THE GEOLOGY AND GEOMORPHOLOGY OF THE VENUS SURFACE AS REVEALED BY THE RADAR IMAGES OBTAINED BY VENERAS 15 AND 16

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A region-by-region condensed description of almost all of the area that was radar-photographed by Veneras 15 and 16 is presented. Using some generalizations, the diversity of terrain was reduced to a discrete set from which a geological-morphological map was constructed. The predominant type of terrain of the studied area is a plain that was tentatively subdivided into five morphological types: ridge-and-band, patchy rolling plain, dome-and-butte plain, smooth plain, and high smooth plain. Stratigraphically, the ridge-and-band plains are the oldest and the smooth plains are the youngest. The stratigraphic position of the other types is yet to be determined. Large sections of the plains show similarities to the mare-type basaltic plains of the moon, Mercury, and Mars. Other types of terrain are combinations of ridges and grooves in various patterns: linear parallel, orthogonal, diagonal or chevron-like, and chaotic. In some places the ridge-and-groove terrain is stratigraphically below the plain material, but in other places it appears to be plain material that has been subsequently deformed. Near the eastern and western boundaries of Ishtar Terra large (several hundred kilometers in diameter) ring-like features can be seen that are named coronae or ovoids. Evidence of tectonic deformation and the presence of flow-like patterns support their designation as volcano-tectonic features. Beta Regio seems to be an uplifted plain showing evidence of rifting and volcanism. All types of terrain are sparesely peppered with craters of obvious impact morphology. Their average density gives the plain an age range of 0,5 to 1×10^9 years. The fact that many impact craters are still in the pristine state indicates a very low rate of surface reworking, at least for the last 0,5 to 1×10^9 years. No evidence for water-erosion-sedimentation processes has been found. The tectonic activity of Venus has no equivalent on the moon, Mercury, or even Mars, and can be

compared only with that of the Earth. Intensive horizontal deformation, previously known only on Earth, occurs on Venus, but in a characteristic Venusian style.

Introduction

From October 1983 to July 1984, Veneras 15 and 16 surveyed the planet Venus from an elliptical near-polar orbit with an altitude of about 1000 km at the pericenter and about 65 000 km at the epicenter (Figure 1). The inclination of the orbit was 92,5°, the period of revolution over the planet was 24 h, and the latitude of the pericenter was 62° N. The survey was made alternatively by Venera 15 and 16 using side-looking radar of 8 cm wavelength. The electrical axis of the radar was at an angle of 10° from the local vertical and was usually toward the right in relation to the movement of the spaceprobe along the orbit. Surveying started when the spaceprobe, moving northward from the south, arrived at latitude 80° N, and continued through the polar area down to 30–35° N on the opposite side of the planet (Figure 2). The area covered by the images is about 115×10^6 km^2, or 25% of total Venus surface (Figure 2). Each period of observation produced an image covering a band of terrain 8000 km long and 120–160 km wide. The resolution of the images was 1–2 km if the reflected signal was computer-processed on Earth, and 3–4 km if the signal was processed only by the on-board computers and the images

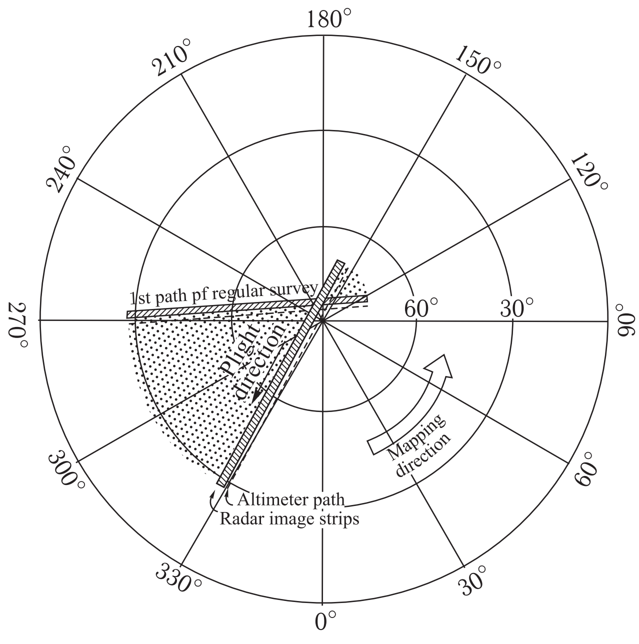

Fig. 1. Venera 15 and 16 coverage of Venus

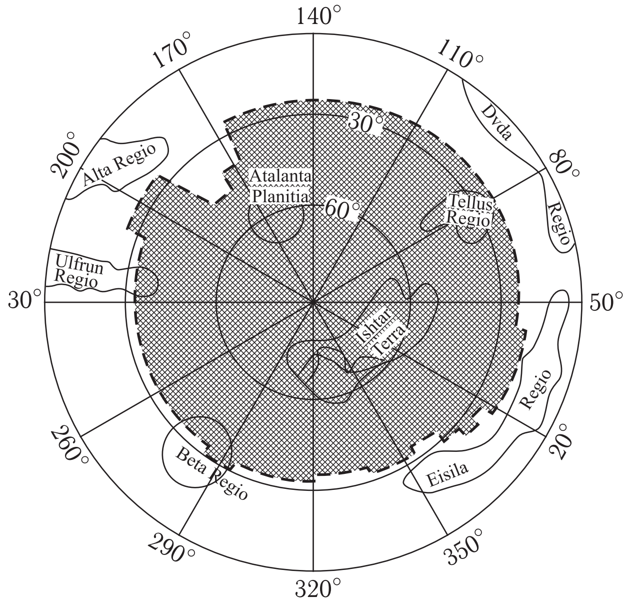

Fig. 2. Surface of Venus surveyed by Veneras 15 and 16.

were obtained in real time. The vertically-looking altimeter acquired data simultaneously with the side-looking radar with a precision of ±50 m. The diameter of the altimeter spot on the surface was 40–50 km; the rather large size of the spot precludes the obtaining of reliable information on the surface relief features less than 40–50 km wide. Sophisticated processing of the data has given a spatial resolution as small as 5 km along the orbit. However, at the time of preparation of this work, this new information is available only for part of the Montes Maxwell arc.

This paper describes the geographic distribution and geomorphology of the terrains, and discusses some geological interpretations for the area from 265° E to 0° E to 205° E. This area is about 90×10^6 km^2, or 20% of total Venus surface. Preliminary results for a smaller area have been given by *Barsukov et al.* [1984*a*,*b*]. Information for this paper was obtained in three different ways: (1) manually assembled photomosaics of 1–2 km resolution, covering almost all the areas of the survey; (2) computer-assembled mosaics of 3–4 km resolution for the north polar area and adjacent high latitude areas; and (3) computer-corrected mosaics of 1–2 km resolution for Montes Maxwell and the adjacent areas. The manually assembled photomosaics do not have a rigorous coordinate system, while the computer mosaics have a coordinate system and obey the appropriate cartographic projection. The altimetry data of Venera 15, 16, and Pioneer Venus Orbiter [*Pettengill et al.*, 1980; *Masursky et al.*, 1980; *U.S. Geological Survey*, 1981] were also used.

General Description of Venus Orography

The large-scale orographic features (Figure 3) show a distinct circumpolar latitudinal zonality. The northern polar region is a plain with an elevation close to the average elevation of planet (distance from the planetary center of mass 6051,5 km). The northern plain is bordered on the south by the Ishtar Terra highlands with the highest mountains on Venus, Montes Maxwell, and by the highlands or Metis Regio and Tethus Regio. This highland band is bordered by the deepest land on Venus, the lowlands of Atalanta Planitia. Therefore, this Ishtar-Thethus-Atalanta belt is a zone with the largest known elevation contrast on the planet. To the south another circumpolar band is located, composed predominantly of plains of elevation close to the average elevation. These plains are Guinevere Planitia, Sedna Planitia, Leda Planitia, and Niobe Planitia. In addition to plains, this band also contains some highlands: Beta Regio, Bell Regio, Tellus Regio, and part of Ulfrun Regio. These highlands are separated from the highlands of the above-mentioned northern highland band by lowland plains. Farther south a near equatorial zone is found that is not covered by the Venera 15 and 16 survey. Here we see the highlands of Aphrodite Terra and Phoebe Regio. The highlands of Alpha Regio may possibly be included here also. Farther south another band composed mainly of plains of average elevation is found. It includes Helen Planitia, Lavinia Planitia, Aino Planitia, among which we see the relatively low highlands of Themis Regio, Tefnut Mons, Hathor Mons, Indar Regio. Farther south is the relatively low Lada Terra, intruding into the high southern latitudes not covered by any radar surveying.

Synoptical Descriptions of the Surveyed Areas

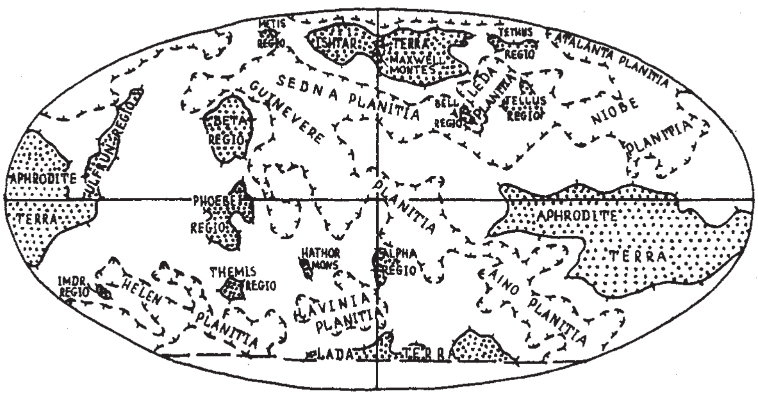

Fig. 3. Circumpolar sublatitudinal zonality of the large-scale orographic features

Northern Polar Region. This region, inaccessible to Earth-based radar studies and not covered by Pioneer Venus, is composed mainly of a plain with an elevation close to the average elevation of the planet. The surface of the plain is in many places complicated by subparallel linear ridges organized either in belts or in approximately equidimensional areas, by furrows, by clusters of small dome-like hills, and by craters (Figure 4).

