PROCEEDINGS OF THE SIXTEENTH LUNAR AND PLANETARY SCIENCE CONFERENCE, PART 2
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. B4, PAGES D399–D411, MARCH 30, 1986

Styles of Tectonic Deformations on Venus: Analysis of Venera 15 and 16 Data

A. T. BASILEVSKY, A. A. PRONIN, L. B. RONCA*, V. P. KRYUCHKOV

V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, U.S.S.R. Academy of Sciences, Moscow

A. L. SUKHANOV AND M. S. MARKOV

Geological Institute, U.S.S.R. Academy of Sciences, Moscow

Analysis of the radar images obtained by Veneras 15 and 16 leads to the conclusion that the ridge-and-groove structures on the surface of Venus are the result of tectonic deformation. Although the mechanism of such deformation cannot yet be unequivocally deduced, several styles of deformation can be described. Areal deformation occurs where horizontal stresses have operated over large areas. Shear deformation appears in bands showing differential longitudinal deformation. Transversal stresses operating over long and relatively narrow areas have produced belt deformation. Circular deformation is related to a specific locus of the stresses. The absence of densely cratered areas indicates that the terrains were deformed after the period of heavy bombardment. The origin of the stresses could be drag of the lithosphere by asthenospheric currents or gravity-induced spreading of surface material over upwellings. A general conclusion is that in the surveyed area of Venus neither terrestrial plate tectonics nor lunar-highland-type terrain exists.

INTRODUCTION

Comparative studies of terrestrial planets [see, for example, *Phillips and Malin*, 1984; *Barsukov and Basilevsky*, 1984] have shown that there is a relationship between the evolution of a body and its size. Venus is particularly interesting because it is similar in size to Earth. The question was often raised as to whether the horizontal displacements typical of Earth's plate tectonics and their ensuing styles of deformation (volcanic arcs, fold belts, transform faults, and trenches) would be present on Venus. Nothing reliably recognizable as any of the above had been found before the Venera 15 and 16 images, which had a resolution of 1–2 km, were obtained. Based on the present data, we intend to show that deformations do exist and are sufficiently different from those on the other terrestrial planets to suggest that Venus will have tectonics of its own. Confronted by the large volume of data from Venera 15 and 16, the authors have decided to start the work of interpretating the tectonics of Venus by describing the styles of deformations. Discussion of possible Venusian tectonics will be left primarily for future publications.

The terrains of Venus shown by the radar images obtained by Veneras 15 and 16 [*Barsukov et al.*, 1984*a,b*, 1986] can be broadly classified into four groups. It must be understood that future work will very likely subdivide each group. No genetic implication is to be assumed by this classification.

Large areas of Venus are plains. They often have complicated patterns of flowlike features, streaks, grooves, and low ridges. In general morphology they are similar to the mare-type plains on the moon, Mercury, and Mars. A basaltic composition was indicated by the landings of Veneras 9, 10, 13, and 14. On the basis of this, the plains of Venus have been interpreted [*Barsukov et al.*, 1984*a,b*] as being a result of basaltic flooding.

The second type of terrain consists of sets of ridges and grooves, commonly intersecting each other. Because of its appearance, this type of terrain has informally been called "parquet."

The third type of terrain is made up of systems of conforming subparallel ridges and grooves, often arcuate, of which some occupy broad zones, but that more commonly extend over long and relatively narrow belts. Other sets of intersecting ridges and grooves generally are not present, with a few exceptions.

The fourth type of terrain is represented by sets of ridges and grooves that distribute themselves in concentric patterns, often with another set oriented radially. The subcircular patterns have been informally called ovoids or coronae.

Evidence exists to show that in all types of terrain the ridges and grooves are the result of deformation and are not aeolian features. This can be deduced from the following observations. (1) The ridges and grooves often have angular, "broken" faces rather than the smooth and rounded outline of an aeolian form. (2) The ridges and grooves in some places form concentric and radial patterns. (3) The ridges and grooves commonly ignore regional contour lines. (4) The ridges and grooves commonly ignore the present wind patterns. (5) The abuttment of one set of ridges and grooves against another is common, forming a sharp angular connection between the sets.

Craters of evident impact origin are present on all types of terrain. Study of these craters is presented elsewhere [*Basilevsky et al.*, 1985; *Ivanov et al.*, 1986]; here they are evidence of the lack of large-scale erosional-depositional processes (good preservation of crater population having an age as large as 0.5–1 b.y.), at least for the geological period represented by the observed Venusian surface features.

Clear evidence of whether the ridges and grooves are constituted of folds or faults has not been found in most cases. Because of the lack of large-scale erosion, one must assume that the deformations have occurred at or very near the surface. Faults rather than folds may be expected in this case, but in the hot surface environment of Venus this may not necessarily be so. Presumably, the subsurface of Venus is as devoid of water as is its atmosphere. On Earth, pore fluid pressure is

*Permanent address: Department of Geology, Wayne State University, Detroit, MI 48202. Presently at the Vernadsky Institute in a program of the Academy of Sciences, USSR, and the National Academy of Sciences, USA.

Paper number 5B7004.
0148-0227/86/005B-7004$05.00

Fig. 1. Lakshmi Planum and surrounding territory, 2000 × 2600 km. Here and elsewhere the bands are oriented approximately north-south.

known to reduce the shear stress required for faulting [*Hobbs et al.*, 1976, p. 320]. The above considerations may be relevant to the conclusions of *Hubert and Rubey* [1959], who have shown that low-angle thrust faulting is practically impossible without water. How these conclusions can be related to the Venusian surface environment is open to debate.

Even without knowing the real nature of the terrains and deformations, it is possible to present a classification of styles of deformation. The first style, called areal deformation, appears to be produced by stresses distributed over a large area. It is found in the case of the parquet and the broad zones of subparallel ridges and grooves. In association with this style, we often see what is called shear deformations—bands showing differential longitudinal deformations, i.e., progressively longitudinally increasing amounts of lateral movement transverse to the band.

