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GEOLOGICAL-MORPHOLOGICAL DESCRIPTION OF THE LAKSHMI PLANUM (PHOTOMAP OF THE VENUSIAN SURFACE SHEET B-4)

A. A. Pronin et al.

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16. Abstract

The morphological description of Lakshmi Planum and its surroundings is given: they are parts of a single structure. It is suggested that the mechanism of plume ascent from planetary interiors and its horizontal spreading is responsible for the structure formation. Folding and/or imbricating are the result of the process. Thus the Lakshmi structure can be considered a local center of radial spreading. The structure dimensions suggest that asthenospheric currents have been involved in its formation.

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GEOLOGICAL-MORPHOLOGICAL DESCRIPTION OF THE LAKSHMI PLANUM (PHOTOMAP OF THE VENUSIAN SURFACE SHEET B-4)*

A. A. Pronin et al.

FOREWORD /83**

One of the goals in radar mapping of Venus from the Venera-15 and -16 unmanned interplanetary stations (AMS) is to create a series of photomaps and geological-morphological maps for the regions scanned. Maps of Venus' surface are created in separate sheets on map frames. Map sheet B-4 covers the Lakshmi Planum in the center, framed by Venus' very large mountain structures -- the Akna and Freiya Montes to the northwest and north and the Maxwell Montes to the east. The southern framing of the planum is the Vesta Rupes.

Corners of the map frame B-4 have Venusian graphing coordinates: $\varphi_1=80^\circ$, $\lambda_1=300$, $\varphi_2=80$, $\lambda_2=60$, $\varphi_3=60$, $\lambda_3=300$, $\varphi_4=60$, $\lambda_4=0^\circ$. When photomaps were created to overlap with related photomaps, their boundaries exceeded the limits of the area of the map frames established.

PLOTTING PHOTOMAPS OF VENUS' SURFACE

From November 1983 through July 1984, the Venera-15 carried out radar scanning of the northern regions of Venus' surface to about 30° latitude. Scanning and radio-profiling for height were done using a set of radar equipment including panoramic /84
radar and a radar altimeter created in the Experimental Design Bureau of Moscow Power Engineering Institute. Signals reflected from the surface were processed, and individual radar panoramas

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* With this and the next article, the editors begin a series on creation of photomaps of the surface of Venus' northern hemisphere on the basis of materials from Venera-15 and -16.
** Numbers in the margin indicate pagination of the foreign text.

and profiles of surface heights were synthesized in the USSR Academy of Sciences Institute for Radio Engineering and Electronics (IRE). Radar panoramas were converted into cartographic projections and plan views of Venus' surface were created jointly by the IRE and the F. N. Krasovskiy Central Research Institute for Geodesy, Aerial Photography, and Cartography /1/. The M. V. Keldysh Institute of Applied Mathematic of the USSR Academy of Sciences precisely determined the station's movement and calculation elements of the orbit of photographic loops. Geological-morphological analysis was done in the USSR Academy of Sciences' V. I. Vernadskiy Institute of Geochemistry and Analytical Chemistry, as well as in the Academy's Geological Institute.

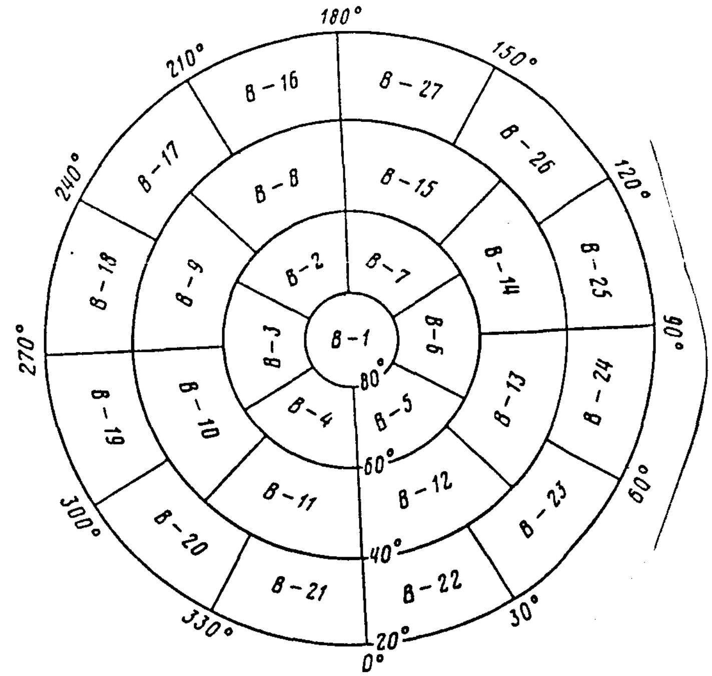

Fig. 1. Breakdown of Venus' northern hemisphere into map frames.