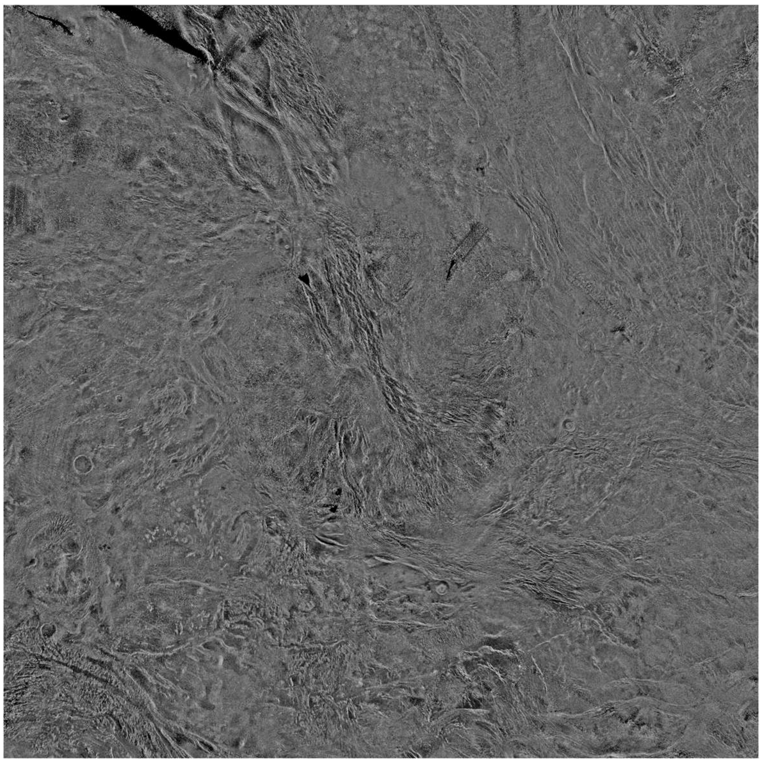

Fig. 4. North polar area. Concentric circles are latitudes 2° apart. Notice the plains, the ridges in belts and wide areas, and the furrows and craters

The ridge belts are several hundreds of kilometers long and tens of kilometers wide (Figure 5). In a few places the width is as much as 100–150 km. The belts are composed of systems of subparallel, conforming ridges up to 100–200 km in length and up to 10–15 km in width. The ridges are separated by grooves of the same size. The longest and most prominent belt extends from Ataianta Planitia to the polar region, following meridian 200° E. In the vicinity of the north pole the belt turns and goes south along meridian 80° E, where it abuts the Ishtar Terra highlands. The ridges of these belts resemble in morphology and pattern the wrinkle-ridges on the mare surfaces of the moon, Mercury, and Mars [see for example *Mutch*, 1970; *Strom et al.*, 1975; *Mutch et al.*, 1976]. In some places this pattern resembles the belts of furrowed terrain on Ganymede [see for example *Shoemaker et al.*, 1982].

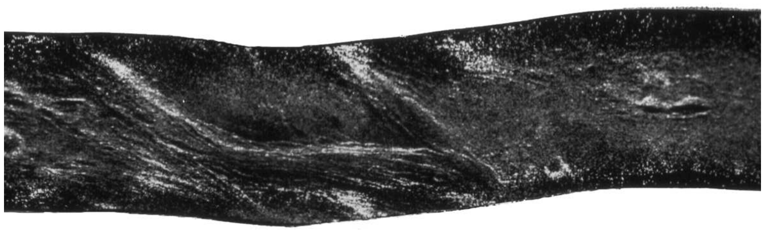

Fig. 5. First image obtained by Venera 15. Area covered is 150 km w 620 km. Notice the ridge belts and the plain and ridged furrows

Ridges that are organized upon wide areas rather than belts are especially characteristic of the area south of 85° N within the longitude range 80–120° E (Figure 6). Each ridge has a width of several kilometers and a length of several tens of kilometers to 100–200 km. The ridges are sufficiently distant from one another so that it is possible to see that the surface separating them is identical to the normal smooth surface of the plain. In many places the ridges longitudinally merge into bright narrow lines lacking the usual topographic illumination-shadow alternation. Because they are the obvious continuation of topographic structures, these narrow lines are likely to be caused by topographic ridges smaller than the resolution of the picture rather than by changes in radar albedo.

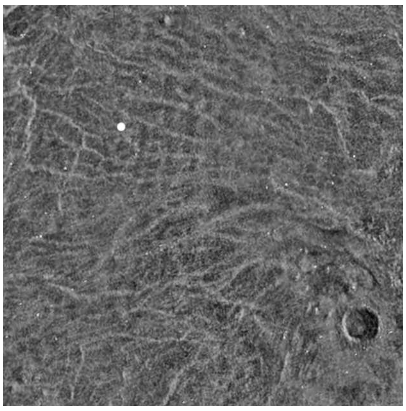

Fig. 6. Wide-area ridges. Center at 77° N, 120° E, area 360 km w 360 km. Ridges cover a plain

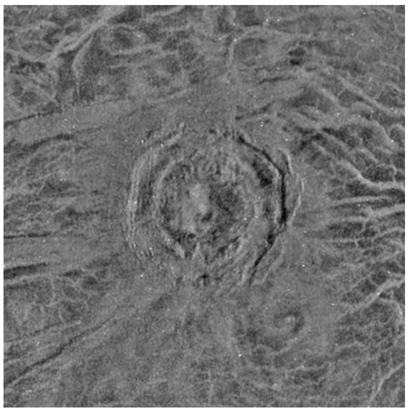

Fig. 7. One of the largest craters. Center at 77° N, 103° E, area 360 km w 360 km. Notice the crater is multi-ringed

Furrows on the polar plain are generally straight, and are slightly sinuous in a few places. In some places they have sharp edges, in other places they are subdued. The length of the furrows can be as much as 100 km with the width up to 10–20 km. Some of these furrows are similar to the furrows on the maria of the moon and on the mare-like plains of Mercury and Mars, but some differ in having raised rims (Figure 5).

The dome-like hills have circular to elliptical planimetric outlines. They have a diameter from the resolution limit of the images (1–2 km) up to 10–15 km. In some cases a summit crater can be seen. The dome-like hills are widely distributed and some form clusters. In morphology they are similar to volcanic domes or cinder cones of Mars and Earth.

Craters not spatially associated with the domes are very similar in morphology to impact craters of other planetary bodies [see also *Ivanov et al.*, 1986]. Most are flat-bottomed with central peaks and prominent surrounding rims. Most of the smaller ones are bowl-shaped. The largest crater of the region and one of the largest anywhere on Venus is situated near Tethus Regio and has a diameter of 140 km. It is very similar in morphology to the two- and three-ring impact basins of the moon, Mercury, and Mars (Figure 7). The morphology of the craters ranges from prominently fresh to highly subdued and deformed. On the whole, the plain of the Northern polar region is similar to the lunar maria and mare-type plains of Mercury and Mars.

Ishtar Terra. The western part of Ishtar Terra is Lakshmi Planum and its mountainous surroundings (Figure 8). Lakshmi Planum is a plateau with an elevation of 6053,5–6055,5 km, which is 3–5 km higher than adjacent Sedna Planitia. Most of the plateau surface is very smooth. Only in a few places can one see areas slightly elevated above the plateau and with the surface cut by systems of grooves with orthogonal or diagonal pattern with a groove-to-groove wavelength of generally no more than 10 km. On the Lakshmi Planum there are two elliptical flat-bottomed depressions: Colette (80 × 120 km) and Sacajawea (140 × 280 km). The first is morphologically more prominent than the second. Colette lacks the prominent and rather narrow rim typical of impact craters. According to the contour lines it is located on the summit of a very gently sloping dome. Colette is bordered by a ring-like system of grooves and narrow ridges resembling some Martian calderas, such as the summit caldera of Arsia Mons [*Mutch et al.*, 1976]. Around Colette one can see a radial system of slightly sinuous radar-bright bands up to 100–300 km in length and 10–20 km in width. Colette is most likely a volcanic caldera having a radial system of lava flows. Sacajawea is probably an older volcanic caldera. On the whole, the smooth surface of Lakshmi Planum seems to have been formed by effusions of low-viscosity lavas and the orthogonal and diagonally grooved areas appear to be remnants of technically disturbed older terrain. On the surface of Lakshmi Planum several craters 4–20 km

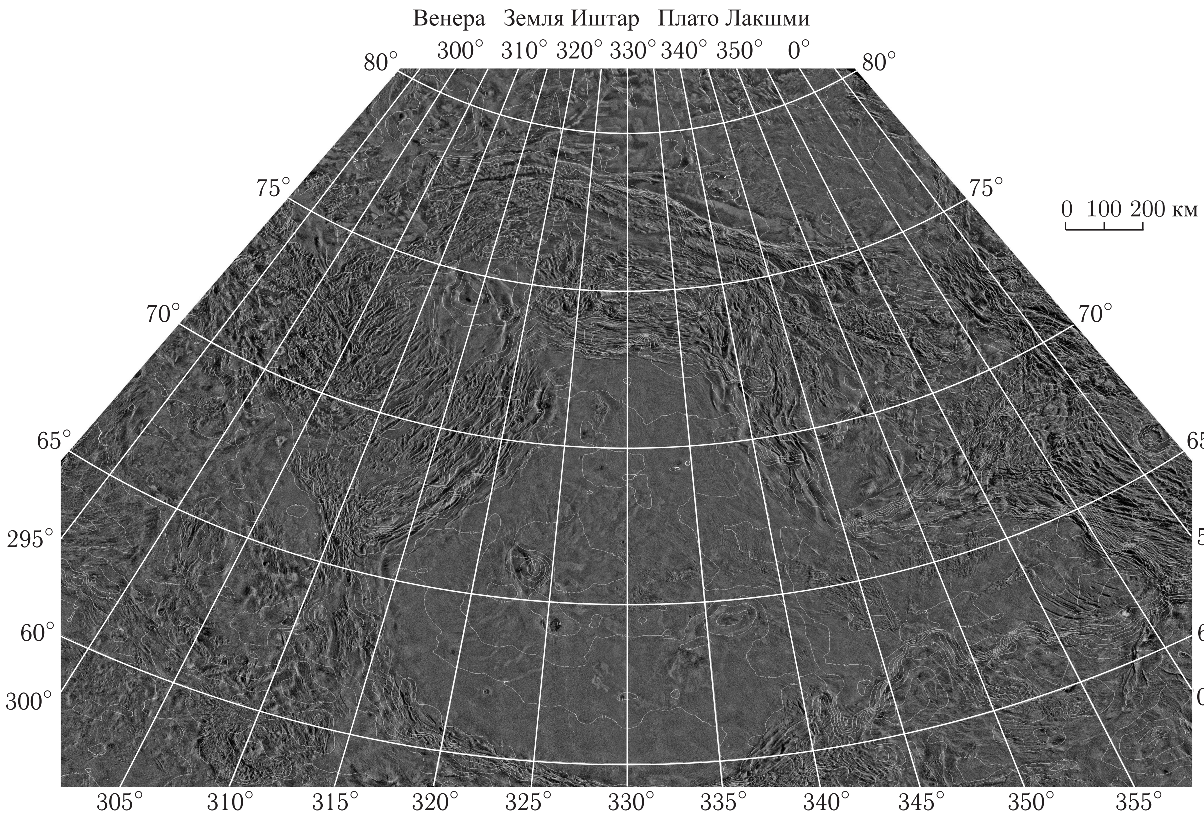

Fig. 8. Lakshmi Planum computer mosaic with coordinate grid. Notice the plateau surrounded by mountains and the two calderas, Colette and Sacajawea

in diameter are observed; in morphology they are similar to the impact craters of other planetary bodies.

Lakshmi Planum is nearly surrounded by zones of subparallel linear ridges and grooves conforming with the borders of Lakshmi: Akna Mountains to the west, Freyja Mountains to the north (Figure 9), Maxwell Mountains to the east (Figure 10), and a narrow belt of ridges between the plateau surface Pand Vesta Rupes (Figure 11) to the south. The Akna, Freyja, and Maxwell Mountains are the highest on Venus — 8, 9, and 12 km, respectively — over the 6051 km datum. Near the plateau, the surrounding ridges are linear or slightly sinuous and have a length up to 300–500 km and a width up to 15–30 km. The total length of each system is 800–1200 km. In a stereoscopic view these ridge-and-groove systems resemble stacks of inclined plates. They could be either imbricated reverse faults or folds, in either case the product of compression [*Basilevsky et al.*, 1986].