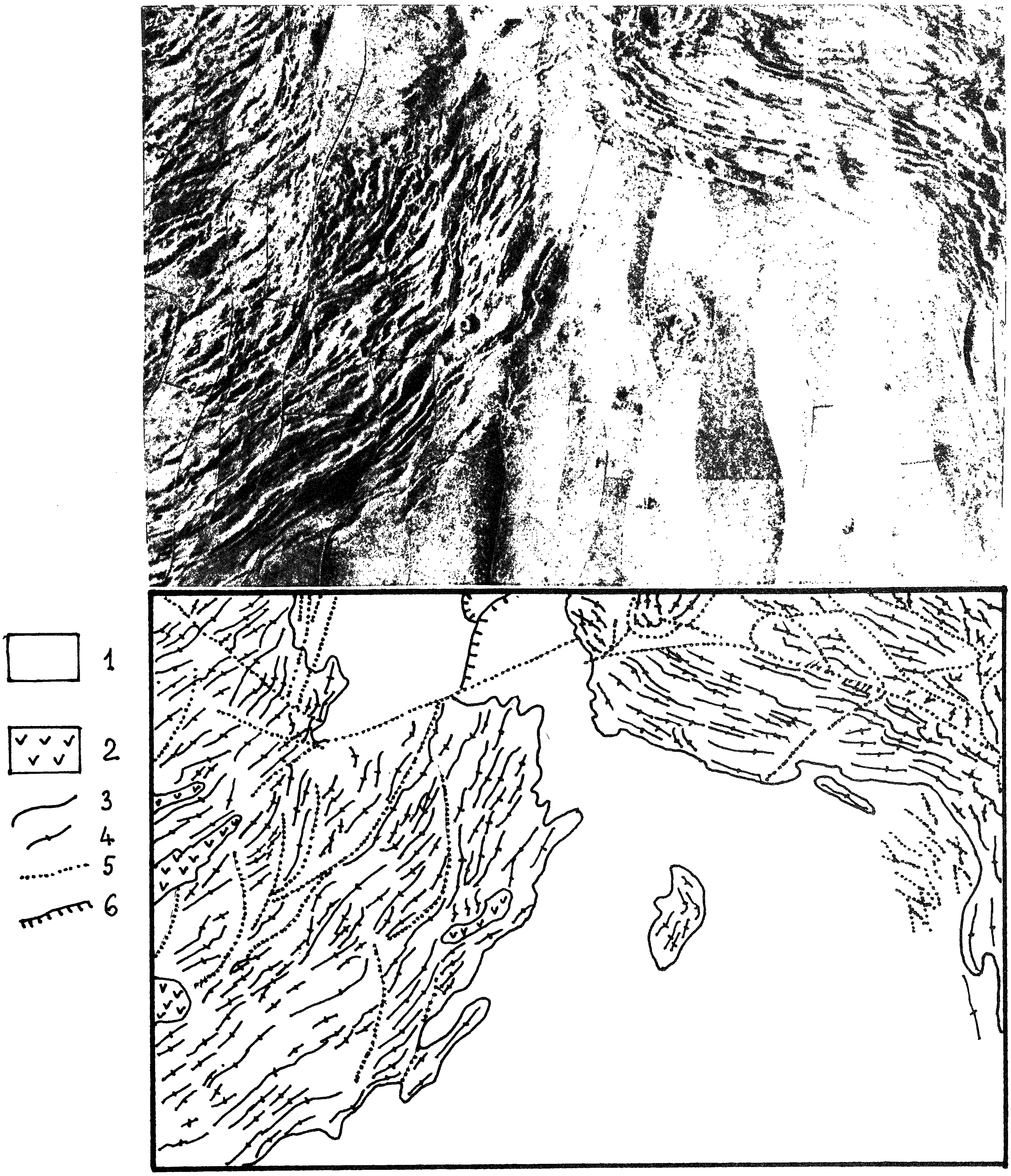

Fig. 2. Akna and Freyja Montes defining the northwest and northern boundaries of Lakshmi Planum. Radar image (top) and line drawing (bottom), 650 × 1000 km. Legend: (1) surface of Lakshmi Planum; (2) fresh lava fillings; (3) geological boundaries; (4) axes of ridges; (5) faults; (6) scarps.

The next style appears to be caused by stressed operating over a long and relatively narrow area that reminds one of a tectonic belt on Earth. It will be referred to as belt deformation.

Structures that seem to be related to a specific locus of the stresses are also present. Some are obviously impact craters, but others, like the aforementioned coronae, represent a style of deformation called circular deformation.

The styles of deformation will be described and discussed using chosen areas as examples. Tectonic interpretation will be presented separately in the last section of this paper.

LAKSHMI PLANUM AND ITS SURROUNDINGS WITH THE EXCEPTION OF MAXWELL MONTES

Lakshmi Planum and its mountainous surroundings form the western part of Ishtar Terra, the largest zone of areal deformation

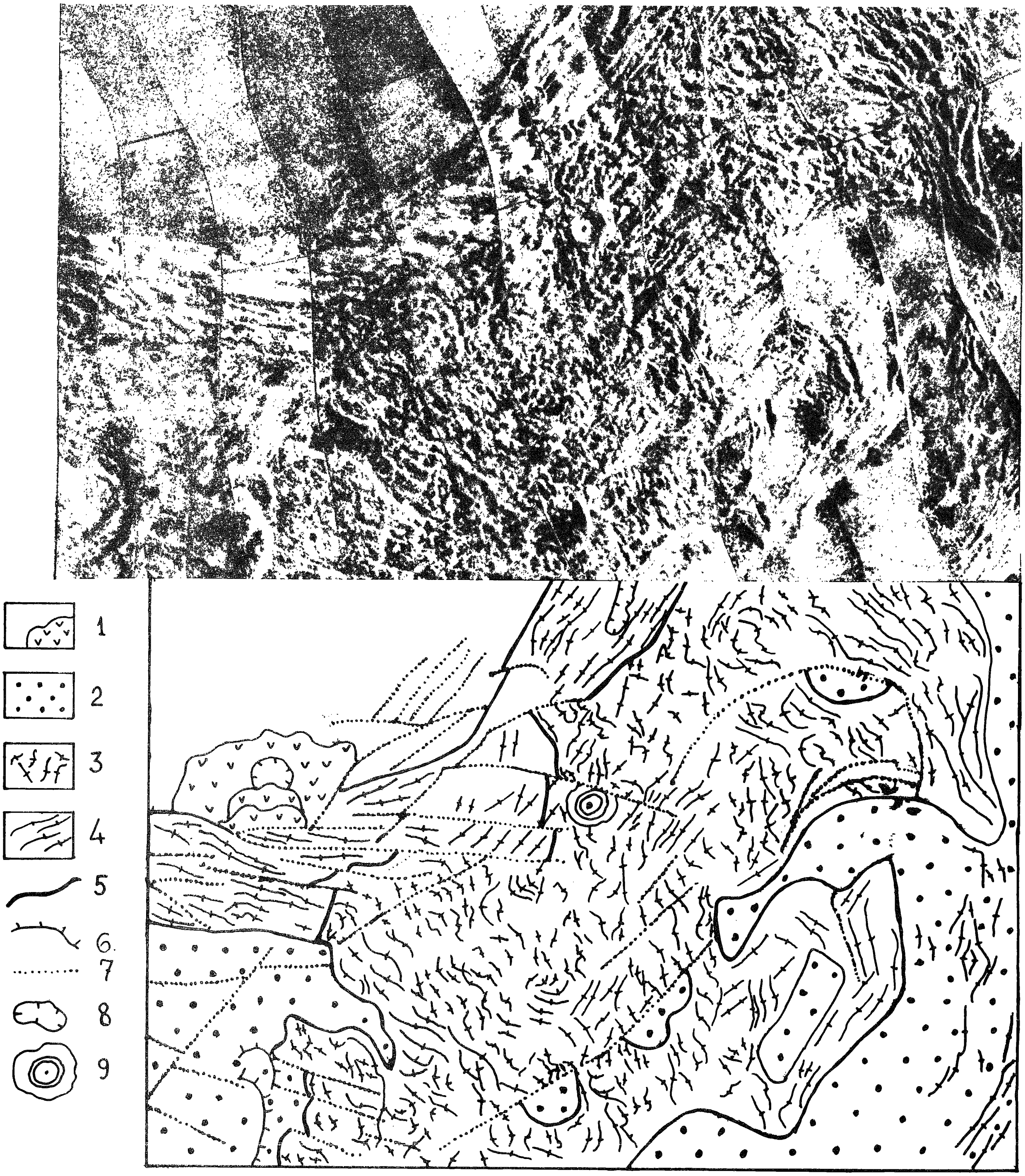

Fig. 3. Vesta Rupes defining the southern and southeastern boundaries of Lakshmi Planum. Radar image (top) and line drawing (bottom), 300 × 480 km. Legend: (1) surface of Lakshmi Planum; (2) lava filling on the floors of intermountain depressions; (3) patchy, rolling plains; (4) groove-and-ridge terrain; (5) belt of subparallel ridges around Lakshmi Planum; (6) geological boundaries; (7) faults; (8) scarps; (9) impact craters.

within the Veneras 15 and 16 coverage (practically all of Venus north of 30°–35°N). The plateau has a hexagonal shape, measuring about 1200 km diagonally with a 600 × 400-km bulge on the east (Figure 1). The smooth surface of the plateau is 3–4 km above the reference datum (which is 6051 km from the planet mass center and close to the average level of the Venus surface). The surface is complicated by two elliptical, flat-bottomed depressions: Colette (80 × 130 km) and Sacajawea (120 × 200 km), probably volcanic calderas [*Barsukov et al.*, 1986]. A radial system of radar-bright, slightly sinuous bands up to 250 km long and 15–20-km wide, resembling basaltic lava flows, occurs around Colette. In places, the surface of the eastern part of the plateau displays patches of terrain cut by closely spaced diagonal and orthogonal ridges and grooves. The surface material of the plateau embays this ridge and groove terrain, suggesting that these patches are possibly remnants of

