominated by rock materials, while the banded terrain surrounding it is rougher, with some areas of soil and some of high dielectric materials (e.g., Akna, Maxwell) (Head *et al.*, 1985b).

Geologic processes

Volcanic activity is the most areally widespread process observed in the mapped region. Three different types of volcanic deposits and probable styles of volcanism are distinguished: (1) broad low volcanic edifices with large central calderas (Colette and Sacajawea) and surrounding plains characterizing Lakshmi Planum (Province I); (2) plains volcanism characterized by smaller, very low coalescing shields and associated flows, analogous to the plains volcanism of Greeley (1982) (Province III); (3) broad plains embaying older terrain, but with little evidence of individual flow features or source vents, occupying most of Guinevere and Sedna Planitiae (Province IV).

Stratigraphic evidence suggests that the distinctive lava flows of Province III seen in the Arecibo images are younger than the homogeneous broad plains of Province IV. A major unresolved question is whether these flows of Province III are distinctive because of differing primary flow characteristics and mode of emplacement, or whether they simply represent younger undegraded flows which will eventually be degraded and homogenized to resemble the Province IV plains. Related information is contained in the way in which the different volcanic units appear in the different illumination conditions of the two radar systems (individual flow units in Province III are distinguished in the Arecibo data but often not visible in the Venera data, while individual flow units are visible in Province I in the Venera data but not in the Arecibo data). Additional studies are underway to understand the implications of these different responses for flow unit physical properties and origin.

Tectonic activity is significant, variable in style, and highly localized. The predominantly compressional nature of the tectonics of Ishtar Terra (the mountainous region in particular) noted by previous authors is further supported by this study, although a local area of extensional features near Maxwell Montes is seen in the Venera and Arecibo data. This arcuate zone of graben-like features may be related to flexure associated with Maxwell Montes. Extensional deformation is also seen in the northern part of Beta Regio in the form of the northern section of the

Devana Chasma rift zone, as previously described (McGill *et al.*, 1981; Campbell *et al.*, 1984). Evidence of strike-slip faulting is difficult to establish. However, the abundance of linear features in Province II, combined with the great width and lateral extent of the province, suggest analogies to terrestrial shear zones and the possibility that strike-slip faulting has occurred. Ovoid structures (Barsukov *et al.*, 1986) are shown to be common in the lowland plains and the Arecibo data reveal numerous structures in addition to those mapped by the Venera data. This comparison, and the complementary aspect of the two radar viewing geometries, indicate that the Arecibo data may be utilized for mapping of ovoid distribution in the latitudes south of the Venera coverage. The areally most significant and least well understood tectonic region in the mapped area is the Southern Ishtar Transition Zone (the broad zone outlined by Province II), representing the steep-sloped transition from the lowlands to the highlands. On the basis of the Arecibo data, it is clear that this region is extensively deformed and that the deformation features generally parallel the edge of the highlands. Venera data show additional structural complexities in this region (Barsukov *et al.*, 1986; Basilevsky *et al.*, 1986) and there is local evidence for compression, extension, and strike-slip offset. Much more detailed examination of the combined Arecibo and Venera data sets is required to establish the nature of deformation in this zone, its distribution within the zone, and its significance for the origin and evolution of the Ishtar Terra plateau.

Impact craters are noted throughout the mapped area, and the Arecibo data reveal the presence of at least one example of a very broad radar-dark halo (smooth area) extending many crater radii from the crater rim. The origin of this feature is not known but it may be related to seismic smoothing associated with the impact event or with fine ejecta emplaced in the atmosphere and broadly dispersed.