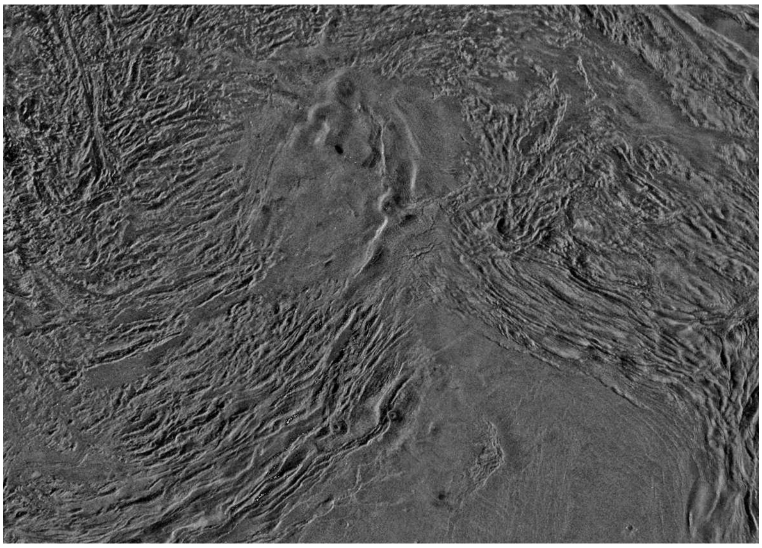

Fig. 9. The northern boundary of Lakshmi Planum and Freyja Montes. Center at 72° N, 320° E, area 880 w 1140 km. Notice the ridge-and-groove pattern bordering the plains

On the border between the plateau and the Maxwell, Akna, and Freyja Mountains a transitional zone is evident, with slight to moderate ridges on the plateau side to prominent ridges on the mountain side. This may indicate that the ridges formed at the expense of the plain-forming material. The opposite is indicated in some places as in the contact zone between Akna and Freyja Montes, for example, where it is possible to see

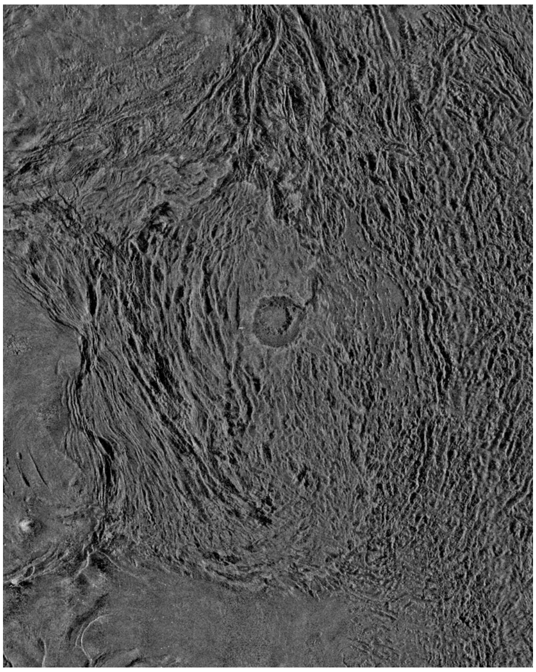

Fig. 10. Maxwell Montes and Cleopatra Patera. Center at 65° N, 77° E, area 1000 w 1150 km. Notice the ridge-and-groove pattern and the crater

plain-forming material flooding the end of the ridge system and embaying it (Figure 9).

Away from the plateau, the ridge-and-groove system of Akna, Freyja, and Maxwell Montes is cut by another set of grooves and by lineations caused by slight displacements of the major set of ridges and grooves. This change correlates with a decrease in elevation from 6057,5–6062 to 6053,5–6050,5 km.

In the Maxwell Montes between the zone of subparallel ridges and grooves and the ridge-and-groove system cut by other lineations, we find the Patera Cleopatra depression (Figure 12). It is a double-ring basin with an outer ring about 100 km in diameter and an inner ring (displaced NNW of the center) about 50 km in diameter. The depth of the outer ring floor is 1–1,5 km. The bottom of the inner crater is 1–1,3 km deeper. The inner ring is very prominent in the SE part of the crater and subdued in the NW part. The outer rim of the crater is only slightly higher than the surrounding terrain. North and east of the crater the ridges of Maxwell Mountains are partly buried by some plain-forming material. Patera Cleopatra is evidently superimposed upon the Maxwell Montes structure.

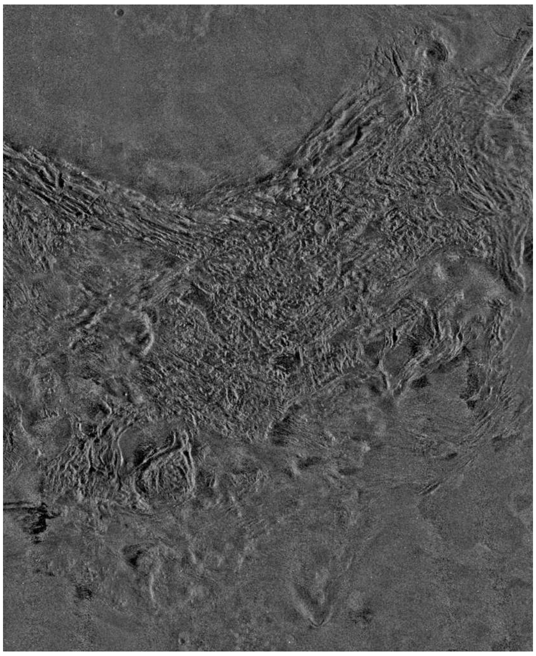

Fig. 11. Southern border of Lakshmi Planum and Vesta Rupes. Center at 60° N, 337° E, area 820 w 1140 km. Notice the boundaries between the Planum and the complicated ridge-and-groove pattern of the Rupes

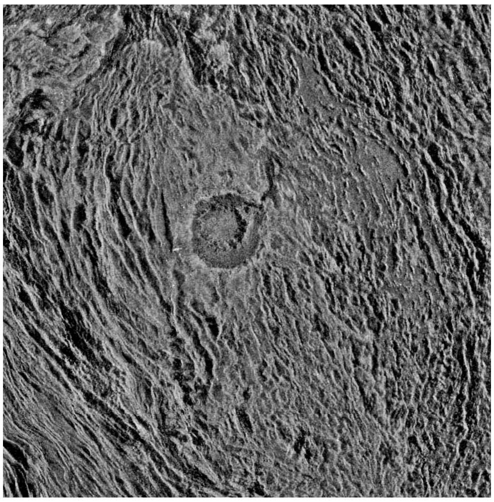

Fig. 12. Patera Cleopatra. Center at 65° N, 78° E. Area 660 w 740 km. Notice the inner rim, the smoothed zone around the crater and the ridge-and-groove pattern

The origin of Patera Cleopatra is subject to debate. An endogenic origin is suggested by an overall curving of the ridges and grooves around the locus of the crater, which indicates a possible relationship between the two. If this is the case, the plain-forming material near the crater could be lavas or pyroclastics. On the other hand, an impact origin is suggested by the general morphology of the crater, which is typical of double-ring impact basins and is not typical of the known volcanic structures of Mars, Earth, or Io. If Patera Cleopatra is an impact crater, then the plain-forming material is the ejecta blanket [see for example *Mutch et al.*, 1976; *Green and Short*, 1971; *Schaber*, 1982].

Several other craters are superimposed on the mountains bordering Lakshmi Planum. They have typical impact-crater morphology, i. e., they are flat-bottomed with a central peak. A radar-bright halo, probably the ejecta, is present around the freshest-looking craters.

South of Lakshmi Planum a system of linear ridges parallel to the plateau borders changes abruptly in to a highly dissected terrain dominated by short (several tens of kilometers) intersecting ridges and grooves and forming diagonal and chaotic patterns (see Figure 11). This terrain occurs between the Vesta Rupes and Ut Rupes. To the south this terrain becomes the Sedna Planitia. In a few places one can observe the plain-forming material superimposed on the terrain with the diagonal and chaotic structural patterns.

East of Maxwell Mountains within the longitude range of 25° to 80° E in the northern part of Ishtar Terra, the terrain is characterized by intersecting ridges and grooves with diagonal or chevron-like patterns and sometimes with ring-like or loop-like patterns (Figure 13). This terrain forms an E-W oriented band approximately 800×2500 km. The terrain immediately east of Patera Cleopatra merges into the zone of diagonal patterns of ridges and grooves rather gradually, although within a narrow (100–200 km) area. Within this transition the elevation of the terrain decreases from 6060,5–6061,5 to 6054,5–6055,5 km. Long undisturbed ridges or grooves are rare here. Ridges and grooves of NE orientation are combined with ridges and grooves of NW orientation. In some cases the NE lineations off-set the NW lineations and in other cases the situation is reversed. Such a variable character of intersections is characteristic of conjugated faults [*Basilevsky et al.*, 1986].

As the northern boundary of this terrain of diagonal systems of ridges and grooves is approached, one set gradually becomes predominant. It has a NW orientation and is roughly parallel to the boundary. At the boundary proper, embayments of the plain-forming material are visible.

Approaching the southern boundary of this are within the longitude range 50–75° E the ridge-and-groove system becomes finer until the ridge-and-groove terrain merges into a plain (Figure 14). The origin of this relationship is being debated. It could mean that the ridge-and-groove terrain is derived from a more ancient plain. On the other hand, the ridge-and-groove pattern may have become finer at the boundary with

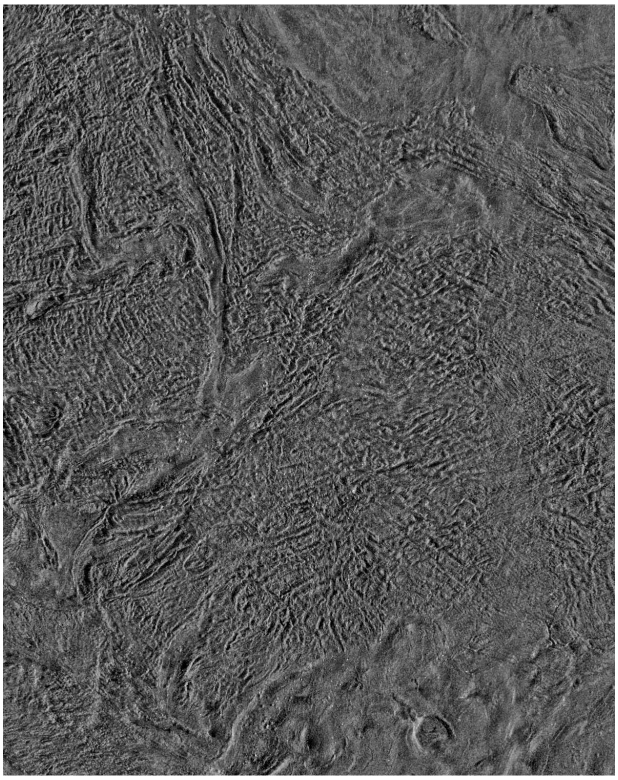

Fig. 13. Diagonal ridge-and-groove pattern east of Maxwell Montes. Center at 70° N, 45° E, area 1100 w 1180 km. Notice the chevron-like pattern

the plain as a result of thermal shrinkage of the plain-forming material overlying the ridge-and-groove terrain. The plain itself displays a system of linear ridges and fine radar-bright lines that make it similar to the northern polar plain. Indistinct circular features that are several tens of kilometers in diameter can also be seen.

Returning to the terrain of diagonal ridges and grooves, along the southern boundary within the longitudinal range 30° to 40° E, an east-west oriented bulge of the terrain with an altitude level 6055–6056 km occurs. The surface here is complicated by numerous ridges and wrinkles, often with a predominance of diagonal structural patterns. A few patches of plain with a system of parallel and intersecting ridges and radar bright bands are also associated with this terrain.

