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Geologic Map of the Lakshmi Planum Quadrangle (V–7), Venus

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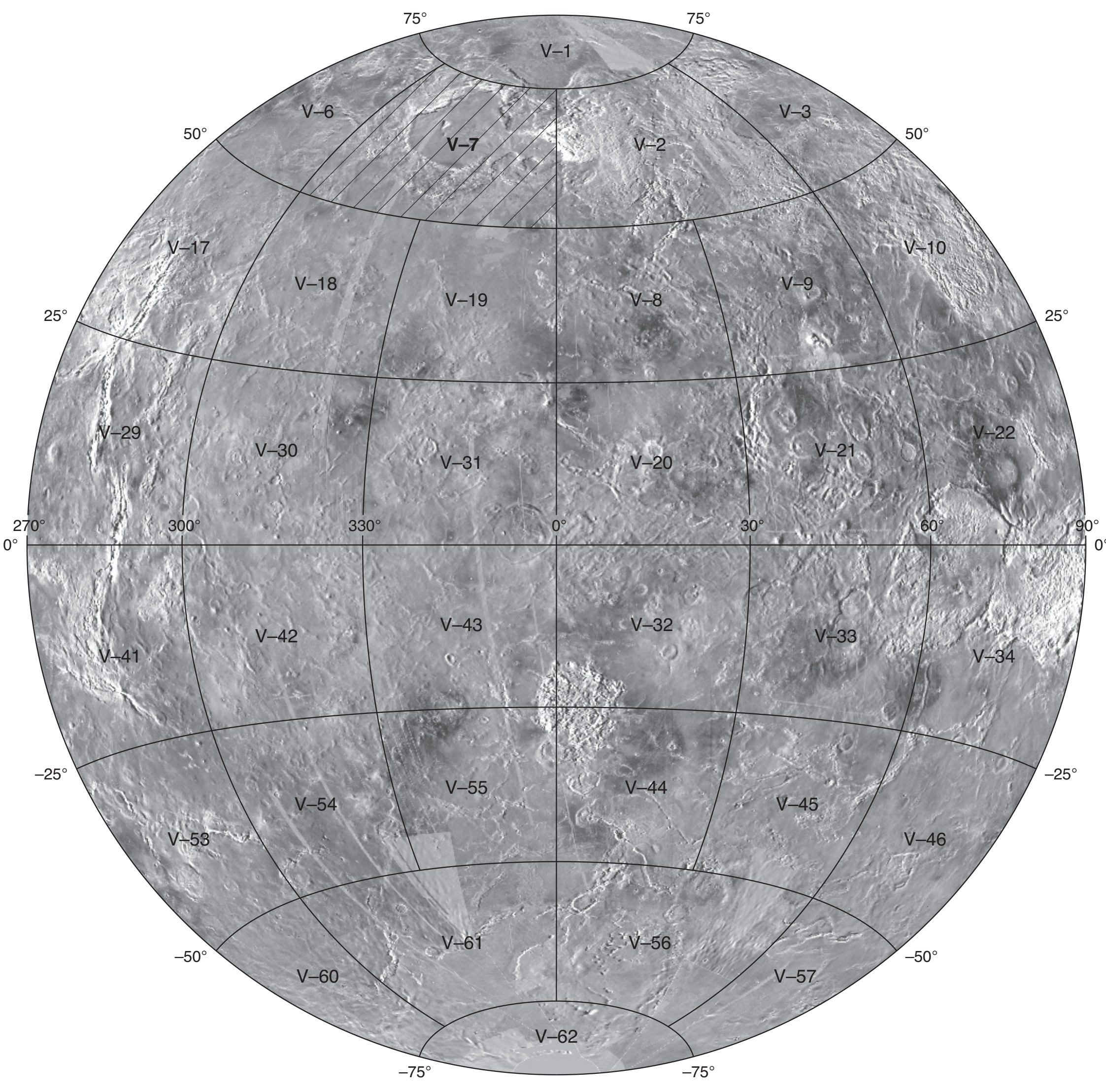

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The Magellan Mission

The Magellan spacecraft orbited Venus from August 10, 1990, until it plunged into the Venusian atmosphere on October 12, 1994. Magellan Mission objectives included: (1) improving knowledge of the geological processes, surface properties, and geologic history of Venus by analysis of surface radar characteristics, topography, and morphology, and (2) improving the knowledge of the geophysics of Venus by analysis of Venusian gravity.