When the 1:5,000,000-scale photomaps were created, the surface of Venus' northern hemisphere covered by radar scanning was arbitrarily divided into 27 map frames (fig. 1). Photomaps numbered from B-2 to B-27 were plotted in normal Lambert-Gauss conical projections in latitudes from 20 to 80°. To reduce distortion in the switch from a spherical surface to the map plane for each 20-degree latitude belt, the values for the latitudes of two standard parallels on the cartographic projection were calculated. For the latitude belt from 60 to 80°, which includes photomap B-4, values for the standard parallel latitudes are as follows:

$$\varphi_1=63°18'00,0'', \quad \varphi_2=77°30'00,1''.$$

Entire photomaps are plotted on the basis of map frames by digital method using a computer and image output systems [1]. The digitizing cell on the photomaps corresponds to a locale of about 1 km. The position of relief cells on the photomaps is given in the Venusian graphic coordinate system recommended by the Working Group on Cartographic Coordinates and Elements of Planet and Satellite Rotation of the International Astronomical Union [4]. Readings of relief point heights are taken, as when cartographic projections are calculated, from the leveled spherical surface 605.1 km in radius used for Venus.

MORPHOLOGICAL DESCRIPTION OF THE REGION

Lakshmi Planum. For the most part, the Lakshmi Planum is, in plan view, an irregular hexagon with rounded corners and cross section of about 1,400 km, a trapezoidal projection to the north, and an extended projection to the east to the foothills of the Maxwell Montes (fig. 2). The planum's level surface is 4-4.5 km above the accepted leveled surface of Venus and is complicated by several small structures. These primarily include Colette in the center of the western half of the planum, which is extended along the meridian of an oval measuring about 130x80 km and about 2 km deep. Within up to 250 km of Colette there are narrow bands and scalloped areas of surfaces which appear bright to radar. These surfaces are oriented radially relative to the pater. On the whole, Collette, with a system of diverging flows, is a gigantic plate volcano about 600 km in cross section slightly extended at the meridian and occupying almost the entire western half of the Lakshmi planum (fig. 3).

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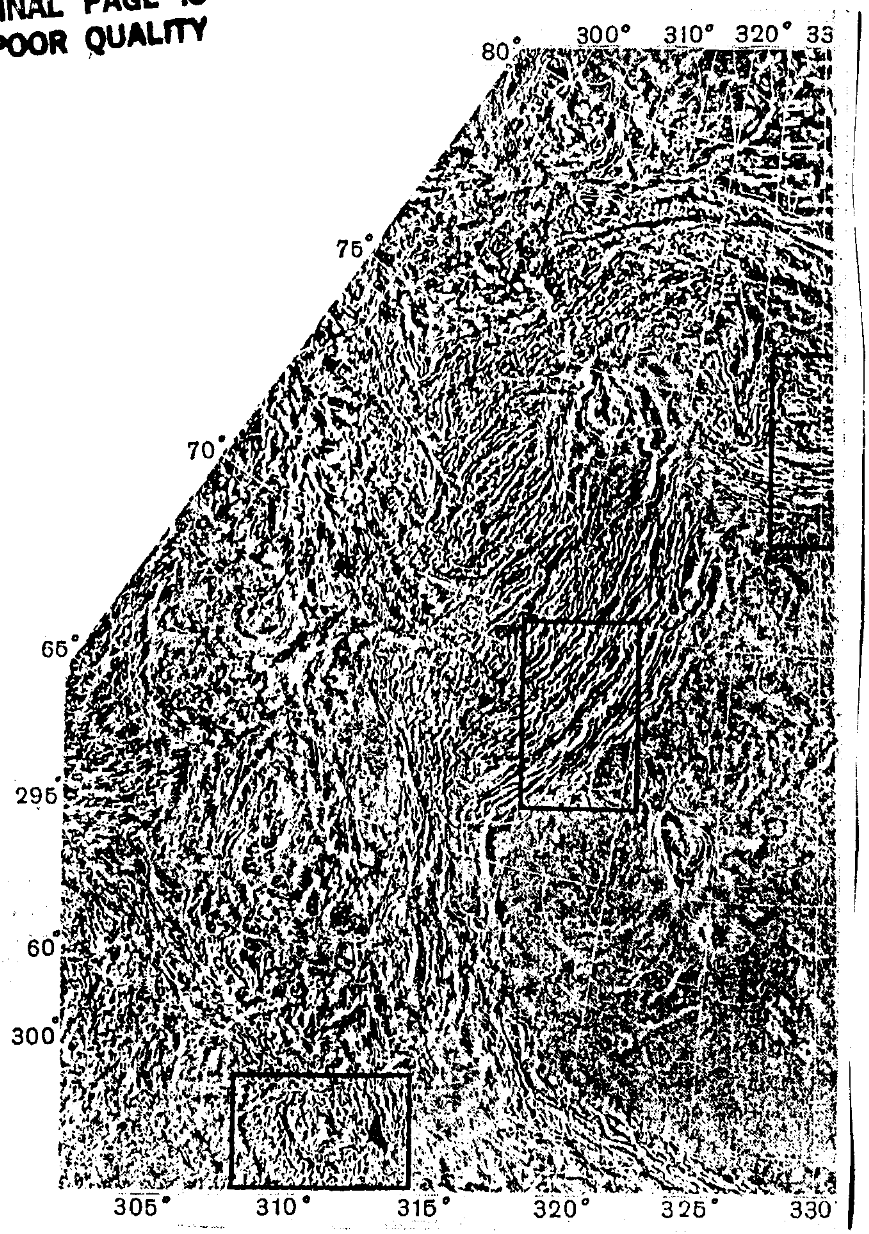

Fig. 2(a)

There is another oval depression -- Sacajewea, measuring 200x120 km and about 1.5 km deep -- in the center of the western half of the plateau. It is oriented northeastward. The depression is less pronounced than Colette. Its presence is indicated not only by hypsometry, but also by two concentric light ovals and a horseshoe-shaped dark spot at its center.