Farther to the south and southwest at an elevation of 6052–6054 km a terrain with characteristic orthogonal structural pattern occurs (Figure 15). Long valleys extend as much as several hundreds of kilometers and have remarkably constant widths of several to 30 km each. The valleys

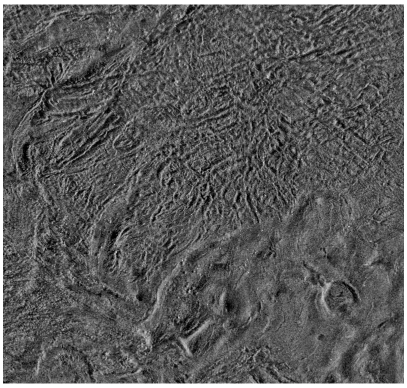

Fig. 14. Transition between diagonal ridge-and-groove pattern and the plain. Center at 67° N, 46° E, area 640 w 720 km. On the eastern part of the transition, notice how the ridge-and-groove system becomes finer

divide the region into several zones. In each of these zones the surface is cut by smaller grooves generally orthogonal to the valleys. In some places these grooves have the shape of an elongated «S», suggesting lateral displacement along the valleys (Figure 16). Several elliptical crater-like flat-bottomed depressions, closed at the north, west, and south sides but open to the east, follow the overall trend of the valleys. Most of the orthogonal grooves are open and suggest tectonic expansion (perhaps differential), causing lateral displacements or shears in latitudinal direction.

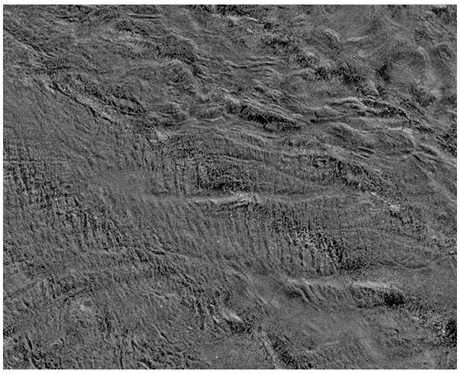

Fig. 15. Orthogonal ridge-and-groove pattern. Center at 52° N, 55° E, area 480 w 600 km. Notice the long valleys and the orthogonal grooves

On the southeast boundary of this terrain the features become finer and perhaps change from open fractures to reverse faults. If this is true, a change from extension to compression may have occurred. On the

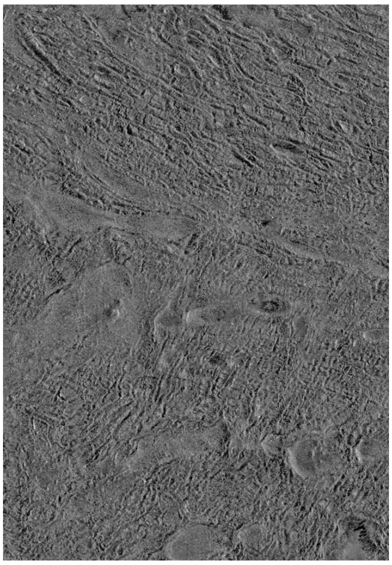

Fig. 16. Ridge-and-groove pattern. Center at 53° N, 42° E, area 850 w 520 km. Notice in the upper right corner, elongated S-shaped grooves suggest horizontal displacements. Also notice the flat-bottomed depressions

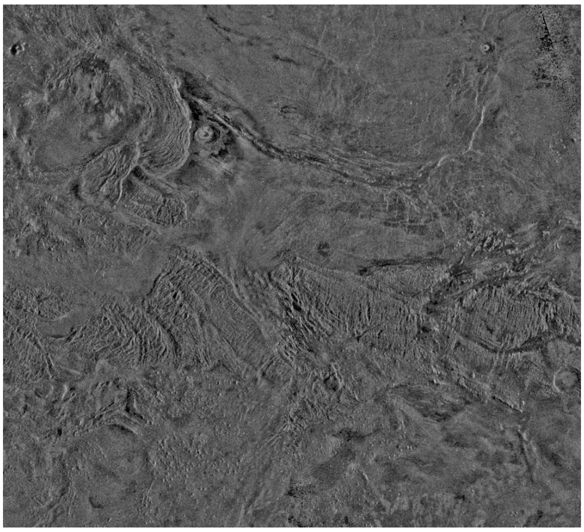

Fig. 17. Orthogonal ridge-and-groove pattern of uplands of Tethus Regio. Center at 68° N, 115° E, area 960 w 1400 km. Notice how the long valleys divide the land into bands

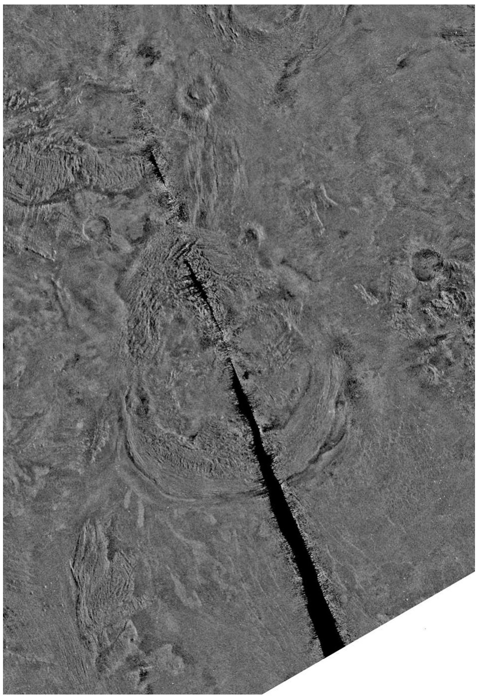

Fig. 18. Corona or ovoid. Center at 61° N, 131° E, area 800 w 1340 km. Notice the ring-like structure and the flow-like patterns on the outside

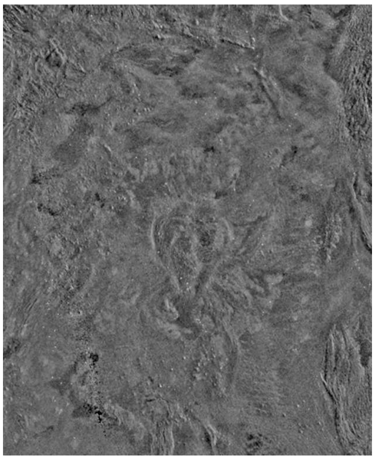

Fig. 19. Postulated shield volcano in Tethus Regio. Center at 63° N, 120° E, area 560 w 740 km. Interpretation of this feature needs the elevation data given in text. Notice the two crater-like depressions and the flow-like bands

southern boundary the overall regularity is lost, the grooves become sinuous, and the pattern becomes diagonal-chaotic (Figure 16).

Tethus Regio. East of Ishtar Terra we find Tethus Regio, an area predominantly composed of a plain, with several isolated uplands (elevation of 6052,5–6054,0 km over the planetary mass center, 0,5–1,0 km above the plain), distributed sublatitudinally. The terrain of these uplands is similar to that of the southern part of Ishtar Terra; i. e., an orthogonal pattern of valleys and grooves (Figure 17). The long valleys divide the area into bands having an east-west or northwest-southeast elongation, cut by the orthogonal grooves.

The plain is in many places covered with dome-like hills, often grouped in clusters. Several large (300–500 km in diameter) ring-like structures are visible (Figure 18). These structures are outlined by concentric

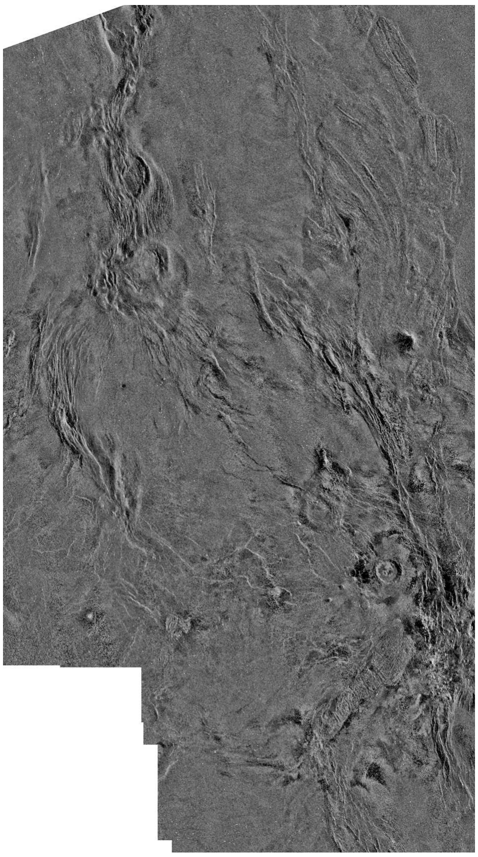

Fig. 20. Portion of Atalanta Planitia. Center at 50° N, 200° E. 1600 km from top to bottom. Notice the ridge belt

systems of ridges having roughly an elliptical form. We have named these features ovoids or coronae. The concentric systems of ridges are higher than the surrounding terrain, while the intraring part of each corona is lower than the ridge system but higher than the adjacent plain. Around the outer limit of the coronae a system of radar-bright flow-like marks is visible; they are possibly flows of volcanic lavas.

At the southern part of Tethus Regio a gently sloping mountain is located with a diameter of about 150 km and with the summit about 1–1,5 km higher than the adjacent plain (Figure 19). At the summit two roughly circular crater-like depressions are. visible. On the slopes a subradial system of radar-bright flow-like bands occurs. This mountain is likely to be a large shield volcano. Within the Tethus Regio several craters having typical impact morphology are also present.

Atalanta Planitia. East of Tethus Regio is Atalanta Planitia, the deepest regional depression on Venus. Elevation at the central part of Atalanta is 6049–6050 km, 6050–6051 km at the periphery. The largest part of Atalanta Planitia is a relatively smooth plain with an even distribution of radar-bright areas (Figures 20–22). It is crossed by ridge belts similar to the ridge belts of the northern polar plain, and together they form a single system. In the western part of Atalanta, adjacent to Tethus Regio, the surface is different. The plain here is complicated by a network of narrow ridges, radar-bright bands, and clusters of dome-like

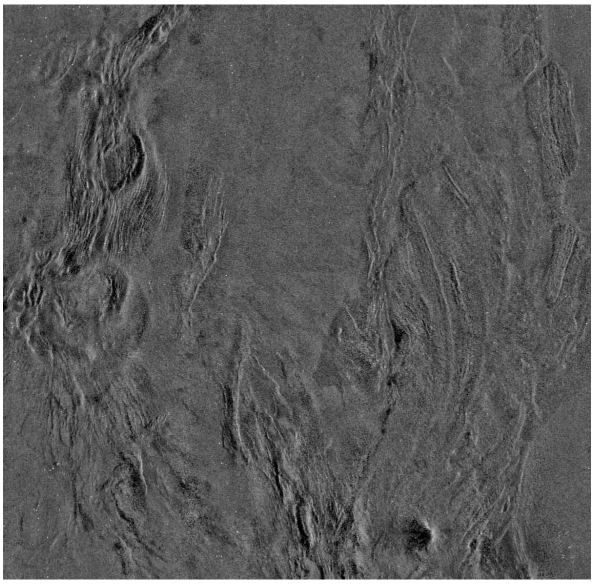

Fig. 21. Part of Atalanta Planitia. Center at 55° N, 195° E, area 800 w 880 km. Notice the ridge-and-groove pattern and the plain

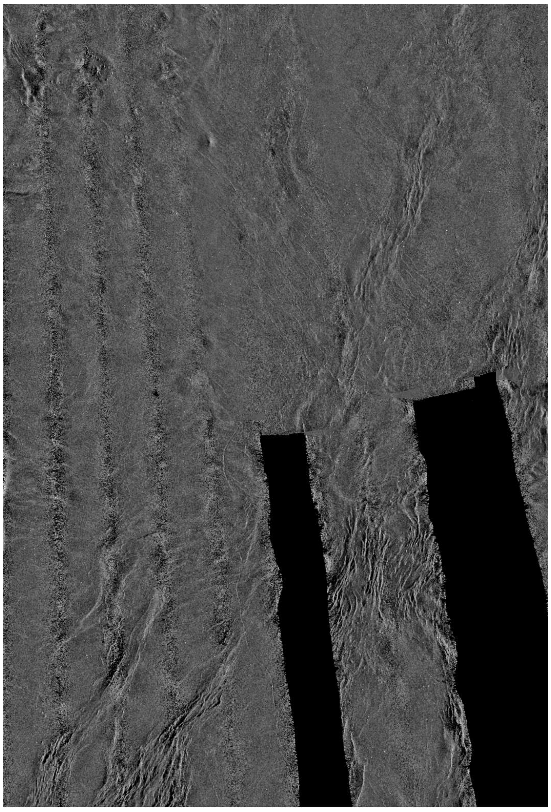

Fig. 22. Part of Atalanta Planitia. Center at 40° N, 152° E, area 1120 w 1660 km. Notice the ridge belts. The alternating light and dark patterns on each swath of the mosaic are an artifact

hills (Figure 23). Within the Atalanta Planitia, especially in its western part, there are several craters similar in morphology to impact craters on other planetary bodies.