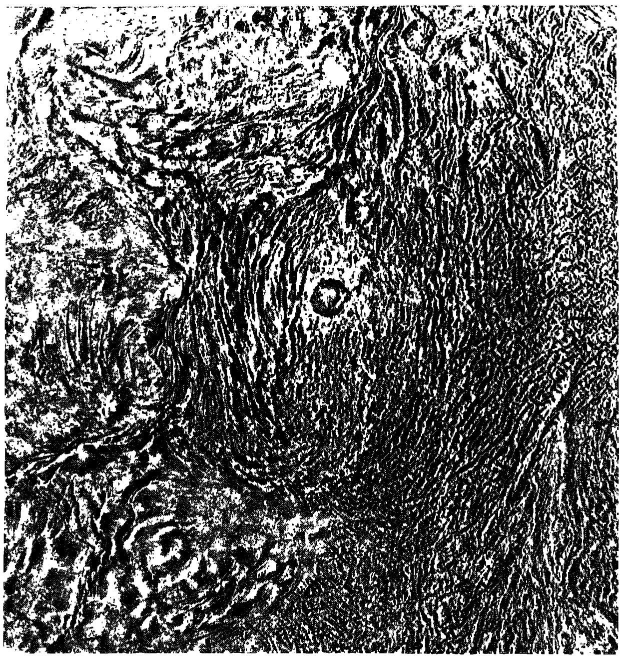

Fig. 4. Maxwell Montes, Cleopatra Patera, and surrounding terrains, 1400 × 1600 km. A transition can be seen from the single-set ridges and grooves west of Cleopatra to the parquet-type terrain to the east.

the plateau basement. The plain-forming material of the plateau is also dissected in several places by superimposed circular depressions having the typical morphology of impact craters on other planetary bodies [*Basilevsky et al.*, 1985; *Ivanov et al.*, 1986].

Lakshmi Planum is bordered on almost all sides by mountains with a very dissected topography: Akna Montes on the northwest; Freyja Montes on the north; Maxwell Montes on the east; and Vesta Rupes on the south. Descriptions of Akna, Freyja Montes, and Vesta Rupes will be given here; Maxwell Montes will be described in the following section.

Akna Montes represents the northwest border of Lakshmi Planum (Figure 2). The summits of these mountains are elevated above the plateau surface by 3–4 km. The highest part of the mountains forms a band 700 km long, parallel to the plateau boundary, and is composed of a northeast-striking system of parallel ridges and grooves up to 300 km long and 30–40 km wide. The ridges are asymmetric with short, steep slopes toward the plateau and long and gentle ones in the opposite direction. Within the transitional zone between the plateau and Akna Montes two craters with a diameter of about 30 km and having a morphology typical of impact features are visible. The eastern parts of the craters are adjacent to the plateau surface and may be superimposed on it. The western parts of the craters are adjacent to the ridge and groove terrains of Akna Montes, which may be superimposed on the craters.

Northwestward, the length of the northeast-atriking ridges and grooves of Akna Montes decreases. The ridges and grooves are commonly disturbed by oblique faults. In some places the oblique system becomes prominent, resembling the terrain east of Maxwell Montes (see below). The elevation decreases from the mountains down to the plateau level and even lower. Further to the west within the highly dissected mountain terrain the northwest and northward orientations of ridges and grooves begin to dominate.

Freyja Montes represents the northern and northeastern borders of Lakshmi Planum (Figure 2). The highest part of the mountains (6–7 km over the average level of the planet) is composed of a system of east-west striking linear ridges and interridge grooves up to 200 km long and 5–15 km wide. Perhaps because of the parallelism of the ridges with the view-line of the radar, the ridges on the images are less prominent than in the Akna Montes. In places one can see that the ridges are asymmetric, with the northern slopes more gentle than the

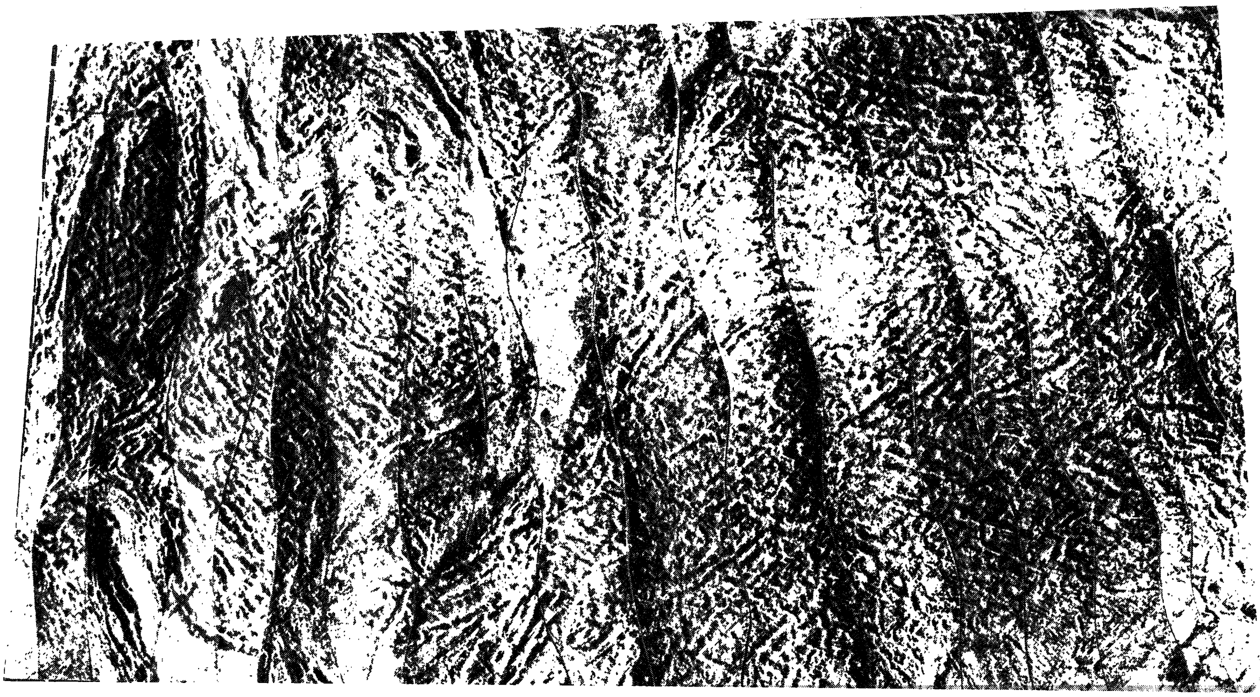

Fig. 5. The northern parquet, east of Maxwell Montes, 600 × 1200 km.

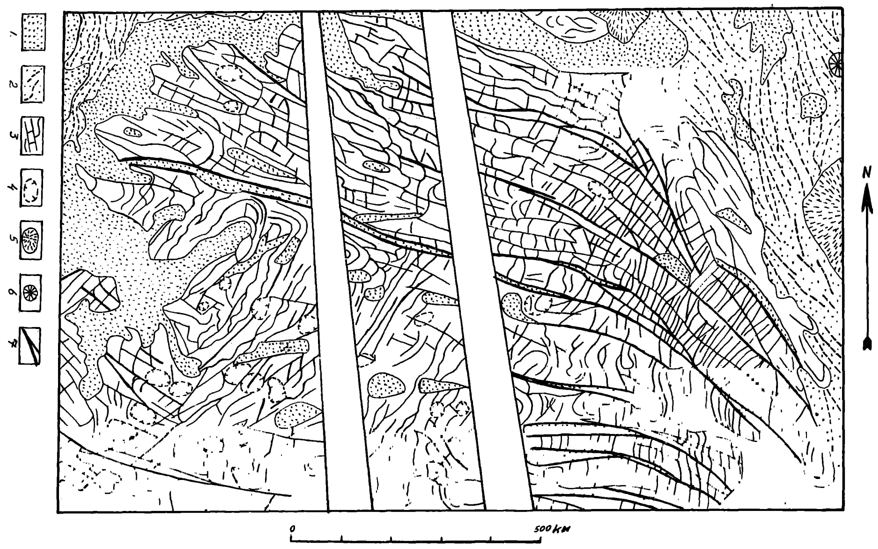

Fig. 6. Structure of parquet in the southeast part of Ishtar Terra. (1) lavas; (2) ridges of linear belts; (3) lineaments in parquet; (4) circular blocks; (5) volcanoes; (6) impact craters; (7) main faults.