The Magellan spacecraft carried a 12.6-cm radar system to map the surface of Venus. The transmitter and receiver systems were used to collect three data sets: (1) synthetic aperture radar (SAR) images of the surface, (2) passive microwave thermal emission observations, and (3) measurements of the backscattered power at small angles of incidence, which were processed to yield altimetric data. Radar imaging, altimetric, and radiometric mapping of the Venusian surface was done in mission cycles 1, 2, and 3 from September 1990 until September 1992. Ninety-eight percent of the surface was mapped with radar resolution on the order of 120 meters. The SAR observations were projected to a 75-m nominal horizontal resolution, and these full-resolution data compose the image base used in geologic mapping. The primary polarization mode was horizontal-transmit, horizontal-receive (HH), but additional data for selected areas were collected for the vertical polarization sense. Incidence angles varied between about 20° and 45°.

High resolution Doppler tracking of the spacecraft took place from September 1992 through October 1994 (mission cycles 4,5,6). Approximately 950 orbits of high-resolution gravity observations were obtained between September 1992 and May 1993 while Magellan was in an elliptical orbit with a periapsis near 175 km and an apoapsis near 8,000 km. An additional 1,500 orbits were obtained following orbit-circularization in mid-1993. These data exist as a 75°by 75°harmonic field.

Magellan Radar Data

Radar backscatter power is determined by (1) the morphology of the surface at a broad range of scales and (2) the intrinsic reflectivity, or dielectric constant, of the material. Topography at scales of several meters and larger can produce quasi-specular echoes and the strength of the return is greatest when the local surface is perpendicular to the incident beam. This type of scattering is most important at very small angles of incidence because natural surfaces generally have few large tilted facets at high angles. The exception is in areas of steep slopes, such as ridges or rift zones, where favorably tilted terrain can produce very bright signatures in the radar image. For most other areas, diffuse echoes from roughness at scales comparable to the radar wavelength are responsible for variations in the SAR return. In either case, the echo strength is also modulated by the reflectivity of the surface material. The density of the upper few wavelengths of the surface can have a significant effect. Low-density layers, such as crater ejecta or volcanic ash, can absorb the incident energy and produce a lower observed echo. On Venus, there also exists a rapid increase in reflectivity at a certain critical elevation, above which high-dielectric minerals or coatings are thought to be present. This leads to very bright SAR echoes from virtually all areas above that critical elevation.

The measurements of passive thermal emission from Venus, though of much lower spatial resolution than the SAR data, are more sensitive to changes in the dielectric constant of the surface than to roughness. As such, they can be used to augment studies of the surface and to discriminate between roughness and reflectivity effects. Observations of the near-nadir backscatter power, collected using a separate smaller antenna on the spacecraft, were modeled using the Hagfors expression for echoes from gently undulating surfaces to yield estimates of planetary radius, Fresnel reflectivity, and root-mean-square (rms) slope. The topographic data produced by this technique have horizontal footprint sizes of about 10 km near periapsis, and a vertical resolution on the order of 100 m. The Fresnel reflectivity data provide a comparison to the emissivity maps, and the rms slope parameter is an indicator of the surface tilts which contribute to the quasi-specular scattering component.

Introduction

The Lakshmi Planum quadrangle (V–7, fig. 1) is in the northern hemisphere of Venus and extends from lat 50° to 75° N., and from long 300° to 360° E. The elevated volcanic plateau of Lakshmi Planum, which represents a very specific and unique class of highlands on Venus, dominates the northern half of the quadrangle (fig. 1). The surface of the planum stands 3–4 km above mean planetary radius (fig. 2*A*) and the plateau is surrounded by the highest Venusian mountain ranges, 7–10 km high (figs. 2*A* and 3).