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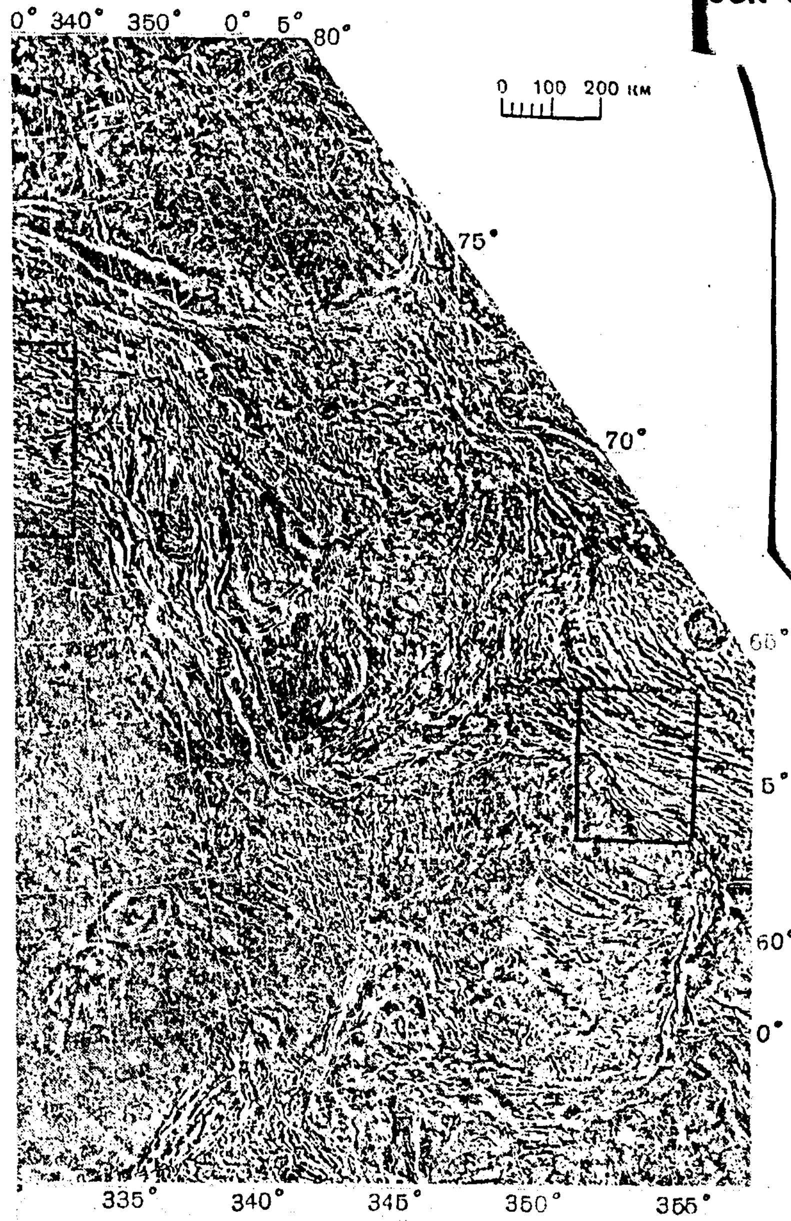


Fig. 2(b)

To the north of Sacajewea, a band of flat-topped uplands extends latitudinally across the entire eastern half of the plateau rising an average of 500 m above the floor of the plateau. The nature of the relationship of the plateau's plains material to that of the uplands along the irregular boundaries makes it possible to consider these uplands residual mountains. Their surface, marked by a diagonal grid of ridges and grooves apparently bears traces of earlier deformations which did not /88

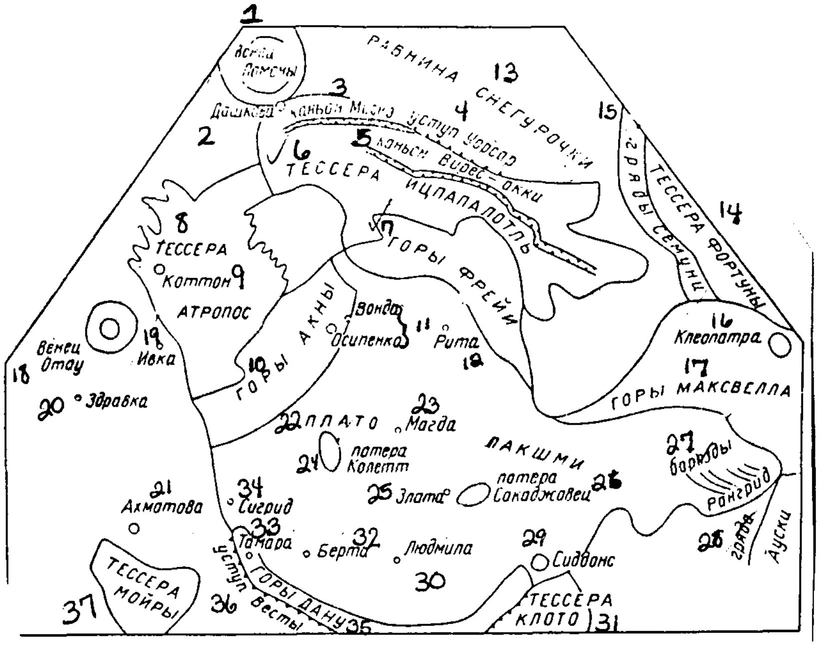


Fig. 2. Photomap of Lakshmi Planum and surrounds. Contours indicate fragments shown in fig. 3-6; (a) diagram of planetographic names (b).