Mnemosyne Regio. West of Ishtar Terra is Mnemosyne Regio, an area characterized by several large (200–500 km in diameter) ring-like structures — ovoids (coronae) — already described above for Tethus Regio (Figures 24, 25). They are quite varied in, morphology. As in Tethus Regio, their common characteristic is the presence at their periphery of roughly concentric systems of ridges. Also as in Tethus Regio radar-bright flow-like features are associated with the coronae. They are usually located outside the structure but sometimes they overlap them. Areas outside the coronae consist of plains with elevations 6051–6052,5 km. In some places these areas are variegated because of the mentioned flow-like features, while in other places they are uniform. In places, the plains are disturbed

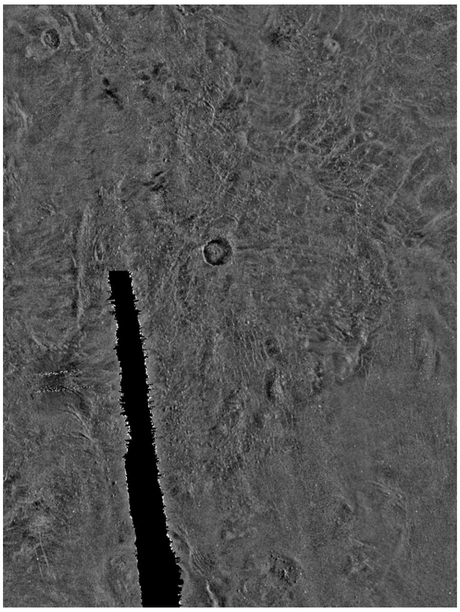

Fig. 23. Western part of Atalanta Planitia. Center at 60° N, 157° E, area 960 w 1360 km. Notice the network of narrow ridges, radar-bright bands, and clusters of dome-like hills, and the crater

by systems of narrow ridges and radar-bright bands, and dome-like hills similar to those described for the northern polar area and Tethus Regio.

Guinevere Planitia. This region is located between Mnemosyne Regio and Beta Regio and has an elevation of 6050–6051 km. Only the northern part is within the area mapped by Veneras 15 and 16. This plain is mainly characterized by a smooth surface complicated in some places by narrow ridges, clusters of small domes, and craters having typical impact morphology. Here two large elliptical structures (250 × 300 km and 400 × × 600 km) are visible (Figures 26 and 27). They probably are coronae considerably overlapped by plain-forming material. At the northwestern part of the Guinevere Planitia there is a circular flat-summit upland, 80 × 100 km in size, around which a ring-like zone with a radial system of radar-bright flow-like features is located (Figure 28). This formation may be a volcanic construction. At the southern part of the mapped zone of Guinevere Planitia is a patch of terrain with a chaotic system of ridges and grooves resembling the terrain located southwest of the zone of orthogonal ridges and grooves at the southern part of Ishtar Terra.

Beta Regio. In the southern portion of the area of Guinevere Planitia surveyed by Veneras 15 and 16 a part of Beta Regio upland is visible (Figure 29). The transition from Guinevere Planitia to Beta Regio is

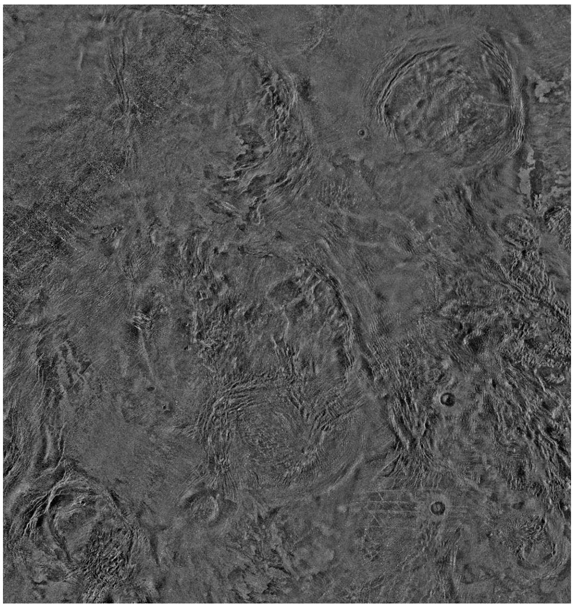

Fig. 24. Coronae in Mnemosyne Regio. Center at 70° N, 273° E, area 1400 w 1480 km. Notice the large ring-like structures and smaller vague circular features

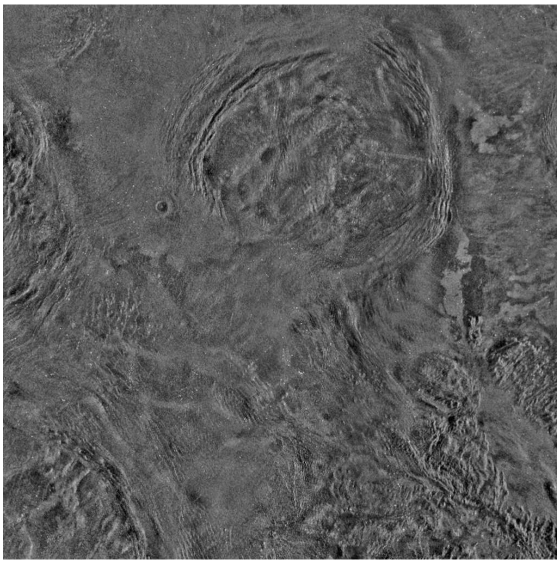

Fig. 25. Detail of Figure 24. Center at 75° N, 272° E, area 780 w 780 km

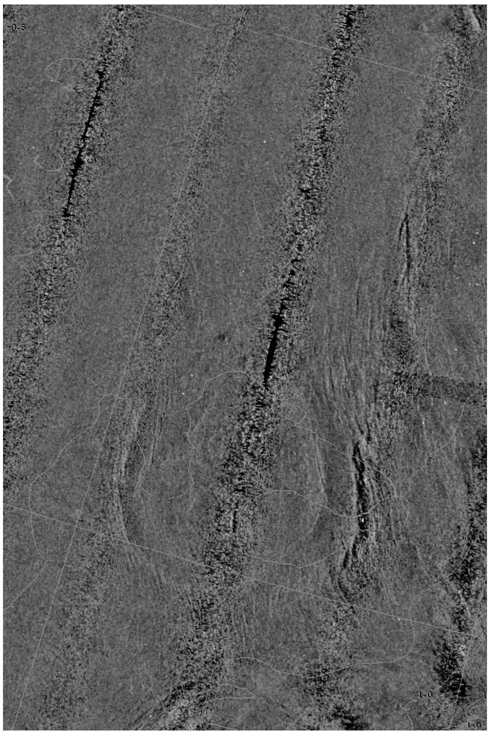

Fig. 26. Elliptical structure in Guinevere Planitia. Center at 43° N, 270° E, area 500 w 700 km

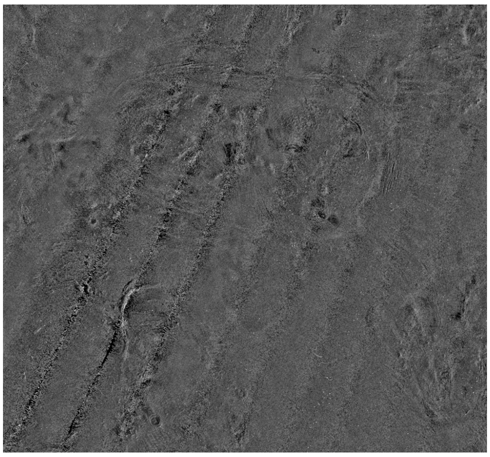

Fig. 27. Elliptical structure in Guinevere Planitia. Center at 54° N, 297° E, area 960 w 1080 km

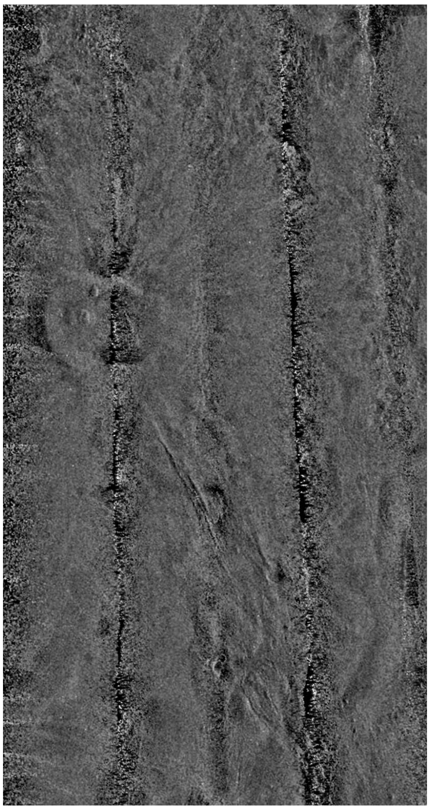

Fig. 28. Circular feature in Guinevere Planitia. Center at 52° N, 264° E, area 400 w 800 km. Notice the radar-bright radial patterns

gradual. Within the longitude range 270–300° E and latitude range 34–38° N we see an increase in elevation and the appearance of submeridional, linear, sometimes arcuate scarps up to hundreds of kilometers in length and 5–10 km in width. The scarps join each other in places, forming graben-like depressions. The southern part of Beta Regio, outside the area surveyed by Veneras 15 and 16, has been studied by *Saunders and Malin* [1977], *Campbell et al.* [1984], and others, and has been interpreted to be a submeridional summit rift zone with associated volcanic manifestations. The above-mentioned system of scarps appears to be the continuation of the postulated rift zone.

In the northeast boundary of Beta Regio we see domes, short ridges, and indistinct ring-like features (Figure 30). Venera 9 landed in this area and determined the basaltic composition of the surface material by gamma-spectroscopy [*Surkov et al.*, 1977].