Before the Magellan mission, the geology of the Lakshmi Planum quadrangle was known on the basis of topographic data acquired by the Pioneer-Venus and Venera-15/16 altimeter (Masursky and others, 1980; Pettengill and others, 1980; Barsukov and others, 1986) and radar images received by the Arecibo telescope (Campbell and others, 1991) and Venera-15/16 spacecraft (Basilevsky and others, 1986; Barsukov and others, 1986; Sukanov and others, 1989). These data showed unique topographic and morphologic structures of the mountain belts, which have no counterparts elsewhere on Venus, and the interior volcanic plateau with two large and low volcanic centers (Colette and Sacajawea Paterae) and large blocks of tessera-like terrain (Barsukov and others, 1986; Sukanov and others, 1986; Pronin, 1986). From the outside, Lakshmi Planum is outlined by a zone of complexly deformed terrains that occur on the regional outer slope of Lakshmi. Vast low-lying plains surround this zone. After acquisition of the Venera-15/16 data, two classes of hypotheses were formulated to explain the unique structure of Lakshmi Planum and its surrounding. The first proposed that the western portion of Ishtar Terra, dominated by Lakshmi Planum, was a site of large-scale upwelling (for example, Pronin, 1986, 1992; Grimm and Phillips, 1990) while the alternative hypothesis considered this region as a site of large-scale downwelling and underthrusting (for example, Head, 1986; Bindschadler and others, 1990).

Early Magellan results (Kaula and others, 1992) showed important details of the general geology of this area displayed in the Venera-15/16 images. Swarms of extensional structures and massifs of tesserae populate the southern slope of Lakshmi. The zone of fractures and grabens form a giant arc thousands of kilometers long and hundreds of kilometers wide around the southern flank of Lakshmi Planum. From the north, the deformational zones consist mostly of contractional structures such as ridges. Corona and corona-like structures are not typical features of this zone but occur within separate branches of extensional structures oriented radial to the edge of Lakshmi. The southeastern edge of Lakshmi appears to be the source of large volcanic flows that extend to the south toward the lowland areas of Sedna Planitia. Colette and Sacajawea Paterae in the interior of Lakshmi are low volcanic centers with very deep central depressions (fig. 2*A*). Lava flows sourced by Colette and Sacajawea form distinctive radial patterns around these volcanoes. Magellan gravity data (Konopliv and Sjogren, 1994; Konopliv and others, 1999) show that the northern and northeastern portions of the quadrangle, which correspond to Lakshmi Planum, represent a significant geoid anomaly with the peak value of about 90 m over Maxwell Montes at the eastern edge of the map area. Maxwell is characterized also by very high vertical gravity acceleration values (as much as 268 mGal). The lowland of Sedna Planitia to the south of Lakshmi has mostly negative geoid values (down to -40 m).

The key geological structure of the quadrangle is Lakshmi Planum, the mode of formation of which is still a major unresolved problem. The topographic configuration, gravity signature, and pattern of deformation inside Lakshmi and along its boundaries make this feature unique on Venus. Thus, geological mapping of this region allows addressing several important questions that should help to put some constraints on the existing models of Lakshmi formation. What is the sequence of events in the formation and evolution of such a unique morphologic and topographic feature? What are the characteristics of the marginal areas of Lakshmi: the compact mountain belts and broad zones of deformation in the transition zone between Lakshmi and surrounding lowlands? How do the units in Lakshmi Planum quadrangle compare with the units mapped in neighboring and distant regions of Venus and what information do they provide concerning models for Venus global stratigraphy and tectonic history? These issues and questions are the basis for our geologic mapping analysis.

In our analysis we have focused on the geologic mapping of the Lakshmi Planum quadrangle using traditional methods of geologic unit definition and characterization for the Earth (for example, North American Commission on Stratigraphic Nomenclature, 1983) and planets (for example, Wilhelms, 1990) appropriately modified for radar data (Tanaka, 1994). We defined units and mapped key relations using the full-resolution Magellan synthetic aperture radar (SAR) data (mosaicked full-resolution basic image data records, C1-MIDR's , F-MIDR's, and F-Maps) and transferred these results to the base map compiled at a scale of 1:5 million. In addition to the SAR image data, we incorporated into our analyses digital versions of Magellan altimetry, emissivity, Fresnel reflectivity, and roughness data (root mean square, rms, slope). The background for our unit definition and characterization is described in Tanaka (1994), Basilevsky and Head (1995a,b), Basilevsky and others (1997), and Ivanov and Head (1998).