Key: (1) Pomona Crown; (2) Dashkova; (3) Misne Canyon; (4) Worsar Scarp; (5) Viresacci Canyon; (6) Tessera Itzpapalotl'; (7) Freiya Montes; (8) Tessera Atropos; (9) Cotton; (10) Akna Montes; (11) Wanda Osipenko; (12) Rita; (13) Snow Maiden Plain; (14) Tessera Fortunae; (15) Semuna Ridge; (16) Cleopatra; (17) Maxwell Montes; (18) Otau Crown; (19) Ivka; (20) Zdravka; (21) Akhmatova; (22) Lakshmi Planum; (23) Magda; (24) Colette; (25) Zlata; (26) Sacajewea; (27) Rangrid Trenches; (28) Auski Ridge; (29) Siddons; (30) Lyudmila; (31) Tessera Clotho; (32) Berta; (33) Tamara; (34) Sigrid; (35) Danu Montes; (36) Vesta Rupes; (37) Tessera Moira.

affect the younger plains deposits of the Lakshmi Planum.

Mountains Framing the Lakshmi Planum. In the south, the main massif of the planum is framed by a belt about 100 km wide (Danu Montes) consisting of linear ranges and valleys between them, which are oriented almost everywhere along the edge of the planum. Individual ranges within the belt extend for tens of kilometers (to 100 km) in length and are 10-15 km wide. In relief, the 3-5-km-high Vesta Rupes, which is turned southward, corresponds to the belt of linear ridges so that the regional descent to the scarp rises in places above the planum's surface. The base of the scarp in places overlies the more southern area of unordered relief and conceals it (fig. 2).

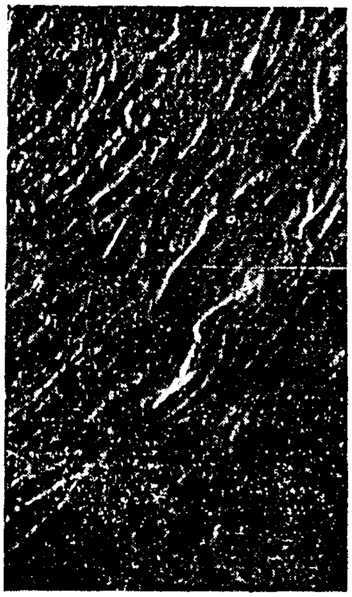


Fig. 3. Point where the Lakshmi Planum and Akna Montes meet. A parallel system of asymmetric ranges with steep sides facing the planum. As one moves away from the planum, the typical length of the range diminishes. Size of the area: 240x400 km.

Fig. 4. Tessera Moira -- presumably the end of a huge flow of plastic material from the southwestern edge of the Lakshmi Plateau. Area size: 240x400 km.

To the west the planum is bounded by a swell running along the meridian, which is broken by the scarp toward the west. The swell's surface displays steep cracks which are most often gaping tension cracks. The largest runs northeastward about 150 km and is less then 10 km wide. A structure of pronounced relief abuts the Lakshmi frame in the southwest corner of the sheet. It takes the form of a disk about 300 km in cross section bounded by a sharp scarp, and it overlies the surface of the hilly plains (fig. 4).

To the northwest, the planum's boundary is the foothills of the Akna Montes, which rise 2.5 km above it. At its highest part, the massif of the Akna Montes is complicated by a series of asymmetric ranges and depressions up to 300 km long and 50 km wide with short, steep sides facing the planum and long flat anticounters. In plan, these are echelon-shaped cuesta complicated by the same structures of higher orders of magnitude (fig. 3). Toward Tessera Atropos, the typical size of structures and height of mountains decreases. The maximum length of an individual range here is no more than 100 km, and this entire complexly structured mountainous land extends northward to the boundary with the Snow Maiden Plain.

In the north, the main massif of the planum has a trapezoidal projection framed by the massif of the Freiya Montes. At its highest, the massif consists of a system of linear ranges up to 200 km long and 5-15 km wide oriented in the sublatitudinal direction. This ordered system of parallel ranges appears in a sublatitudinal band 150 km wide and 400 km long. The eastern band of ranges bends southward, and at the planum's adjoining surface there are bands, which appear light on radar, /90
less than 10 km wide parallel to the edge of the planum and, at the bend of the frame, forming a grid with rhombic cells. The highest parts of the massif rise 2.5-3.0 km above the planum (fig. 5).