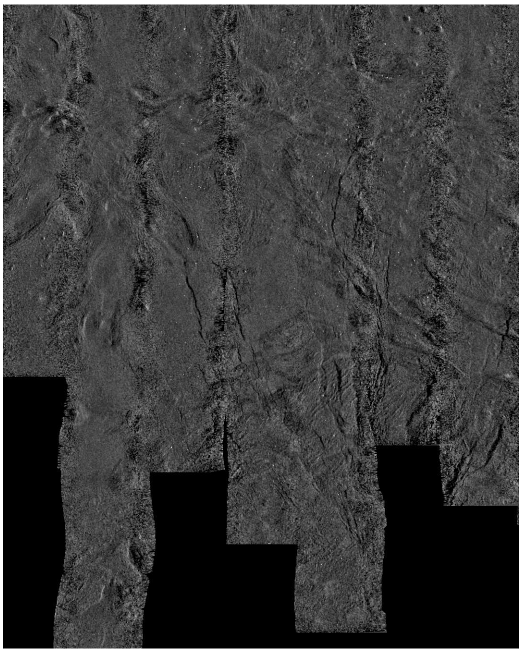

Fig. 29. Part of Beta Regio. Center at 38° N, 280° E, area 760 w 1140 km. Notice the scarps, graben-like depressions, and vague circular features

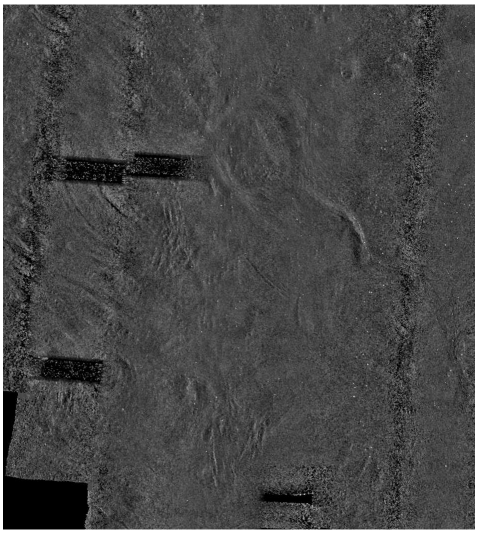

Fig. 30. Domes, short ridges, and unclear ring-like features at the NE boundary of Beta Regio

Sedna Planitia. This plain is similar in morphology and elevation to Guinevere Planitia. A smooth plain predominates, in some places complicated by ridges, domes, and impact craters, and in a few places patches of the terrain have the ridge-and-groove pattern resembling that of the southern part of Ishtar Terra (Figure 31). In the northern part of Sedna Planitia near the border, with Lakshmi Planum to the south, numerous and sometimes large radar-bright and radar-dark streaks and patches are visible (Figure 32). These streaks and patches are associated with long prominent lineaments of northeast orientation located approximately 1200 km south of the eastern part of Lakshmi Planum, suggesting that these features are lava flows. In the southwestern part of Sedna Planitia a system of narrow subparallel (and at some places intersecting) ridges are visible that resemble the wrinkle-ridges of the lunar maria.

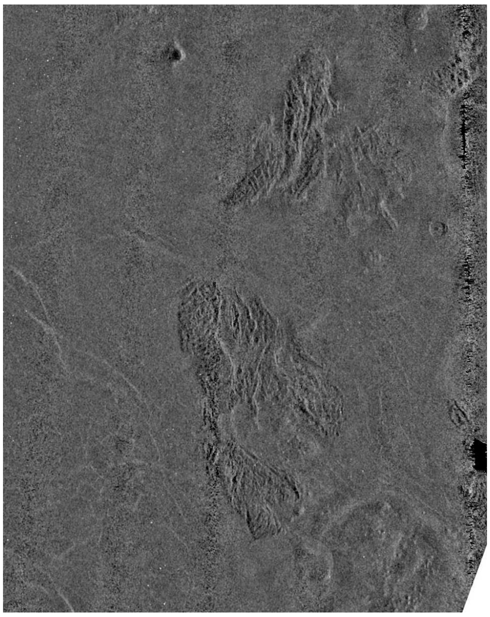

Fig. 31. Patches of ridge-and-groove terrain in Sedna Platinia. Center at 43° N, 357° E, area 640 w 820 km

The Area Between Sedna Planitia and Bell Regio. A characteristic plain can be seen here, with an elevation of 6050,5–6051,0 km. Especially in the eastern portion, the plain is complicated by numerous ring-like features with diameters of 50–120 km (Figure 33). The features are outlined by ridges or radar-albedo bands. In places the ridges are big (100–200 km in length, 10–20 km in width) and form the radial and concentric patterns of the ring-like features. In a few places the ridges are gathered in braids and belts that merge with the radial and concentric

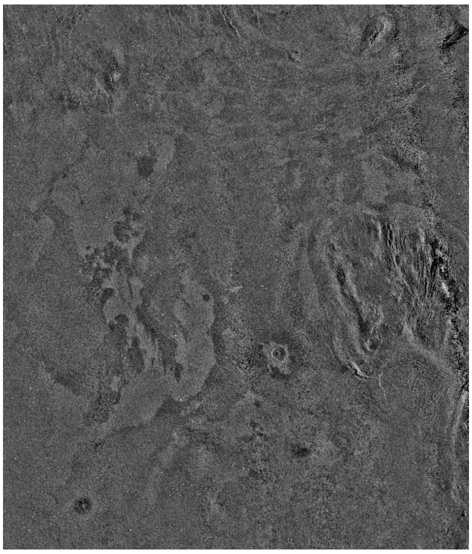

Fig. 32. Flow-like patterns on Sedna Platinia. Center at 52° N, 355° E, area 760 w 980 km

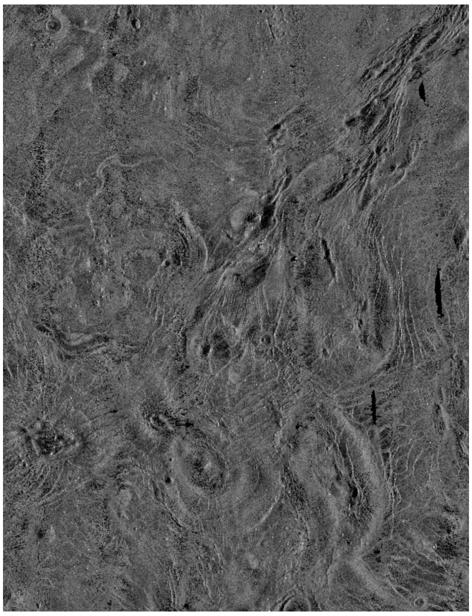

Fig. 33. «Spiders-and-cobwebs» in the area between Sedna Platinia and Bell Regio. Center at 43° N, 19° E, area 1400 w 1060 km. These puzzling features have been informally called arachnoids

ridges. A few clusters of dome-like hills can be seen. The combination of these patterns forms a strange «spiders and cobwebs» appearance informally called «arachnoids» (Figure 33). In the southern part of this zone there are irregularly shaped radar-bright patches 20–50 km in size. In the northwestern part the plain is cut by a northeast-directed belt (250×1000 km) of intersecting furrows up to 100 km long and 10–15 km wide (Figure 34).

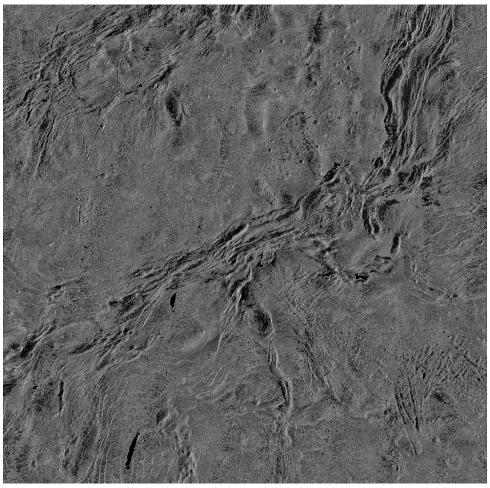

Fig. 34. Part of the area between Sedna Platinia and Bell Regio. Center at 49° N, 22° E, area 940 w 980 km. Notice the furrow belt in the upper right and ridge belt diagonally across the center. Also several vague circular features are apparent

Bell Regio. This is an upland area (6054 km elevation), most of which is a plain. Radar-bright irregular patches and flow-like patterns can be seen (Figure 35). A mountain with gentle slopes is located in the central part of Bell Regio and a flatbottomed crater, 40 km in diameter, is visible at the summit. A radar-bright zone extends westward from the crater, about 300 km in length and 80 km in width. As the winds presently blow westward, it could be a pyroclastic train.

Leda Planitia. The plain of Leda Planitia (6050,5–6051 km elevation) has a variegated appearance because of the presence of diffuse radar-bright and radar-dark spots combined with a network of narrow radar-bright ridges (Figure 36). At the transitional zone between Bell Regio and Leda Planitia two large craters are superimposed on the plain (Figure 37). One of them is a double-ring basin with a diameter near 100 km. The other, 50 km in diameter, has a central peak and a prominent radar-bright apron with clear bilaterial symmetry. Both are probably impact craters.

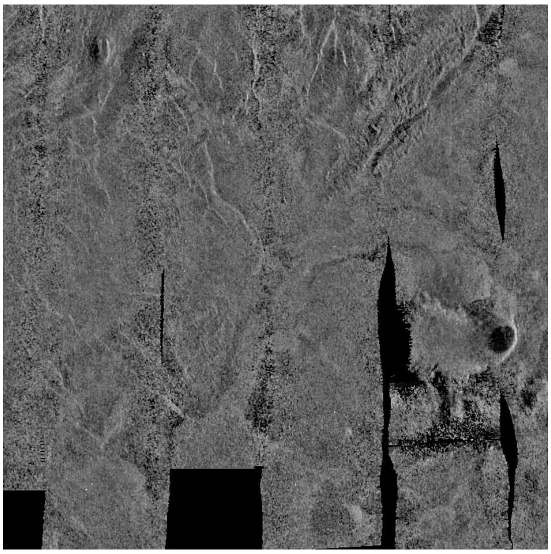

Fig. 35. Part of Bell Regio. Center at 31° N, 43° E, area 680 w 680 km. Regional elevation increases toward the right. The crater on the right edge is at the summit. Notice the train-like radar-bright zone west of the crater

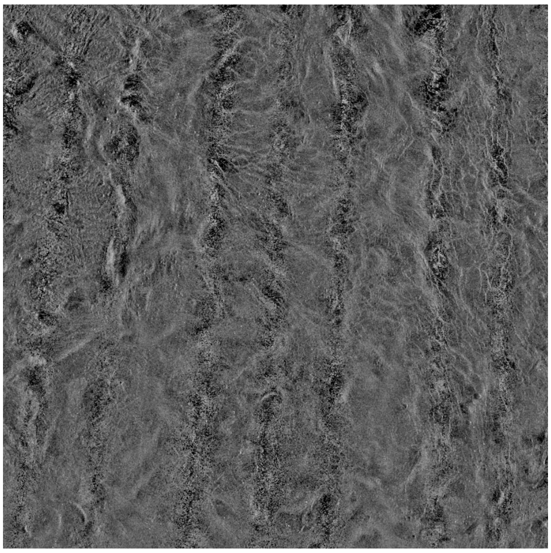

Fig. 36. Part of Leda Planitia. Center at 43° N, 59° E, area 920 w 920 km. Notice the variegated appearance

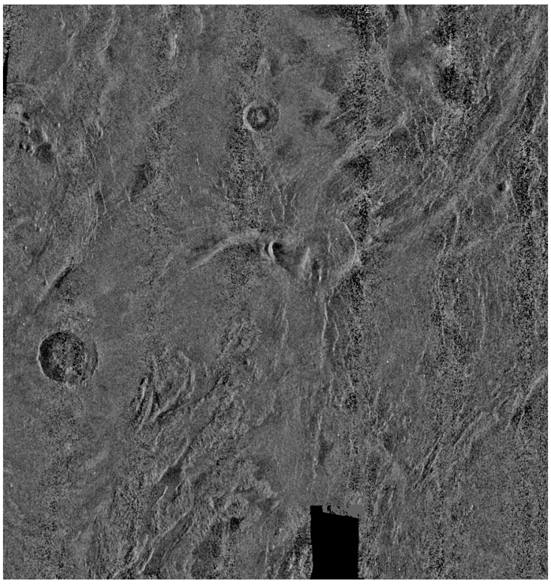

Fig. 37. Transitional zone between Bell Regio and Leda Planitia. Center at 32° N, 57° E, area 860 w 880 km. Notice two circular craters

Tellus Regio. The upland of Tellus Regio is located southeast of Leda Planitia (Figures 38, 39). Elevations here reach 6054 km. The area is characterized by diagonal and chevron-like systems of short ridges and grooves that gently and sometimes sharply change orientation. In the southern part, several wide (20–30 km) and long (hundreds of km) trough-like arcuate valleys occur, forming in total a complex, doubly-elliptical pattern. In association with these valleys there are several irregular flat-bottomed depressions 80 to 120 × 100 to 150 km in size. The depressions and valleys are conformable with the ridge-and-groove system, so that the grooves form a «moat» around the ridges that define the valleys and depressions. Several small dome-like hills are visible inside the valleys and depressions.