southern ones. This system of subparallel ridges forms a band about 400 km long and 150 km wide. On the east, the band turns southeastward by an angle of 90°–120°. On the adjacent surface of Lakshmi plateau, thin low ridges merging into narrow radar-bright bands with indistinguishable relief are oriented parallel to the mountain ridge systems. On the places where the surrounding mountains deform these thin ridges and bands a network with rhombic cells is formed. Farther to the north and northeast, the highland surrounding Lakshmi is composed of systems of relatively short (20–50 km) intersecting ridges and grooves having a predominant diagonal pattern and commonly united into blocks of about 100×200 km, separated by prominent grooves. In the periphery of the northern and northeastern surroundings of Lakshmi, the overall pattern is arcuate and similar to the generally arcuate shape of the system of Freyja Mountains and its southeastern continuation.

Vesta Rupes is a giant scarp bordering Lakshmi on the south (Figure 3). From the plateau to the adjacent Sena Planitia, the elevation decreases by 3–4 km. Planimetrically, the border consists of two branches with an angle of about 120° between them. A relatively narrow (50–100 km wide) belt of subparallel ridges and grooves similar to those of Freyja Mountains borders

Fig. 7. Northwest portion of the region shown in Figure 6, 750×900 km.

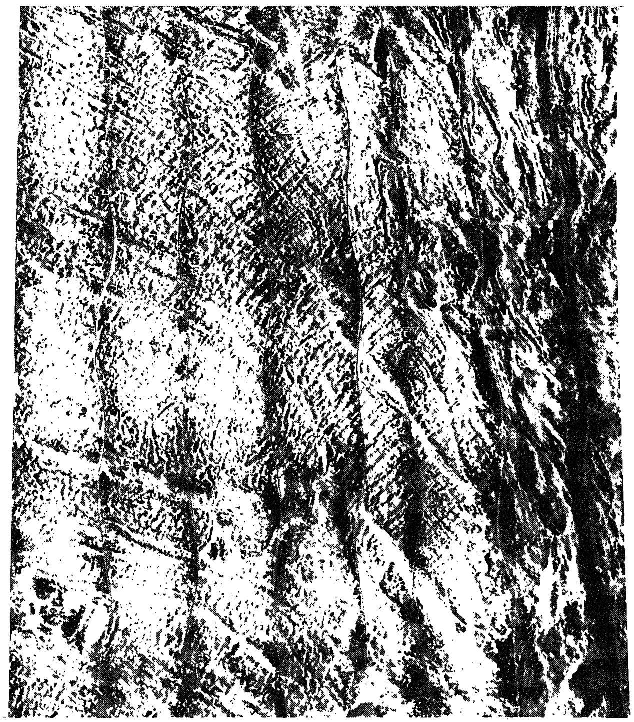

Fig. 8. Eastern portion of the region shown in Figure 6, 750×900 km.

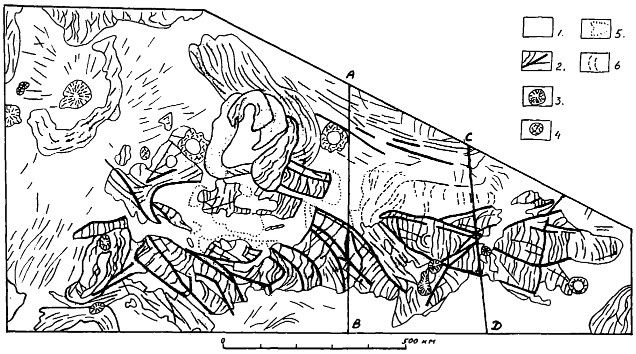

Fig. 9. Structure of Tethus Regio. Legend: (1) parquet; (2) main and secondary lineaments; (3) volcanoes; (4) impact craters; (5) supposed limits of parquet; (6) lineaments of parquet that can be traced under lava cover; lines A-B and C-D denote cross sections shown in Figure 10.

the plateau. The western branch with west-northwest orientation is about 1000 km in length; the eastern, with northeast orientation, is about 500 km in length. Inside the belt ridges and interridge grooves are up to 100 km long and 10–15 km wide. At the joining place, both west-northwest and northeast systems coexist, intersecting at an angle of about 60°. Southward, a 400 × 1000 km sublatitudinal band of terrain of relatively short intersecting ridges and grooves in a diagonal-chaotic pattern is observed.

MAXWELL MONTES AND THE NORTHERN PARQUET

The area of Maxwell Montes and the parquet to the east is an example of three styles of deformation (Figures 4 and 5). The sets of subparallel ridges and grooves of Maxwell Montes (the highest on Venus, more than 11 km above datum) merging eastward with the parquet are examples of areal deformation. Some of the sets of subparallel ridges and grooves also appear to be part of a long system of belt deformations that extends into the plains to the north and south of Maxwell Montes. Apparent shear deformation is present south and southwest of Maxwell Montes.

The eastern slope of Maxwell Montes is dominated by the crater Cleopatra, approximately 200 km east of the summit (Figure 4). The crater has a diameter of about 100 km and displays an inner crater. The land near the crater shows a smoothing of the terrain, apparently caused by partial burial of the ridges and grooves by material expelled from the crater. Approximately 1000 km east of the crater, as well as south and southeast, another set of lineations is apparent, trending approximately north east-southwest northwest-southeast, often showing minor offsets on the major north-south ridges and grooves and no consistent offset on each other. These new sets probably represent small shear zones. As a whole, however, they may be conjugate faults.

Farther east (Figures 4 and 5), the type of terrain called parquet is present, forming a sublatitudinal zone 1000 × 2000 km. Although the transition from Maxwell Montes to the parquet cannot be followed completely because of a gap in coverage, there are sufficient indications to suggest that the predominant single set of ridges and grooves of the Maxwell Montes area is replaced by two (or more) equally (or nearly so) prominent sets. Immediately to the east of Maxwell Montes both sets of ridges can be seen together.

The parquet farther east is varied but has as a "common denominator" sets of linear ridges and grooves that intersect each other nonorthogonally and show no consistent offset with each other. The general parquet-like appearance of the area is a result of these intersecting sets. In places, prominent chevron-like patterns are visible as part of the nonorthogonal pattern. Bisectrices of the smaller angle (direction of maximum stress if the pattern results from conjugate faulting) are oriented east-west in agreement with the latitudinal orientation of the whole parquet zone.

Irregularly shaped areas of smooth topography also occur that are different from the areas of smooth topography near Maxwell Montes, which were obviously produced by burial of basement by younger material. The origin of these smooth areas on the parquet is unclear. In a few cases if is possible to see that some ridges and grooves vaguely continue across the smooth areas. The ridges and grooves of Maxwell Montes are abruptly terminated at the south side of Maxwell Montes by a smooth plain, and the boundary does not appear to result from stratigraphic burial. On the east, however, the boundary is gradual and may result from stratigraphic burial.

A prominent set of arcuate, open chasms is located farther west and may be caused by anastomosing east-west transcurrent faults, i.e., by a shear belt. The progressively increasing width of the chasms, their arcuate geometry, and their abutting alinear zone that continues into the Maxwell Montes dissecting local ridge-and-groove structures suggest that these chasms are not simple graben, and the mentioned linear zone is a shear belt.