The mountain lands to the north (Tessera Itzpapalotl') are characterized by a less orderly relief. Their eastern portion is dominated by sublatitudinal stretches of ranges, but they are relatively orderly only within the limits of phacoidal blocks measuring 200x100 km. They are also sublatitudinal and are divided by fractures which appear along the transitions from structures and troughs (Misne and Viresacci Canyons). To the north, Tessera Itzpapalotl' is bounded by the steep 2.5-km-high Worsar Rupes, which frames the Lakshmi structure from the north for 1,500 km (fig. 2).

East of the Freiya Montes, the Lakshmi Planum's generally continuous framing is interrupted by an expansive basin whose bottom adjoins the Snow Maiden Plain. Swell-like structures of Lakshmi's exterior framing descend from the northwest to the isometric depression of the basin 600-700 km in cross section and a bottom 2.5-3.0 km above the surface. They are submerged beneath the material of the plain, which covers them along meandering contact areas. The eastern boundary of the basin is Semuna Ridge -- a band of structures 600-700 km long. Ridges and associated grooves extend along the meridian and are typically 100 km long and 10-15 km wide. The northern end of the belt is submerged beneath the surface of Snow Maiden Plain, while the southern end abuts the massif of the Maxwell Montes. To the east of Semuna Ridge, in the field of development of the Tessera Fortunae there are swell-like structures which are apparently a continuation of the Lakshmi's external framing. Their T-shaped conjugations with the belt of Semuna Ridge indicates that the belt is a superimposed structure (fig. 2).

On the southeast side of the basin is a snakelike range about 400 km wide and 50-60 km long cramped between two rifts. Its center consists of three separate massifs, which look like phacoidal masses measuring 50x60 km of relatively rigid rock submerged in a more plastic mass. The similarity is emphasized by systems of narrow conjugated ridges and grooves oriented conformally to these masses and resembling flow lines. Farther to the southeast a steep uplift toward Maxwell massif begins.

Eastern ledge of the Lakshmi Planum and Maxwell Montes. On the latitude of Sacajewea the Lakshmi Planum has a 200-300-km-wide scarp extending eastward for 800 km. Its eastern

extremity rests in the foothills of the Maxwell Montes, which rise more than 5 km in a steep scarp over the planum. The planum's surface rises slightly to the east: at center, the Lakshmi Planum is 3.0-3.5 km high, but at the foothills of the Maxwell Montes, it is 5.5 km above ground level. In the southeastern corner of the ledge, the planum's surface is intersected by the series of parallel arc-shaped Rangrid /91
Trenches which run northwest; their southeastern ends are as wide as 10-15 km, disappearing toward the northeast. Judging by the nature of the radar reflection, they are V-shaped in cross section with no indication of swells along the sharp edges. Similar smaller trenches exist along the entire southern edge of the planum's scarp. Tension conditions were obviously necessary to form these trenches (cf. figure 6).

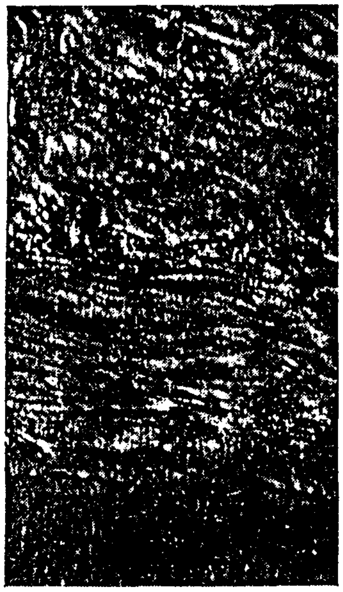
The northwestern part of the Maxwell Montes massif appears on sheet B-4. It is divided into several zones according to hypsometry and the figure on the relief. The southwestern slope of the massif is cut subparallel to the foothills by a system of conjugated ridges and trenches as much as 5 km wide and 100 km long. On the basis of the displacements of the striated structure, one can identify several large masses, phacoidal in plan, also subparallel to the foothills. On the Planum's surface along the edge of the massif, there is a system of asymmetric ridges with sharp western and gently inclined eastern slopes. These ridges are not pronounced in hipsometry and lie on a high level of the planum. One gets the impression that it is precisely here that the Lakshmi Planum's surface layer cleaves into lamellar masses sloping to the east which are "tightly packed" on the western slope of the Maxwell massif.

The relief in the massif's center varies drastically; the boundary with the steep western slope is almost straight, coinciding with the structure's fault line. This part of the massif is typified by asymmetric ridges (to 200 km) 20-25 km wide, seemingly consisting of plates sloping to the west, since their eastern "illuminated" slopes are usually narrower (less then 10 km), while the western slopes are wider. On the whole, the picture of the slopes facing the radar resembles a system of screen cells highly stretched to the northwest. This zone reaches the area of maximum massif altitude, but during mapping with a resolution of 500 m, the peak of the massif seems almost flat (gradients here are one order of magnitude lower than on the western slope). The zone is 200 km wide and 400 km long. To the northwest, the surface of the massif gradually descends toward an area of chaotic relief, where altitudes are, on the average, the same as those on the eastern scarp of the Lakshmi Planum. There is a large (130-km diameter along the external swell) double-ring structure similar to an impact crater approximately in the center of the slope.