A plain is present in the northern part of the Tellus Regio, surrounding an upland area 300 × 400 km in size. The morphology of the upland area is similar to the previous ridge-and-groove type, but seems to be more sinuous.

Niobe Planitia. Niobe Planitia, with an elevation of 6050,0–6051,5 km, is located east of Tellus Regio and south of Tethus Regio (Figure 40). The plain displays numerous dome-like hills that are more abundant than in other plains. Patches of ridge belts and chaotic ridge-and-groove upland terrains are also visible.

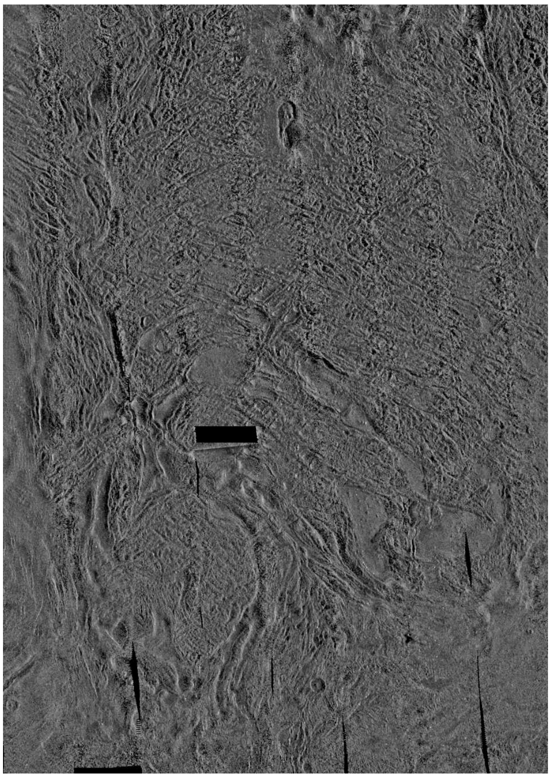

Fig. 38. Tellus Regio. Center at 35° N, 78° E, area 1000 w 1600 km. Notice the complicated ridge-and-groove patterns and depressions

Discussion

The described diversity of terrains can be reduced with some generalization to the limited set of terrain types used for the construction of the included geological-morphological map (Figure 41). The plains can be subdivided into five morphological types.

Ridge-and-band plains are plains that are complicated by areal systems of numerous narrow ridges and radar-bright bands. Ridge belts and impact craters are common. Elevation of ridge-and-band plains is usually lower than 6050,5 km. Plains belonging to this type are characteristic of the northern polar region, the central part of Atalanta Planitia, and some parts of Mnemosyne Regio.

Band-and-ring plains are plains that are complicated by systems of ring features and linear ridges and narrow bands, often combining into «spider-and-cobweb» patterns. Elevations are generally between 6050,5–6051 km.

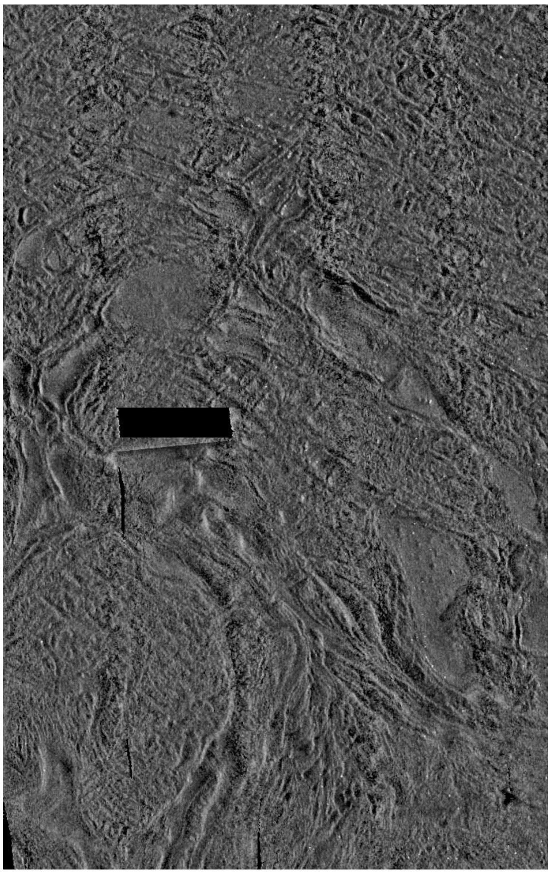

Fig. 39. Detail of Figure 38. Center at 33° N, 78° E, area 840 w 550 km. Notice the flat-bottomed depression and, on center left, the «moat» effect described in the text

Plains belonging to this type are present northwest and northeast of Bell Regio.

Patchy rolling plains are characterized by varying radio-albedo and gently rolling topography. Some of the patches have the shape of lava flows. Elevations are between 6051–6051,5 km. Plains of this type occupy most of Bell Regio, the land that borders to the north with the Ishtar Terra, and some intermountain depressions of Ishtar Terra. Large shield-like volcanos are locally present within this terrain, e. g., the volcano with the «train» feature at Bell Regio, and the volcano in Tethus Regio.

Dome-and-butte plains are complicated by buttes of the ridge-and-groove type (see below), fragments of ridge belts, and numerous domes. Summit craters are visible on some domes. Elevation of the dome-and-

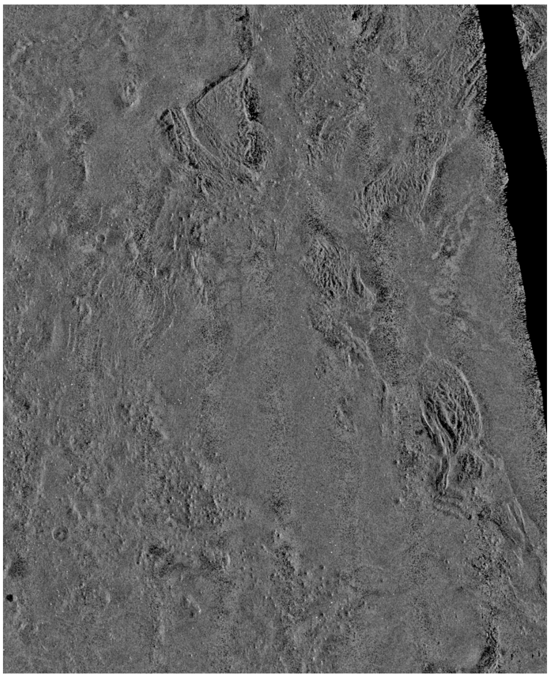

Fig. 40. Niobe Planitia. Center at 43° N, 127° E, area 920 w 1360 km. Notice the dome-like hills and the patches of ridge-and-groove terrain

butte plains is usually 6051,5–6052 km. Plains belonging to this type are present within the Niobe Planitia, Guinevere Planitia, and Sedna Planitia.

Smooth plains are smooth topographically, some featureless and some with prominent radar-bright features resembling lava flows in shape. Smooth plains are widely distributed, occupying large areas within Guinevere Planitia, Sedna Planitia, and Atalanta Planitia at an elevation of 6050,5–6051 km. Morphologically similar to the described smooth plain is the high plain of the Lakshmi Planum, which is at an elevation of 6053,5–6055,5 km and is referred to as high smooth plain, a subtype of smooth plains.

The plains are similar in general morphology, including the presence of furrow-like features, to the mare-type basaltic plains on the moon, Mercury, and Mars. Soviet landers Venera 9, 10, 13, and 14 descended to the surface of Venusian plains and determined that the surface material was of basaltic composition [*Surkov et al.*, 1977; *Barsukov et al.*, 1984]. It seems reasonable to conclude that the essential topography of the plains is a result of flooding with basaltic lava. Contributions from weathering, erosion, and sedimentation are either insignificant or are limited to minor features (see below).

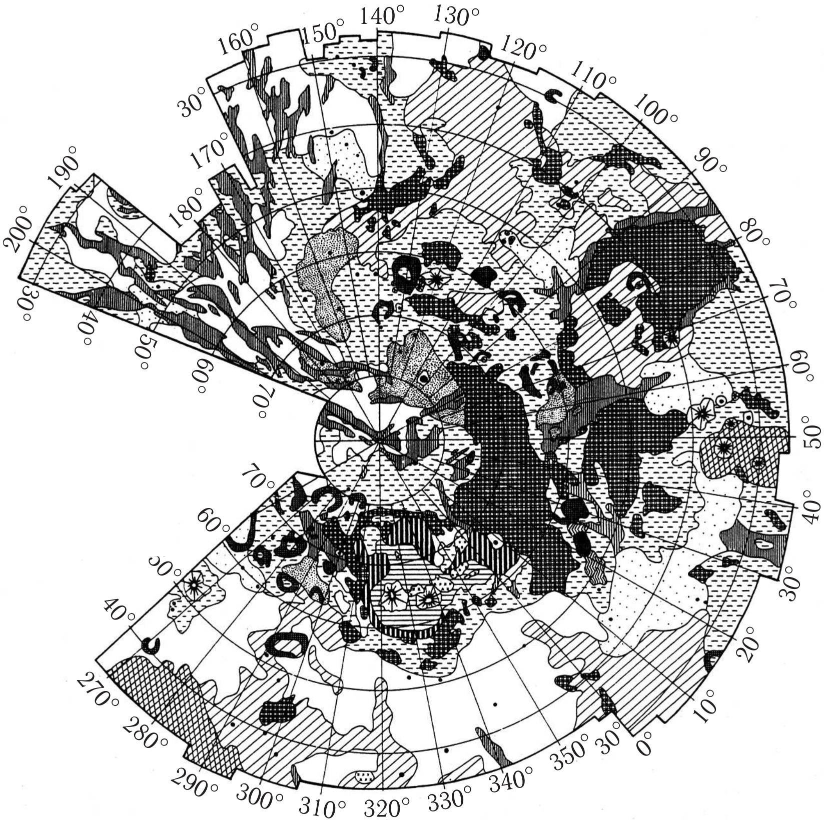

Fig. 41. Geographical distribution of the terrain described in the text

The law of superposition gives the following age relationships: The most ancient plains are the ridge-and-band plains (consistent with their relatively high density of impact craters), and the youngest are the smooth and the high smooth plains. The others are intermediate and their relative positions are yet to be determined.