SOUTHEASTERN PART OF ISHTAR TERRA

A characteristic terrain occurs within the area of 45–58°N and 30–60°E (Figure 6). Most of this area is cut by long northwest-oriented furrows up to 15–20 km wide that define a series of bands 250–300 km wide in the northwest part and 40–100 km wide in the southeast part. Every band is crossed by long northwest and short northeast furrows, which divide them into many small rectangular blocks. The pattern vaguely resembles the pattern of transform faults as well as fractures on the surface of mountain glaciers and outlet glaciers.

In the northwest part (elevation 3–4 km above the datum) these blocks are large, smooth and slightly elongated; this part seems to be covered by shallow lava embayments and pools (Figure 7, top left). In the southeast part of the area (0–1 km above the datum) the transverse fractures become more frequent and narrower; here the protruding tongues of material have a height of several hundreds of meters above the plains (Figure 8).

Several flat-bottomed, crater-like depressions of 20–50-km width show long, taillike extensions that become narrower and finally vanish to the southeast (Figure 7, bottom right; Figure

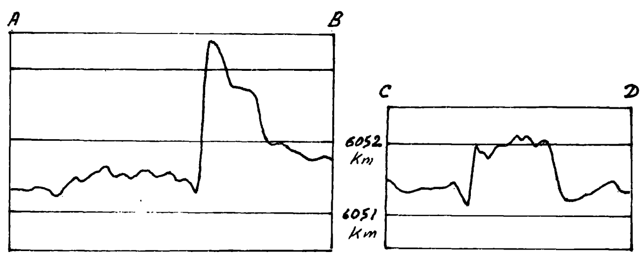

Fig. 10. Cross sections of the area (A-B, C-D) shown in Figure 9.

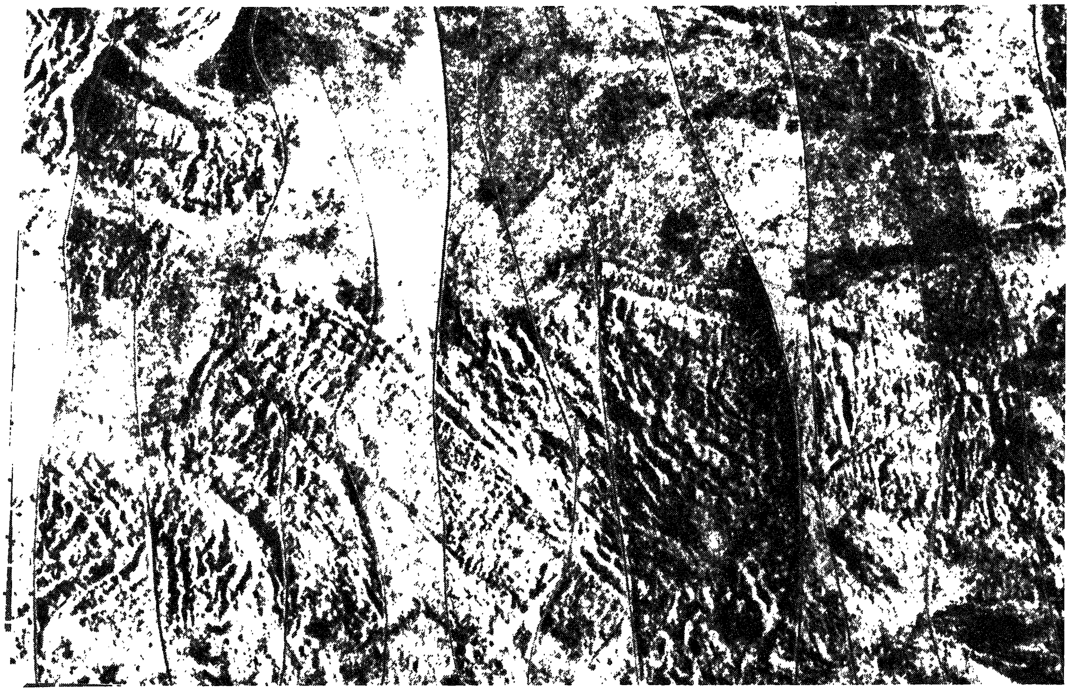

Fig. 11. Central part of Tethus Regio, 450 × 600 km.

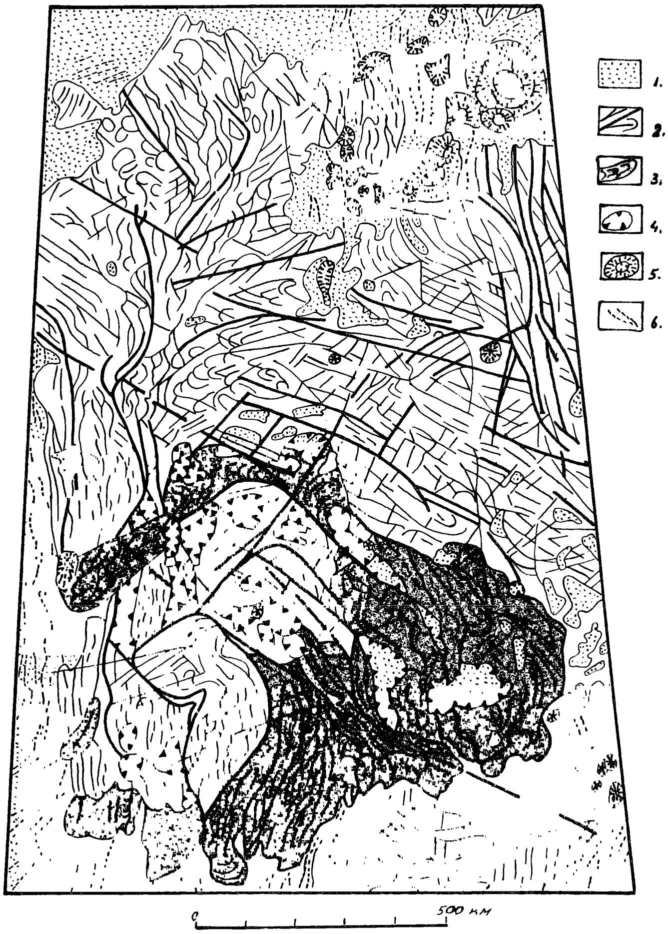

Fig. 12. Structure of the western part of Tellus Regio. Legend: (1) lavas; (2) main and secondary lineaments; (3) chaotic and flowlike patterns; (4) lava-filled depressions with moats; (5) volcanoes; (6) ridges on the plains.

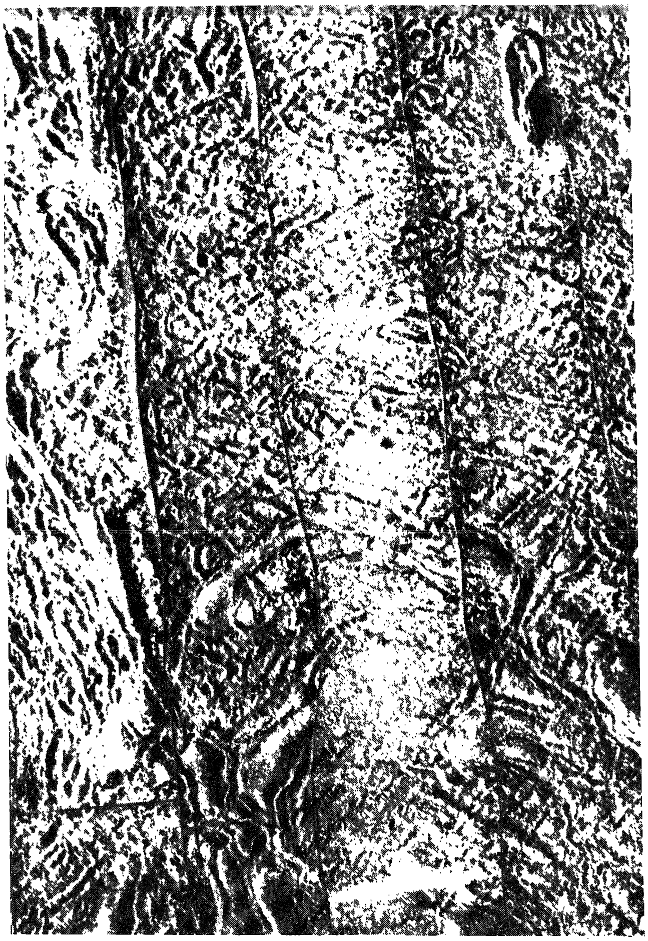

Fig. 13. Central part of the area shown in Figure 12, 500 × 750 km.