All the massif's slopes except that facing Lakshmi on the southwest are characterized by a radar-bright surface and "unordered" relief. In the northwest, the jagged, irregular boundary of the massif's central zone, which has a large relief pattern, meets an area drastically different in structure pattern, orientation, and surface roughness. The areas extend 400 km to the northeast; the area's northwestern boundary is relatively straight, and in the southeast it has two triangular ledges projecting into the massif's central zone. The irregularities of the gently sloping "wrinkly" relief are /92
intersected by blotches and lines with low reflectance which look like gaping rifts on a stereo model.

The relief of the massif's northwestern slope (off the sheet) is also unordered: there are relatively short (20-30 km) ridges and hillocks and only in individual places is the parallel-striated ordered structure preserved.

The unordered relief, whose components are short ridges and trenches, is also pronounced on the massif's southern slope (off the sheet). Here it is organized into something resembling swells repeating the outline of the massif's boundaries and almost precisely following the direction of the isohypse, which may be attributable to material slipping downward along the slope.



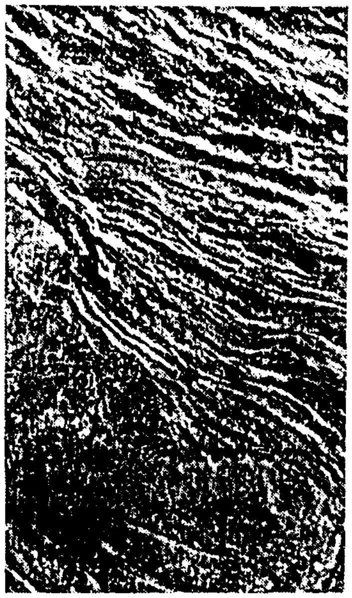


Figure 5. Conjugation of the Lakshmi Planum and the Freiya Montes. The system of asymmetric subparallel ranges in the center becomes the area of unordered relief at the top. The area measures 240x400 km.

Figure 6. The point where the eastern ledge of the Lakshmi Planum merges with the Maxwell Montes. In the center, compressed structures of the steep southwestern slope of the massif, which is abutted by the area of the planum broken up into lammelar masses; at the top is the area of the central zone of crevices on the anticline of the uplift. Bottom left, Ringrid Trenches. The fragment measures 240x400 km.

The exterior boundaries of the radar-bright areas of the massif's slope are traced according to the abrupt change in albedo in the radar range, while the similarity of reliefs

makes it possible to combine them into an independent system /93
or type of locale framing the central zone of the Maxwell Montes massif (see also [2]).

IMPACT CRATERS

In addition to the Cleopatra Crater mentioned above, presumably originating in an impact, the Lakshmi Planum and its mountainous frame contain several craters bearing clear evidence of origin in impact. Noteworthy among these are the crater Ivka (68°N, 304°E) lying on flat terrain and exhibiting a bright butterfly-shaped zone of ejecta, and the crater Cotton (71°N, 300°E), superimposed on the mountainous terrain and also with a bright zone of ejecta. Several smaller craters appear on the surface of the planum itself: Rita, Magda, Zlata, Berta, and Lyudmila.

INTERPRETATION OF GEOLOGICAL STRUCTURE

The youngest formations on the Lakshmi Planum are areas of the planum itself formed by outflows of molten lava from the two largest centers -- Colette and Sacajewea, as well as from several smaller ones. The considerable spread of the relief of Colette, equal in size to Sacajewea, and the clearly pronounced boundaries of individual flows evidence Collette's relative youth. Elevated monadnocks with intersecting systems of cracks which indicate a tension stage preceding formation of a lava plane, project from beneath the surface of the lava flows [3].

On the margins of the planum (the foothills of the Frain and Maxwell Montes) it is obvious that planum material is involved in formation of the mountainous framing. One can assess the structure of the mountainous regions on the basis of stereo models of places where scanning conditions permit. The adequacy of the stereo model is assured by comparing it to altimeter data and to the relatively well known morphology of impact craters. Analysis of stero images shows that significant parts of the Akna and Freiya Montes massifs are systems of asymmetric chains with uplifts conforming to the planum, and this may obliquely point to their common origin. These systems of asymmetric subparallel chains may occur both with a mass (lamellar) and scalar structure. However, regardless of the mechanism, their formation requires the presence of a relatively rigid surface layer about 10 km thick [5] and conditions for horizontal compression. Toward the periphery of Lakshmi's structure, the degree of disorder in the structure of the Akna and Freiya Montes structures (Tessera Atroposa and Itspapalotl') increases, which may indicate a complicated history of deformations and an increase in the age of the structure in this direction (fig. 7).

The zone of linear ranges in the southern framing generally /95 does not rise or rises slightly over the surface of the planum, and the slopes on the Vesta Rupes may amount to several degrees. Given this regional gradient in the structure of Lakshmi's framing, they can form in the south if there is passive gravitational flow of the planum's massif, which may be promoted by high surface layer temperatures [6]. More active forces of horizontal compression apparently took part in the development of the Akna and Freiya Montes, which rise above the level of the planum.

The disk-shaped structure to the southwest of Lakshmi's exterior framing (Tessera Moira) is indirect evidence of the horizontal flow of matter from the Vesta Rupes. This structure resembles the end of a gigantic flow of plastic material emerging or expelled from beneath the edge of the planum. Toward the planum, its surface with flow structures gradually assumes a hummocky relief with fissures resembling settlement cracks. This pattern may occur when a flow trapped by the roof of the niche where it begins moves.