Magellan Sar and Related Data

The synthetic aperture radar (SAR) instrument flown on the Magellan spacecraft (12.6 cm, S-band) provided the image data used in this mapping and interpretation. SAR images are a record of the echo (radar energy returned to the antenna), which is influenced by surface composition, slope, and wavelength-scale surface roughness. Viewing and illumination geometry also influence the appearance of surface features in SAR images. Guidelines for geologic mapping using Magellan SAR images and detailed background to aid in their interpretation can be found in Elachi (1987), Saunders and others (1992), Ford and Pettengill (1992), Tyler and others (1992), Tanaka (1994), and Campbell (1995). In the area of the Lakshmi Planum quadrangle, incidence angles (16.3–21.3 for Cycle 1 and 19.7–25.1 for Cycle 2 [Ford and others, 1993]), are such that backscatter is dominated by variations in surface roughness at wavelength scales. Rough surfaces appear relatively bright, whereas smooth surfaces appear relatively dark. Variations also occur depending on the orientation of features relative to the incident radiation (illumination direction) with features normal to the illumination direction being more prominent than those oriented parallel to it. Full-resolution images have a pixel size of 75 m; C1-MIDRs contain the SAR data displayed at ~225 m/pixel. Altimetry data and stereo images were of extreme importance in establishing geologic and stratigraphic relations between units. Also essential in the analysis of the geology of the surface are data obtained by Magellan on the emissivity (passive thermal radiation), reflectivity (surface electrical properties), and rms slope (distribution of radar wavelength scale slopes). Aspects of these measurements were used in unit characterization and interpretation; background on the characteristics of these data and their interpretation can be found in Saunders and others (1992), Ford and Pettengill (1992), Tyler and others (1992), Tanaka (1994), and Campbell (1995).

General Geology

Several geologic processes have influenced the Lakshmi Planum quadrangle and have combined to form its geologic record. Volcanism is apparently the dominant process of crustal formation on Venus (Head and others, 1992) and produced most of the observed geologic units in the map area. These units typically have a plains-like appearance. There are two meanings of the term "plains" (Mescherikov, 1968). In a strict morphological sense, plains define morphologically uniform surfaces with relatively small differences in relief. In a broader sense, plains are counterparts of highlands and define vast flat terrains. In the strict sense, the term "plains" is simply a descriptor of a type of surface and does not bear an interpretative meaning. At the higher level of interpretation, the term "volcanic plains" implies knowledge or inference of the nature of material that makes up the plains. In the case of Venus, the materials that form plains are interpreted to be volcanic on the basis of a wide variety of data (for example, see Head and others, 1992). In the broader sense, the term “plains” usually describes large physiographic provinces (for example, North American Plain, Russian Plain). Thus, the same term can be applied to define two different classes of morphologic and (or) physiographic features. Although the specific meaning of the term “plains” is usually clear from the context, misunderstanding in the usage of it may occur. Fortunately, in planetary nomenclature the physiographic and physiographic-topographic meanings of the term “plains” are strictly defined. A vast plainlike and mainly homogeneous physiographic province is called planitia if it is at middle to low elevations (for example, Atalanta Planitia of Venus or Isidis Planitia of Mars) or called planum if it is elevated (for example, Lakshmi Planum of Venus or Hesperia Planum of Mars). Following this rule, we use the term “plains” in the nongenetic, morphological sense throughout the map text and the Description of Map Units. On the basis of their specific morphologic and physical property characteristics, we define various plains units, for example, lobate plains, shield plains, and so forth.

The principal structures of the western portion of Ishtar Terra and the map area are Lakshmi Planum and its mountain surroundings (figs. 1, 2). Lakshmi is a high standing volcanic plateau, the surface of which is covered by weakly to moderately deformed plains units. Two distinct volcano-tectonic features (Colette and Sacajawea Paterae) dominate the central portion of the plateau and appear to be sources of abundant lava flows. The most prominent parts of western Ishtar are mountain ranges that almost completely encircle the volcanic plateau of Lakshmi Planum. Topographically, the ranges are the highest tectonic constructs on Venus and morphologically they strongly resemble ridge belts elsewhere on the planet (Solomon and others, 1992; Squyres and others, 1992).

The distinct volcanic and volcano-tectonic features of smaller scale that occur within the quadrangle and are related to the larger and more distinct sources are listed in table 1. Tectonic activity has modified some of the crustal materials (for example, Pronin, 1992; Solomon and others, 1992; Kaula and others, 1992) in a variety of modes (extension and contraction). In places deformation is so extensive, as in the case of mountain belts and densely lineated plains, that the deformational features become part of the definition of the material unit (see also Tanaka, 1994; Scott and Tanaka, 1986). Impact cratering (table 2) has also locally affected regions in the quadrangle but has not been an influential process over the map area as a whole.