Other terrains are in obvious contrast with the plains. ,In; general they are combinations of ridges and grooves in various patterns: linear-parallel as found in Akna, Freyja, and Maxwell; orthogonal as found in Ishtar Terra adjacent to Leda Planitia and in Tethus Regio; diagonal or chevron-like as found in Ishtar Terra, in the land 1000–3000 km east of Maxwell, and in some areas of Tellus Regio; and chaotic as found in isolated areas centered at 50° N, 130° E and 50° N, 80° E. Transitions between these types also occur. For more details about these terrains the reader is referred to a companion paper [*Basilevsky et al.*, 1986].

Where the terrain is cut by two or more sets of ridges and grooves it has been informally called «parquet», and is named for its obvious appearance. This type of terrain is the result of deformation, and evidence of both compression and extension can be found. Also, the parquet appears to be the result of several periods of deformation.

The relative age relationships between these terrains is not fully known. The linear-parallel systems of Akna, Freyja, and Maxwell are locally even younger than the plain-forming material of the Lakshmi Plateau. The parquet is embayed in many places by various types of plain-forming material. The ridge-and-band plain material has a direct stratigraphic relationship with the parquet only at the NE termination of Ishtar Terra where the plains seem to be older than the parquet.

As more fully described in the companion paper [*Basilevsky et al.*, 1986], belts of ridges and grooves are widespread. They are older than the youngest plain-forming material, as stratigraphic overlapping can often be seen. They are also younger than the oldest plain-forming material, as in many cases it is possible to see that the belts are the result of deformation of such material.

The coronae or ovoids are located mainly near the eastern and western boundaries of Ishtar Terra. They are the result of deformation, but since they are also associated with volcanism, they are likely to be the result of some volcano-tectonic process.

The terrain of Beta Regio seems to be distinct. It does not seem to be a shield volcano [*Saunders and Malin*, 1977; *Masursky et al.*, 1980]. Uplifting of plain-type terrain in combination with rifting and volcanism may be factors in its formation [*McGill et al.*, 1981; *Campbell et al.*, 1984].

A second companion paper [*Ivanov et al.*, 1986] discusses the problem of impacts of Venus. The following considerations will suffice here. All types of terrain are sparsely peppered with craters of clear impact morphology (139 discovered). The clear impact craters range in size from 8 km (although a few possible ones are as small as 4 km) to 140 km. The smaller ones are sometimes bowl-shaped, and the larger ones have a double-ring morphology. Most of the craters have a central peark and a distinct rim. A sequence of crater type exists, from morphologically sharp with a radar-bright halo to more subdued forms. A plot of the crater density versus crater diameter shows a considerable deficiency of smaller craters with respect to a lunar distribution. A comparison with Hartmann's graph [*Hartmann*, 1983] of planetary ages versus crater density gives an age range of 0,5 to $1{,}0 \times 10^9$ years.

An additional 500 circular features of unclear origin have been counted on the plains alone. Figure 42 shows the distribution of these features on part of the surveyed area. Some examples of these features can be seen on Figures 24, 29, 30, and 34. These features range in size from 10 km to 600 km. The analysis of these features is in progress. Their size distribution is different from that of the craters of clear impact origin but can be made consistent by making allowance for the probable more common obliteration of smaller craters than larger craters. If they are impact craters, then their plotting on Hartmann's graph [1983] results in an age of 4,0 to 4,5 × 10^9 years. A possible interpretation of these results is that the plains of Venus have an average age of 0,5 to 1,0 × 10^9 years. However, previous structures have not been completely obliterated and still show through.

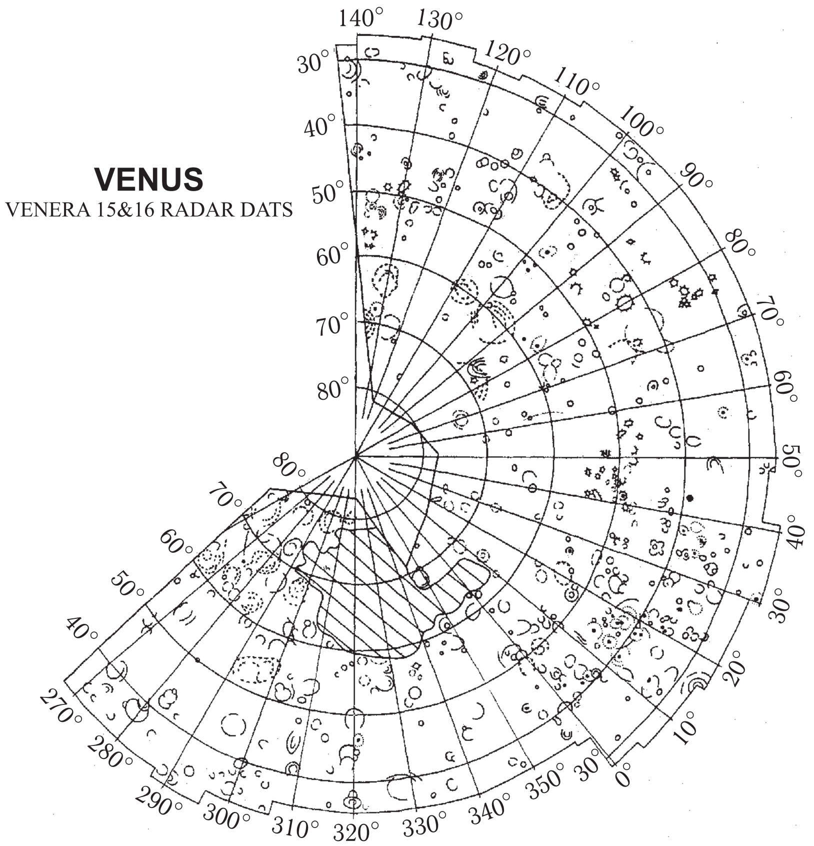

Fig. 42. Geographical distribution of the circular features (excluding impact craters) described in the text

A few considerations about atmospheric effects must be included. The images give two pieces of evidence — one direct, the other indirect — of weathering/erosion-deposition. As mentioned before, the craters that show an obvious impact morphology also show a range of morphologic age. Volcanism can cause some filling, but chemical and aeolian processes must be the cause of the smoothing of the rims and the disappearance of the radar-bright haloes. In general, however, the kilometer-scale effects of aeolian processes in the last one-half to one billion years are very small. Data for centimenter-scale effects have been discussed from the panoramas obtained by the Venera landers [*Florensky et al.*, 1977*a*,*b*, 1983; *Basilevsky et al.*, 1986].

The second indirect evidence comes from radar-dark patches that are found in depressions or near many positive features (Figure 43). In both cases the location suggests a control by the wind. The size of these spots ranges from 10–20 km but some are as big as 200 km. Some boundaries are sharp, while others are gradual. Work is planned to determine the character of their locations.

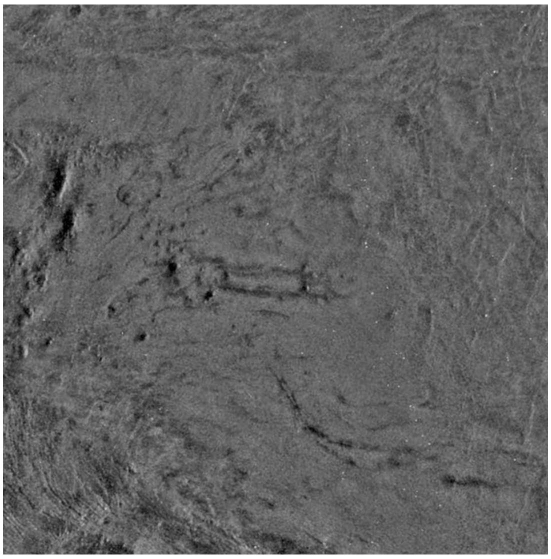

Fig. 43. Example of the radar-dark pattern described in the text. Center at 73° N, 103° E, area 520 w 520 km

Conclusions

Radar images obtained by Veneras 15 and 16 give evidence for the geological structures and processes on Venus — the Earth-sized planet with a developed atmosphere but without a hydrosphere. The position of Venus in a sequence of terrestrial planetology bodies from the moon to the Earth is a question of great planetological significance.

The intensity of exogenic processes on Venus is much lower than on Earth and is rather close to the intensity characteristic of small planetary bodies such as the moon, Mercury, and Mars, On the Earth impact craters lose their morphology after several million years [*Masaitis et* *al.*, 1980]; on Venus such craters preserve a prominent morphology for 0,5 to $1{,}0 \times 10^9$ years. No evidence for water erosion or other processes involving liquid water was discovered on the images. Aeolian redistribution of matter seems to operate on the Venusian surface but its intensity has been very small for at least the last billion years. The intensity of exogenic activity in earlier periods is unknown. A reason for the low rate of exogenic reworking of the Venusian surface could be the stability of the Venusian environment; i. e., the absence of seasonal and daily changes of temperature and a stable wind regime.

The low rate of exogenic reworking means that many of the volcanic and tectonic features are still close to their pristine state, allowing a look at tectonics unavailable on Earth [see companion paper, *Basilevsky et al.*, 1986]. In general, the tectonic activity of Venus is different from that of the moon, Mercury, and even Mars, and can be compared only to that of Earth. Intensive horizontal tectonic deformations, previously known only on Earth, are also now seen on Venus. However, a basic difference between the Earth and the studied portion of Venus is the absence on the latter of trenches, large transform faults, and «mid-oceanic» ridges, features that are the basis for the theory of plate tectonics.

On Venus, more intensively than on Mars, basaltic volcanism has manifested itself in areal volcanism, large shield volcanos, and smaller volcanic domes. Basaltic volcanism is a universal mechanism of differentiation for the internal matter of the terrestrial planets [*Florensky et al.*, 1981]. Moreover, the larger the body, the more prominent the role of basaltic volcanism. On Venus, the presence and composition of nonbasaltic rocks is still a matter of conjecture, but K, U, and Th abundances measured at the Venera 8 landing site [*Vinogradov et al.*, 1973] suggest a possible nonbasaltic (syenitic) composition of the surface rock [*Barsukov et al.*, 1981]. Unfortunately, the geology at that site is still unknown. A comparison of geochemical data from all five landing sites suggests that differentiation on Venus may be toward alkali enrichment rather than silica enrichment as on Earth. Metamorphic rocks are even more conjectural, but the tectonic stresses and the elevated temperatures offer the possibility of the existence of such rocks on Venus. However, the absolute predominance of CO_2 over H_2O could suggest the presence of different suites of metamorphic facies.

On Venus, as on Earth, terrains typical of the ancient highlands of the moon, Mercury, and Mars have not been discovered. Either the Earth and Venus had such terrains that were later obliterated, or the environments on Earth and Venus were such that these terrains developed differently.

The properties of the circular features of unclear origin counted on Venus and previously described suggest that traces of the ancient terrains, whatever they were, may still exist on Venus. The unusual circular features referred to as coronae or ovoids could be the result of endogenic reworking of large impact basins, in accord with some ideas about the origin of some very old terrestrial structures [*Salisbury and Ronca*, 1966;

Ronca, 1966; *Goodwin*, 1974; *Frey*, 1980; *Grieve*, 1980; *Florensky et al.*, 1981]. It is in the Early Precambrian of the Earth that corona-like features have been discovered, although as a rule they are much smaller [*Saul*, 1978; *Gintov*, 1978; *Eggers*, 1979; *Salop*, 1982; *Ilyin et al.*, 1983; and others]. Perhaps Venus will lead us to an understanding of the early unobservable Earth. The geological work on Venus has just begun.

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