The eastern projection of Lakshmi abruptly merges into the steep foothills of the Maxwell massif with its scarp 5 km high,

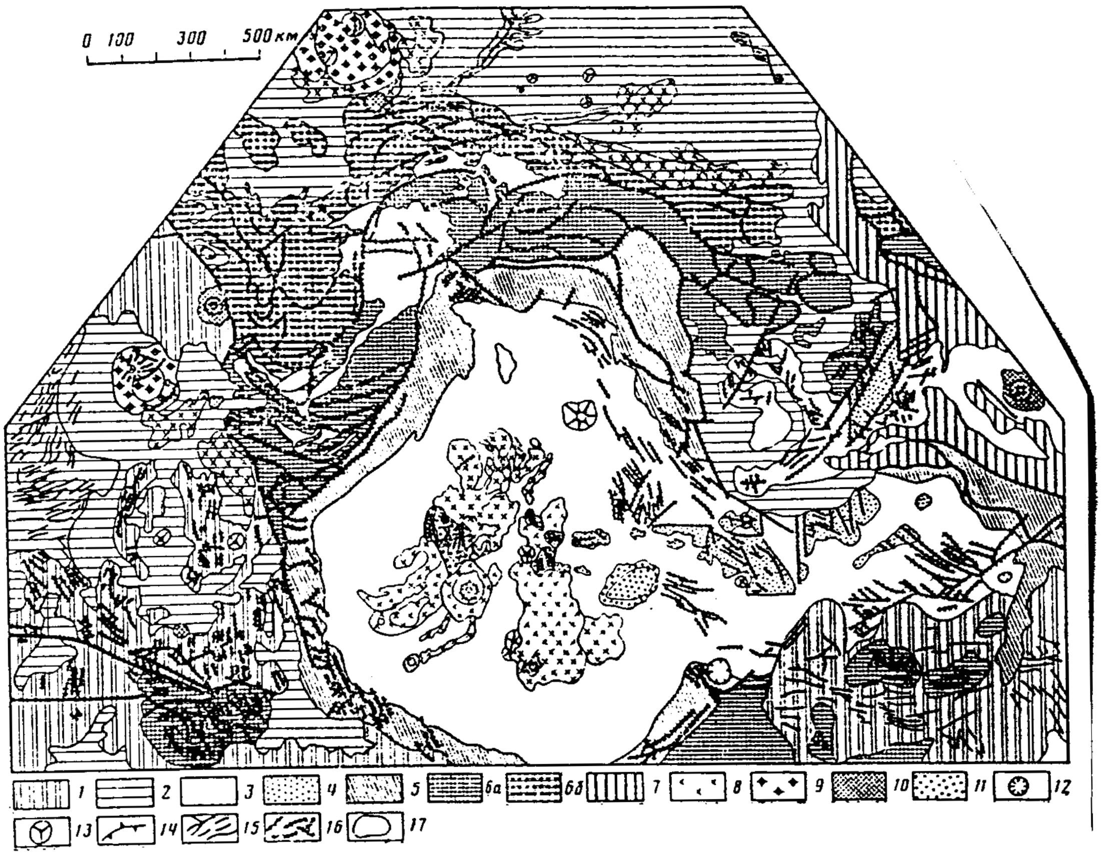


Figure 7. Geological-morphological map of the Lakshmi Planum and surrounds. Labeling: 1 - System of hilly plains; 2 - System of relatively young plains and lava flows; 3 - System of rocks on the Lakshmi Planum itself; 4 - Monadnocks of the intersected relief within the Lakshmi Planum; 5 - System of interior framing of the Lakshmi Planum; 6 - System of exterior framing (a, b - less and more disordered relief, respectively); 7 - System of linear structures in the anticline of the Maxwell massif and Semuna Ridge; 8 - Individual lava flows with visible borders; 9 - Ovoids; 10 - Impact craters with zones of ejecta; 11 - Caldera; 12 - Rounded depressions of unknown origin; 13 - Cupola; 14 - Axial swell lines; 15 - Lineaments on the surface of the plains with pronounced albedo; 16 - Fault lines (discontinuity or displacement in structures); 17 - Geological boundaries.

where compressed structures are oriented across the direction of the bench. Structurally, the situation is similar to that of the foothills of the Akna and Freiya Montes. Here also, material in the planum's surface layer is involved in formation of the massif, along with active forces of horizontal compression. All three situations are explained from the standpoint of horizontal surface flows of matter, emerging radially from the center of Lakshmi (cf. figure 8).

In the case of the Maxwell massif, the picture is augmented by the existence of sublatitudinal shears on its northern and southern borders. Shear on the northwest boundary is evidenced by protracted channels marking "ground in" fault lines and, squeezed between them, hard phacoidal blocks on one side of the faults and gaping rifts on the other. This situation is part of a pattern of rightward shear interrupting the Maxwell Montes massif on the northwest. In the south, the eastern projection of Lakshmi and the Maxwell Montes are intercepted by an extended latitudinal fault line which is also a shear, but with leftward movement and a significant vertical component. Evidence of shear are the Rangrid Trenches -- primarily shears -- and the Auska Ridges, which resemble compression swells meeting the shear in the south at an acute angle. Latitudinal shears which bound the planum's bench and the Maxwell massif obviously act as transformation faults which permit flows of matter to move in various places at various speeds.