In places, preferentially in the midlands that surround Lakshmi Planum to the south, clusters of small shield volcanoes less than about 15 km in diameter (Aubele and Slyuta, 1990; Guest and others, 1992; Aubele, 1994, 1995; Crumpler and Aubele, 2000; Addington, 2001; Ivanov and Head, 2004a,b) are common in spatial association with deformation belts. Individual small shields, however, are relatively rare within the vast extent of regional plains that cover the surface of lowlands to the south of Lakshmi Planum (Sedna Planitia). The small shields are low in elevation, commonly have a summit pit, do not appear to have distinct associated flows, and are commonly embayed by subsequent regional plains deposits (for example, Kreslavsky and Head, 1999; Ivanov and Head, 2001b; Ivanov and Head, 2004b). One steep-sided dome (Pavri and others, 1992, Crumpler and Aubele, 2000, table 1) occurs inside the plateau of Lakshmi Planum near its mountain surroundings.

Five coronae and one arachnoid (fig.3, table 1) occur at the eastern and western edges of the map area. They are concentrated mostly within the heavily deformed midlands while the territory of Sedna Planitia lacks coronae (Stofan and others, 1992, 2001; Crumpler and others, 1993; Crumpler and Aubele, 2000). Extensive complexes of lava flows (fluctūs) occur to the south and west of Lakshmi Planum (table 1). The lava complex to the south of Lakshmi, Neago Fluctūs, appears to be associated with Muta Mons (fig. 1) and the fluctus to the west, Djata Fluctus, is at the northern edge of Omosi-Mama Corona and merges with another fluctus apparently sourced by Lunang Vallis (fig. 1). The flow-like features that compose fluctūs clearly indicate both the source regions and flow paths. The flows of the most distinct fluctūs follow the present-day topography, which indicates that the relief in the areas of the flows has not changed significantly since their emplacement.

The southern half of the map area and the central portion of Lakshmi Planum are dominated by plains of relatively homogeneous radar brightness that are interpreted to be of volcanic origin, and are mildly modified by sparse wrinkle ridges. The source vents of this plain-forming material are not known. The composition of the homogeneous and inhomogeneous volcanic plains is not known from data in this quadrangle, although Venera 9 (northeastern and southeastern slope of Beta Regio) and Vega 1 and 2 (Rusalka Planitia) lander geochemical analyses of sites in similar terrains suggest compositions similar to terrestrial basalts (Basilevsky and others, 1992; Abdrakhimov, 2001a,b,c).

The area of the Lakshmi Planum quadrangle displays several occurrences of tesserae (fig. 3) where multiple tectonic styles have operated together or in sequence to produce terrain more heavily deformed than typical regional plains and where the deformation is so intense that it becomes a major part of the unit definition (for example, Bindschadler and others, 1992a). The largest (hundreds of kilometers across) tesserae, the surface of which consists of both contractional and extensional structures, are Clotho, Moira, and Itzpapalotl Tesserae (Itzpapalotl is within the Snegurocka Planitia, V–1 quadrangle). They occur within the heavily tectonized outer slopes of Lakshmi Planum to the south, southwest, and north of it. There are smaller and heavily flooded occurrences of tesserae in the interior of Lakshmi Planum. These occurrences display less evidence for contractional structures and are dominated by intersecting extensional structures.