Fig. 14*a*

Fig. 14. Belt of furrows (diagonally across the center) and ridges (lower right) south of Maxwell area, 800 × 1200 km. Radar image (*a*) and line drawing (*b*). Legend: (1) small ridges; (2) fractures; (3) separate ridges; (4) scarps; (5) depressions; (6) faults; (7) impact craters with bright haloes; (8) boundary between terrains; (9) groove-and-ridge terrains (parquet); (10) plains.

8, middle). In the northern part of the territory, peculiar S-like patterns can be seen that suggest a shearing (Figure 7, top right). The southeastern section of the area is primarily covered by northeast furrows, commonly sinuous or looplike; several rounded blocks 30–50 km across are present here and surrounded by grooves. The eastern section of this parquet is bordered by a submeridional belt that seems to deflect the bands to the south. The orientation of the belt ridges can be traced inside the marginal part of parquet; however, the parquet material seems to overlap the belt structures in places, making their relationships uncertain. The intricate embayments at the parquet margins indicates a younger age for the plain-forming material in this area.

TETHUS REGIO

Tethus Regio appears to be an eastern section of Ishtar Terra, separated from it by a northeast trough (Figures 9, 10, and 11). The western part of the area is a domelike feature with two broad summits (heights of about 2 km above the surrounding plains). On each of the summits a deformed corona is visible. The eastern slope of the northern corona is covered by numerous subconcentric wrinkles. A tongue of material 120 km in length stretches down the slope. The southern part of the area is an elevated latitudinal belt of about 200 × 1300 km in size, made of en echelon bands 50–100 km in width with a southeast orientation. Each band is transected by numerous transverse ridges and furrows and resembles the predominant pattern found in the southeast part of Ishtar Terra. According to the Venera 15 and 16 altimetry the bands have high elevations (0.5–1.5 km) and are bordered by rather steep slopes. There is evidence of material overlapping parts of the surrounding area, although the contacts are usually covered by younger material.

A wedgelike trough extending from the northern corona cuts the belt. Its structural lines can be traced on both sides of the trough. The structure as a whole vaguely resembles the Red Sea zone.

TELLUS REGIO

Tellus Regio is a giant, gently sloping dome about 1500 km in diameter, elevated 1.5–2 km above the adjacent plains, which are close to the 6051-km datum. The surface of the dome is covered by systems of rather short (20–100 km) ridges and furrows with predominantly northwest and northeast orientations, causing orthogonal and diagonal patterns (Figure 12). The orthogonal system is most evident in the central apical part of the dome where the northwest and northeast lineaments can be almost continuously traced. On the slopes of the dome

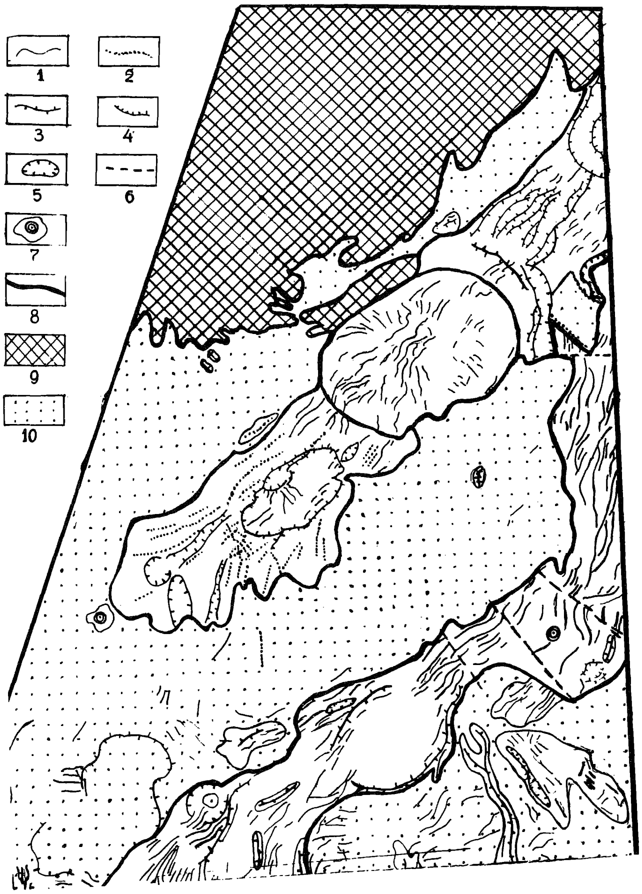

Fig. 14*b*

Fig. 15. Corona located at 64° N, 129° E, 450 × 530 km major diameters.

this pattern is gradually transformed into chevron-like and U-shaped patterns, with the "keystone" directed toward the borders of the dome (Figure 13).

The entire dome is transected by several large submeridional lineaments, some of which seem to be zones of detachment separating marginal parts from the main body of the dome. The southwest part of the dome is separated by several arc-like lineaments along which there is a system of flat-bottomed depressions parallel to the lineaments. Generally, the northwest and northeast lineaments can be traced in separate parts of the dome, but in the zone of flat-bottomed depressions the pattern becomes chaotic or shows flowlike structures oriented downslope. On the west and east the dome is bordered by linear belts, and, in places, material of the dome overlaps marginal parts of the belts. The northern and southern margins of the dome are covered with plain-forming material.

Near Tellus Regio, as well as in other places, there are commonly parquet areas with chaotic patterns scattered about the plain. The largest area of this type is at 47°-57° N, 125°-143° E; this area has dimensions of 500 × 1500 km and the appearance of a rectangular block elongated to the northeast 0.5-1.5 km high. The surface is deformed by irregular sinuous furrows having no definite orientation or constant angle of intersection. Within the block one can see deformed outlines of large craterlike features.

BELTS OF FURROWS AND RIDGES 2000 KILOMETERS SOUTHEAST OF MAXWELL MONTES

A unique feature in the surveyed territory is found here: a belt of furrows (Figure 14). This feature, about 1000 km long and 100-150 km wide, consists of subparallel systems of furrows both conformable with and oblique to the belt orientation. The furrows look morphologically fresh and are several kilometers wide and tens of kilometers long. At the southwest termination of the belt the furrows are braided into the plain and seem to be covered by the radar-bright, flowlike features of the plain. In the central part of the belt the furrows and intrafurrow ridges are arranged in radial-concentric patterns. In the northeast part of the belt the furrows are again subparallel to the general

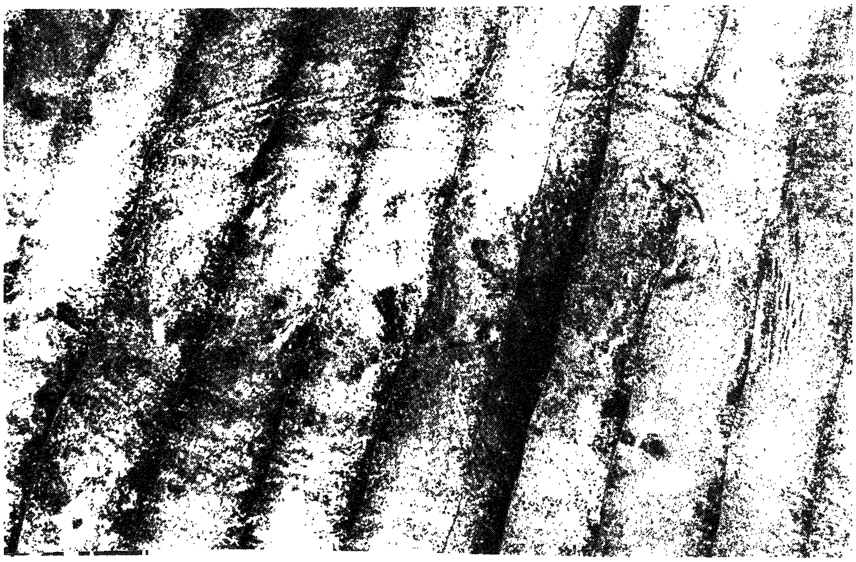

Fig. 16. Double corona located at 54°N, 295°E, 600 × 350 km major diameters.

orientation of the belt. Southeast of the furrow belt there is a belt of ridges more than 1000 kilometers long, 100–200 km wide that, in the southwest, merges into an areal system of the riages. The ridges are up to 100–200 km long, 10–20 km wide, and are closely spaced in subparallel and en echelon patterns.