We must discuss a type of radar-bright locale with disordered relief on the slopes of the Maxwell massif. It is apparently a single geological system, as can be judged from the relief pattern, phototone, and the clarity of the dissemination boundaries. On the northwestern slope of the massif, it looks like a mantle lying on the striated structures of the Semuna /96
Ridges and central zone of the massif. However, the mantle's disordered relief indicates that it probably deformed when the belt formed and underwent tension until gaping rifts appeared.

Light areas with irregular edges which in terms of relief might be mantle separations are involved in the structure of the surface of the offshoot of the Maxwell massif which extends far to the west, especially since there is a dark striated structure between them which is typical for the central zone of the massif. On the other hand, these areas are almost tightly abutted against the northern edge of the eastern projection of the Lakshmi Planum. This gives rise to the thought that the mantle itself may be complicated by deformed lava beds of the planum. The system of the steep western slope of the massif is essentially also complicated by deformed rock of the Lakshmi Planum's surface layer, since it is clear that the planum's matter is involved in formation of the massif at its foothills. However, here we see the result of deformations from intense compression, which led to "tight packing" of lamellar masses "cut" from the planum's material.

The central zone of the massif, with its large striated relief, looks entirely different from the compressed structures of the western slope. It most resembles a system of huge conjugate echelon-structured rifts which arose due to tension on the massif's anticline. On the basis of this assumption, the formation of the massif may be considered the result of heaving with clefts on the anticline and end of the thick horizontal flow of matter from Lakshmi's center, which was accompanied by slippage of the surface layer on the slopes of the uplift being formed. There arose a zone of compressed structures in the west, where the flow from Lakshmi ran into the massif being formed, along with a disordered relief on the remaining slopes due to slippage in the direction of the flow or across its movement.

On the basis of the idea of flows diverging from a common center, formation of the tensed, folded framing of Lakshmi may be the result of crowding of the surface layer material, which should be more rigid than that below the surface, as follows /97

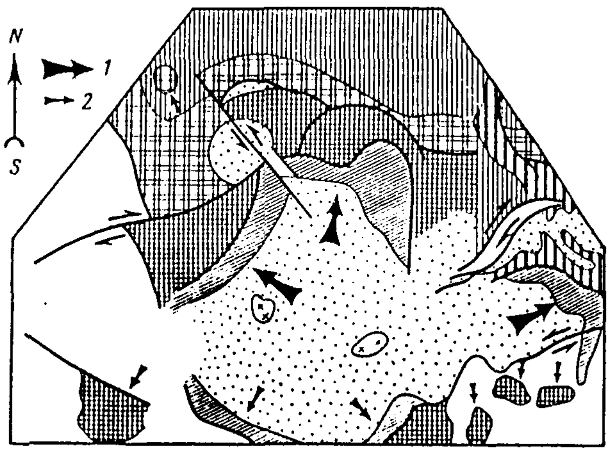


Figure 8. Tectonic structure of a region, illustrating the direction of astenospheric flows (large arrows) and gravitational slippage (small arrows).

from the reasonable hypothesis of the existence of a vertical temperature gradient on Venus. This leads to the unavoidable conclusion that the plastic deep layer had to have separated from the more rigid surface layer and that it warped and broke up into lamellar blocks or crumpled into the latter's folds. Obviously, we observe traces of precisely this process more clearly where the eastern bench of Lakshmi abuts the Maxwell Montes massif. The central area of Lakshmi's structure, closed on nearly all sides, must be regarded as a possible site for the origin of subsurface flows. The huge scales of young vulcanism and the presence of the huge calderae of Collette and Sacajewea, which indicate the influx of hot core matter in this region, support this.

Considering the overall dimensions of Lakshmi and those of its framing, it is appropriate to call the flows astenospheric; the rigid surface layer, Venus' lithosphere. From this standpoint, the structure of Lakshmi deserves to be called a unique center of radial spreading developing above an ascending flow of heated matter from the depths.

CONCLUSIONS

1. The Lakshmi Planum and its framing are a single structure formed by a single process, as indicated by the compactness and conformity of the framing.

2. The mechanism by which the structure formed is based on the process by which matter rises from the planet's core toward the surface and its horizontal spread, which is accompanied by deformations such as the folding and (or) formation of tectonic slivers. This makes it possible to consider Lakshmi a unique local center of radial spreading. However, the process of spreading ceases after the lithosphere is crowded into massifs of mountainous structures, which was accompanied by separation of the astenospheric flow from the more rigid lithosphere of the planet. When the structure formed, the lithosphere was about 10 km thick.

3. Large-scale horizontal movements make it possible to speak of Venus as a planet with a more complex tectonic life than the primitive members of the terrestrial group (the Moon, Mercury, Mars), where the tectonic style is limited primarily by vertical movements. This justifies considering Venus a link in the series of increasingly complicated deformations between Earth, with its tectonic plates, and Mars, whose tectonic life has been defined at the stage where giant canyons and broad uplifts crowned with large plate-like volcanoes form.

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