Other tectonic features in the Lakshmi Planum quadrangle (fig. 3) are present in several deformation belts that consist of either contractional or extensional structures. Belts of contractional structures correspond to the mountain ranges of Danu, Akna, Freyja, and Maxwell Montes that are respectively to the south, west, north, and east of the upland volcanic plateau of Lakshmi Planum. These belts, which are about 200–300 km wide and thousands of kilometers long, are the most prominent topographic structures on Venus and represent dense swarms of ridges that are typically 5 to 15 km wide. Wrinkle ridges are widespread throughout plains units that cover most of the surface of the lowlands around Lakshmi Planum and make up the majority of the surface of the plateau itself. The typical length of wrinkle ridges is several tens of kilometers and width is a few kilometers. A large, 2,000-km long, easterly trending zone of extensional structures (fractures and grabens) extends from Omosi-Mama Corona through Ut Rupes to Clotho Tessera and outlines the southern edge of the Lakshmi Planum. The typical width of this zone is about 150–200 km. Another branch of grabens and fractures extends from Omosi-Mama Corona southward to Beiwe Corona at the southern margin of the map area. These belts of grooves outline rims of both coronae. To the northeast of Lakshmi Planum there is a corona-like feature; the rim of the feature is made up of swarms of arcuate grabens. Slightly elongated and heavily embayed outcrops of extensional structures also occur within the volcanic plateau of Lakshmi Planum and the rim areas of Colette and Sacajawea Patera are represented by arc-like zones of grabens and fractures. Extensional features in the quadrangle also include individual narrow (less than about 1–2 km) grabens hundreds of kilometers in length that are concentrated at the southern edge of Lakshmi Planum and apparently relate to some volcanic centers (Rangrid Fossae).

Twenty-three impact craters have been mapped in the quadrangle (table 2, fig. 3). The craters range in diameter from 4.3 km for the unnamed crater at lat 55.1° N., long 360.6° E. to 48.1 km for crater Cotton (Herrick and others, 1997; Schaber and others, 1998, table 2). Five splotches (surface markings and deposits interpreted to be formed from airblasts from projectiles traversing the atmosphere; for example, Schaber and others, 1992; Ivanov and others, 1992) were detected in the quadrangle. The surfaces around craters Cotton, Stefania, Lind, and the unnamed crater (lat 55.1° N., long 360.6° E.) display radar dark haloes that likely were emplaced during the cratering event (Schaber and others, 1992; Phillips and others, 1992; Campbell and others, 1992; Schultz, 1992). There are no areas within the quadrangle apparently covered with fragmental surface materials that have been redistributed by aeolian processes.

Stratigraphy

On the basis of an analysis of the global size-frequency distribution and inferred flux of impact craters, a crater retention age of 800 Ma (McKinnon and others, 1997), 500 Ma (Schaber and others, 1992; Phillips and others, 1992) or 300 Ma (Strom and others, 1994), for the present surface of Venus has been proposed. The crater areal distribution cannot be distinguished from a spatially random population, which, together with the small total number of craters, means that crater size-frequency distributions cannot be used to date stratigraphic units for an area the size of the Lakshmi Planum quadrangle (Hauck and others, 1998; Campbell, 1999). Therefore, attention must be focused on the definition of geologic units and structures, and analysis of crosscutting, embayment, and superposition relations of structures and units to establish the regional geologic history.

Although we have mapped tectonic structures independently of geologic units, in a few cases tectonic features are such a pervasive part of the morphology of the terrain that it becomes part of the definition of a unit. For example, our unit of tessera material is analogous to aureole member 4 of the Olympus Mons Formation on Mars (“Forms broad...lobes; corrugated, cut by numerous faults that formed scarps and deep troughs and grabens”, Scott and Tanaka, 1986) and ridged plains material is similar to ridge band material on Europa (“... linear to curvilinear features consisting of alternating ridges and troughs...”, Figueredo and Greeley, 2000). In recently published Venus maps, the same approach of unit definition was successfully applied for mapping several quadrangles that portray geologically diverse provinces (Rosenberg and McGill, 2001; Bridges and McGill, 2002; Campbell and Campbell, 2002; Hansen and DeShon, 2002). In other cases, the approach depends on scale and density of structures. For example, where the structures are more discrete and separated, we mapped them separately and not as a specific unit. In other cases, where structures are very dense, tend to obscure the underlying terrain, and are embayed by younger material units, we chose to map such occurrences of pervasive tectonic structures as specific units. Here we summarize the stratigraphic units and structures and their relations.