CORONAE

Coronae are large (150–600 km diameter) circular feature made of subconcentric ridges and grooves (up to a dozen of them) that surround an inner zone of irregular relief. They are distributed mainly in a latitudinal belt 55°–80°N along the borders of Ishtar and Tethus Regio. Some of them are present on the plains to the south of this belt as a series of disconnected annular ridges protruding above the plains level.

Coronae differ from one another in their internal structures. The corona centered at 64°N, 129°E is one of the largest (450 × 530 km) and freshest (Figure 15). Altimetric cross sections show that it lies on a general southward slope, with parts of its interior being at a higher elevation than the surrounding terrain and some parts at a lower elevation. The annular structure, represented by a giant ridge 100–200 km wide and 0.7–2 km high, is surrounded in places by a broad moat. The slopes of the ridge are corrugated by concentric wrinkles, and its crest on the south is covered by short grooves perpendicular to the crest. On the inner slope of the north ridge is material with a flowlike or landslide-type pattern. The western and eastern parts of the ridge are covered by domes and flowlike features from several centers along the crest.

Similar though subdued structures are found in a double merging corona located at 54°N, 295°E (Figure 16). This structure is predominantly covered by plain-forming material,

Fig. 17. Corona located at 77°N, 279°E, 400 km in diameter.

Fig. 18. Corona located at 67°N, 280°E, 400 km diamter.

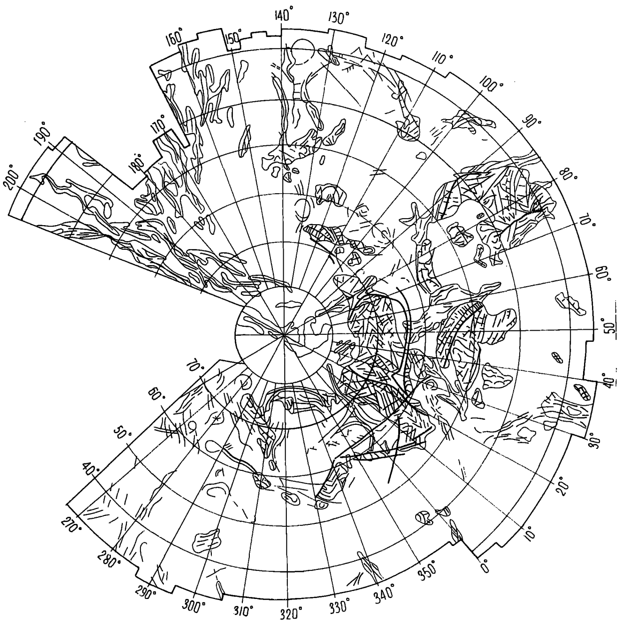

Fig. 19. The major orientations of the lineations of the terrains described in the text. Thick and thin lines correspond to major and minor lineations.

but a moat, a slightly uplifted interior, and an annular ridge 0.7–1.1 km high are present. Another example is a lesser corona at 68° N, 131° E. It is a dome 1.5 km high with base diameter of 300 km and a summit calderalike plateau 150 km across; the slopes of the dome are covered subconcentric ridges atypical of volcanoes. The same structure characterizes a 200-km corona at 68° N, 299° E.

The corona at 77° N, 279° E (Figure 17) is also a dome 0.7 km high with concentric structures on the slopes, but instead of being a plateau its summit seems to be made of several domelike constructions. Like the first of the previously mentioned coronae, it is surrounded by a gentle annular moat; radar-bright, flowlike features occur around the corona.

The corona at 67° N, 280° E (Figure 18) looks in cross section like a broken plateau uplifted to 0.5–1.2 km, and in plain view it is a combination of concentric external ridges and furrows and subradial ridges and furrows in the inner part. A subradial system of radar-bright, flowlike features surrounds the corona. Some coronae have internal parts lower than the surrounding terrain (40° N, 272° E), but they are usually mantled with plain-forming material and are difficult to interpret. Other coronae are associated with belt deformations, but their relations are not obvious.

INTERPRETATIONS

Because of the lack of large-scale erosion [*Ivanov et al.*, 1986] the described structures must have been formed at the surface of the planet, and *Anderson's* [1951] considerations apply. He pointed out that since the surface of a planet must be a plane across which there is no shearing stress, for surface deformations to occur one of the principal directions of stress must be vertical. This should simplify the geodynamic interpretation of the structures. *Hobbs et al.* [1976] stated that the easiest case to interpret is that of conjugate faults. The intersecting sets located on the parquet to the east of Maxwell Montes satisfy the criteria of being conjugate faults, i.e., they intersect nonorthogonally, and one set does not consistently offset the other. The direction of maximum stress then bisects the smaller angle of intersection of the lineations; the direction of minimum stress is perpendicular to it, both lying on the surface of the planet. In the case of the single set of lineations, as found on Maxwell Montes and on the belts, the direction of maximum stress is perpendicular to the lineation, and the direction of minimum stress is vertical. The shear zone southwest of Maxwell Montes confirms this interpretation (Figure 4). In the case of the orthogonally patterned parquet southeast of Ishtar Terra and in Tethus Regio, the maximum stresss seems to be at a small angle to the elongated valleys, along which shearing may have occurred.

Figure 19 depicts the major orientations of the lineaments in the described terrains, Figure 20 shows the approximate direction of the major stresses on different areas of Venus. Work is in progress not only to refine this map, but also to include the orientation of the intermediate stress, which changes from vertical to horizontal as a result of tectonic conditions yet to be interpreted [*Ronca and Basilevsky*, 1985].

Although preliminary, Figures 19 and 20 show a strong east-west orientation that is reminiscent of the east-west zonality of the large-scale orographic features [*Barsukov et al.*, 1986].

Possible relationships with the axis of planetary rotation have yet to be analyzed. The origin of the stresses themselves could be the drag of the lithosphere by asthenospheric currents, gravity-induced spreading of surface material above upwellings in a manner similar to glacier flow, a combination of the two, or other precesses not yet postulated.

Whatever the causes of the stresses, there is little doubt that both compressions and extensions have occurred. The parallel ridge-and-groove terrains surrounding Lakshmi appear to result from compression. Evidence of extension, at least in places, can be seen in the orthogonally patterned parquets of the southeast part of Ishtar Terra and in the Tethus Regio in the form of systems of transveral open faults; there is evidence as well of shearing that is probably from differential stress.