SEQUENCE OF EVENTS

The number of impact craters in this region (average age about 0.5 to 1.0 billion years; Ivanov *et al.*, 1986) is insufficient to provide a statistically reliable discrimination of province ages. However, a general sequence of events can be defined for the region using cross-cutting, superposition, and embayment relationships. Province IV, the lowland plains, appear to represent the relatively oldest terrain. This is based on (1) multiple remnants of ovoid structures and the variable state of preservation of these features, which suggest that ovoids have formed and been modified by plains volcanism over extended periods of time, while the plains in other areas appear to be more homogeneous (Province I) or less complexly related to structural features (Province III), and (2) the distinctive linear boundary between Province IVa and II which suggests that the intense deformation associated with Province II deformed preexisting plains material of Province IV. The next youngest terrain appears to be the distinctive deformation zone (Province II) associated with the steep-sloped transitional zone between the lowlands and the

NW trending features in the NW part of Province II crosscut the NE trend of Akna Montes (Figure 3), suggesting either an age sequence or a major change in the style of deformation. The next youngest terrain appears to be the volcanic calderas and associated volcanic plains of Lakshmi Planum (Province I). These plains appear to flood and embay structural features in the plateau and to flow over portions of Vesta Rupes down the slope into Province II (Barsukov *et al.*, 1986). On the flanks of Akna and Freya Montes in areas outside of the part of Ishtar mapped here, there is evidence for the disruption of local areas of Lakshmi Planum by the mountain-forming deformational processes, suggesting that mountain formation and flooding partly overlap in time (Barsukov *et al.*, 1986). Province III, dominated by distinctive volcanic flows, is also younger than the tectonically disrupted transitional zone of Province II, on the basis of its clear embayment of structural elements and the abrupt termination of the major structural trends. The relative age of these latter two terrains is unknown. In summary, in contrast to the typical situation on the Moon, in this part of Venus the lowlands appear to be dominated by the oldest terrain and the highlands by some of the youngest terrain, with the heavily deformed transition zone of intermediate age.

Origin of the Highlands

At least four hypotheses have been put forht to account for the Ishtar Terra highlands: (1) that Lakshmi Planum is an uplifted plateau of lowland plains (Basilevsky *et al.*, 1982); (2) that Ishtar Terra is an ancient remnant of crustal material possibly formed by tectonic processes no longer active on Venus (Phillips *et al.*, 1981); (3) that Ishtar Terra is formed and dominated by 'hot spot' activity associated with Colette and Sacajawea, and tectonic activity is related to this (Basilevsky *et al.*, 1986; Pronin, personal communication), and (4) that Ishtar Terra is dominated by horizontal compressional deformation, crustal thickening, uplift, and that volcanic activity is associated with this (Campbell *et al.*, 1983; Crumpler *et al.*, 1986; Head, 1986). The relatively young age of the surface of Lakshmi Planum and the distinctive difference in detailed morphology and volcanic style between Lakshmi and the lowland plains argue against the first two hypotheses. Current observations in the mapped area support a strong link between the processes of tectonism and volcanism in the formation and evolution of the highlands, but do not provide evidence to distinguish between the latter two hypotheses. The centrally located calderas and deposits strongly suggest that major thermal anomalies play a role, but it is not clear whether they are a cause or a consequence of the deformation. A simple model of an extremely large volcanic construct (analogous to Olympus Mons on Mars, for example) which has undergone gravitational collapse and annular compressional deformation seems highly unlikely on the basis of the distinctly linear structural boundaries and the large elevations of the surrounding mountain ranges relative to the heights of the volcanic constructs themselves.

COMPARISON TO BETA REGIO HIGHLANDS

On the basis of these data and other studies previously discussed, we find that Ishtar Terra differs from Beta Regio in the following ways: Ishtar is a plateau surrounded by steep slopes while Beta is a broad rise (Sharpton and Head, 1985); Ishtar is surrounded by linear mountain belts while Beta has an apparent lack of linear mountain chains (McGill *et al.*, 1981; Campbell *et al.*, 1984); Beta is dominated by extensional features, with a median rift valley, while Ishtar is dominated by compressional features, as evidenced by the banded terrain (Campbell *et al.*, 1983; Solomon and Head, 1984), with little evidence for extensional deformation. The two highland regions are similar in that both are characterized by large-scale volcanic edifices. The Beta Regio volcanic structures, however, have a clear link with tectonic activity, while the Ishtar Terra features have a less apparent tectonic association. These significant differences between the two regions suggests that highlands on Venus do not necessarily have a unique single mode of origin.

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