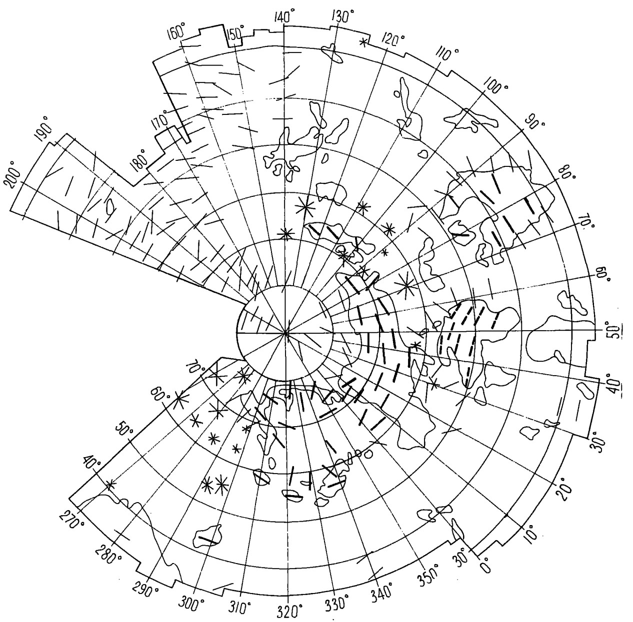

Fig. 20. The inferred orientations of the direction of maximum stresses as deduced by the method described in the text. Dashed lines represent a more approximate direction than full lines. Thin lines refer to belt deformations.

Belt deformations occurred mainly on the plains and indicate concentrations of horizontal stresses within relatively narrow zones. They generally conform with the stress orientation of the adjacent zones of areal deformations, suggesting their possible consanguinity. The belt of furrows 2000 km southwest of Maxwell Montes is very likely to be the result of extensional deformations. The ridge belts, which in their morphology resemble the systems of subparallel ridges surrounding Lakshmi Planum, may be the result of compressional deformations.

An example of areal deformation merging with belt deformation can be seen on Maxwell Montes and its surroundings, again suggesting consanguinity of the two types. Their difference stems from changes in the orientation of the direction of the intermediate stress, which may be caused by changes in characteristics of the deformed material or of the asthenospheric currents.

The circular structures referred to as coronae tend to be locally concentrated, especially at the eastern and western margins of the areal deformation zones of Ishtar Terra (Figures 19 and 20). Many of them are associated with patterns that appear to be lava flows, suggesting a relationship with volcanism and therefore endogenous processes. Applying *Anderson's* [1951] principle that one of the principal axes of stress must be perpendicular to the surface, the coronae appear to be the result of having the maximum axis of stress vertical, as could be caused by a vertical plume (hot spot) and possible accompanying gravity tectonics. Work is in progress to develop models for this process.

The age of the deformations is not clear. The absence of densely cratered terrains indicates that all the observed surfaces, including the tectonically deformed areas, are significantly younger than the period of heavy bombardment of the planets (4×10^9 years). The average age of the area under study, deduced from the statistics of large impact craters, is about 0.5–1.0 $\times$ 10^9 years [*Ivanov et al.*, 1986]. The age of individual types of terrain could be in some cases older than these values, in other cases, younger, possibly up to very recently. However, the areal distribution of craters is quite uniform [*Ivanov et al.*, 1986] so that very young areas, both in their formation and their deformation, can only be local.

Judging by the presence of the patches of parquet covering parts of the studied area, their boundaries often embayed by plain-forming material, it is likely that parquet terrain has been stratigraphically covered in many places and therefore areal deformation was more extensive in the past than can be seen

CONCLUSIONS

Until the hazes of Venus were pierced by Veneras 15 and 16, the predominant question on its tectonics was whether plate tectonics operated or whether the surface consisted of ancient terrains partly covered by lavas. Now we can conclude that, at least in the area covered, terrestrial-style plate tectonics does not exist, but ancient terrains are also not observed. The surface of Venus was subjected to a different type of tectonics, consisting of three major types of deformations: areal, beltlike, and circular. The first two were formed by horixontal stresses, which are typical of the Earth but not of the moon, Mars, and Mercury. The circular features, probably caused by vertical stresses, have possible analogs only in some ovoidal structures of the early Cryptozoic period of the Earth [*Glukhovsky and Pavlovsky*, 1984]. These considerations verify the planetological "law" that the larger the terrestrial planet, the more complex is its endogenic life.

REFERENCES

Anderson, E., *The Dynamics of Faulting*, 206 pp., Cliver A. Boyd, Edinburg, 1951.

Basilevsky, A. T, B. A. Ivanov, V. P. Kryuchkov, R. O. Kuzmin, A. A. Pronin, and I. M. Chernaya, Impact craters of Venus according to data from radar images of Venera 15 and Venera 16 (in Russian), *Dokl. SSSR, 282*, 671–674, 1985.

Barsukov, V. L., and A. T. Basilevsky, Comparative planetology: Some results and outlooks (in Russian), *Proc. 27th Int. Geol. Congress, 19*, 3–11, 1984.

Barsukov, V. L., A. T. Basilevsky, A. A. Pronin, R. O. Kuzmin, V. P. Kryuchkov, O. V. Nikolaeva, I. M. Chernaya, G. A. Burba, N. N. Bobina, V. P. Shashkin, V. A. Kotelnikov, O. N. Rzhiga, G. M. Petrov, Yu. N. Alexandrov, A. I. Sidorenk, V. M., Kovtunentko, R. S. Kremnev, A. F. Bogomolov, M. N. Meshkov, N. V. Zherikhin, Yu. S. Tyuflin, E. L. Akim, M. S. Markov, and A. L. Sukhanov, First results of geologic-morphologic analysis of radar images of Venus surface obtained by Venera 15 and 16 space probes (in Russian), *Dokl. SSSR, 279*, 946–950, 1984*a*.

Barsukov, V. L., A. T. Basilevsky, R. O. Kuzmin, A. A. Pronin, V. P. Kryuchkov, O. V. Nikolaeva, I. M. Chernaya, G. A. Burba, N. N. Bobina, V. P. Shashkina, M. S. Markov, and A. L. Sukhanov, Venus geology according to the results of analysis of radar images obtained by Venera 15 and 16 (preliminary data), (in Russian), *Geokhimiya, N12*, 1811–1820, 1984*b*.

Barsukov, V. L., A. T. Basilevsky, G. A. Burba, N. N. Bobina, V. P. Kryuchkov, R. O. Kuzmin, O. V. Nikolaeva, A. A. Pronin, L. B. Ronca, I. M. Chernaya, V. P. Shashkina, A. V. Garanin, E. R. Kushky, M. S. Markov, A. L. Sukhanov, A. I. Sidorenko, A. F. Bogomolov, G. I. Skrypnik, M. Y. Bergman, L. B. Kudrin, I. M. Bokshtein, M. A. Kronrod, P. A. Chochia, Yu. S. Tyuflin, S. A. Kadnichansky, and E. L., The geology and geomorphology of the Venus surface as revealed by the radar images obtained by Veneras 15 and 16, *Proc. Lunar Planet. Sci. Conf. 16th*, this volume, 1986.

Glukhovsky, M. Z., and E. V. Pavlovsky, The rings structures of the early stages of Earth's development (in Russian), *Proc. 27th Intl. Geol. Congress, 19*, 65–74, 1984.

Hobbs, B. E., W. D. Means, and P. F. Williams, *An Outline of Structural Geology*, 571 pp., Wiley, New York, 1976.

Hubert, M. K., and W. W. Rubey, Role of fluid pressure in mechanics of overthrust faulting, *Geol. Soc. Am. Bull., 70*, 115–206, 1959.

Ivanov, B. A., A. T. Basilevsky, V. P. Kryuchkov, I. M. Chernaya, Impact craters of Venus: Analysis of Venera 15 and 16 data, *Proc. Lunar Planet. Sci. Conf. 16th*, this volume, 1986.

Phillips, R. J., and M. C. Malin, Tectonics of Venus. *Annu. Rev. Earth Planet. Sci., 12*, 411–443, 1984.

Ronca, L. B., and A. T. Basilevsky, Maxwell Montes and Thesera Fortuna: A study of Venera 15 and 16 radar images, *The Earth, Moon, and Planets*, in press, 1985.

A. T. Basilevsky, A. A. Pronin, and V. P. Kryuchkov, V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

A. L. Sukhanov and M. S. Markov, Geological Institute, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

L. B. Ronca, Department of Geology, Wayne State University, Detroit, MI 48202.

(Received March 15, 1985;
revised August 6, 1985;
accepted August 19, 1985.)