Tessera material (unit t, fig. 4) is interpreted to be among the stratigraphically oldest units in the quadrangle. The total area covered by tessera material within the quadrangle is about 0.62 10^6 km^2 or ~8.6 percent (table 3). The radar bright tessera material is deformed by at least two sets of intersecting ridges and grooves and is a result of tectonic deformation of some precursor terrain (Barsukov and others, 1986; Basilevsky and others, 1986; Bindschadler and Head, 1991; Sukhanov, 1992; Solomon and others, 1992). Tessera material is embayed by most of the other units within the map area. Arches, ridges, grooves, and grabens are tectonic features, so structure is an essential component of the tessera terrain and a key aspect of the unit definition. Globally, tessera occupies about 8% of the surface of Venus (Ivanov and Head, 1996) and occurs as large blocks and small islands standing above and embayed by adjacent plains. Several medium-sized occurrences of tessera are exposed in the map area: 1) Clotho Tessera (about 1000 by 400 km, southern portion of the map area), 2) Moira Tessera (about 300 by 300 km, southwestern portion of the quadrangle), and 3) southwestern portion of Itzpapalotl Tessera (about 500 by 300 km, northeastern corner of the quadrangle). Outliers of tessera material also occur within the volcanic plateau of Lakshmi Planum. Based on the Venera-15/16 data (spatial resolution about 1–2 km/px), the area of Atropos Tessera at the northeastern corner of Lakshmi Planum was considered as tessera terrain (Barsukov and others, 1986; Sukhanov, 1992; Pronin, 1992). However, images of this region taken by Magellan spacecraft (spatial resolution 100–200 m/px) show that the surface of Atropos Tessera displays morphology that is transitional between tessera and less tectonically deformed units.

Densely lineated plains material (unit pdl, figs. 5, 6) forms apparently the oldest plains unit. This material is characterized by relatively flat surfaces on a regional scale and cut by swarms of parallel and subparallel lineaments (resolved as fractures if they are wide enough) having typical spacing of less than 1 km. Densely lineated plains occur predominantly in the western portion of the quadrangle. In the southwestern corner of the map area, the plains are within the midland deformational zone surrounding Lakshmi Planum from the south, often in close association with belts of grooves. Occurrences of the unit are typically small (about 100–200 km across). In the northwestern portion of the map area densely lineated plains material forms the massif of Atropos Tessera area that is many hundreds of kilometers across. Broad arches additionally deform the surface of unit pdl in the region of Atropos Tessera (fig. 6). Along the boundary of Atropos Tessera and Akna Montes, the arches within the region of densely lineated plains material are roughly parallel to the trend of the Akna Montes mountain belt. Morphologically, densely lineated plains material in Atropos Tessera resemble the tessera transitional terrain described in the 30N geotraverse (Ivanov and Head, 2001b). The total area of the plains is about 0.43 x 10^6 km^2 or about 5.9% of the area of the quadrangle (table 3). Although the unmodified precursor terrain for the densely lineated plains material is not observed, the flatness of the surface suggests that it was plains. The fractures that deform the densely lineated plains material are structural elements. They, however, are such a pervasive part of the morphology that it becomes a key aspect of the definition of the unit (see Campbell and Campbell, 2002; Hansen and DeShon, 2002, or several of the Mars examples cited above).

Ridged plains material (unit pr, fig. 7) is commonly deformed by relatively broad (2–5 km wide) ridges tens of kilometers long that dominate morphological appearance of the unit. In the Lakshmi Planum quadrangle, this unit is not abundant and occurs in the form of small (many tens of km long and a few tens of km wide) elongated fragments in the southern portion of the map area. The area occupied by ridged plains material is about 0.03 x 10^6 km^2 or about 0.4% of the quadrangle (table 3). Although occurrences of this unit are small, they illustrate features that are analogous to the ridge belts of Kryuchkov (1990), Frank and Head (1990), Squyres and others (1992) and to units mapped in the other quadrangles on Venus (Rosenberg and McGill, 2001; Bridges and McGill, 2002). Although the ridges are structural elements, they are important features that help to define and map the material unit of ridged plains. For instance, there is not much doubt that wrinkle ridges deform materials of regional plains. Hypothetically, a wrinkle ridge or collection of them would represent kipukas of material of regional plains if younger lavas would flood the rest of the unit. If this hypothetical situation is mapped at a scale sufficient to outline individual wrinkle ridges, then the true structural elements, the ridges, should be mapped as a material unit. The scale of our mapping is mostly sufficient to map exposures of a material unit represented on the surface by ridges of ridged plains. This is unit pr and it is a material unit, although it is represented mostly by structures. Ridged plains material, thus, is probably volcanic plains material deformed by compressional stresses.

Shield plains material (unit psh, fig. 8) is characterized by abundant small shield-shaped features ranging from a few kilometers in diameter up to about ten to twenty kilometers, many of them with summit pits. Although small clusters of shields were recognized earlier globally (Head and others, 1992), they were considered as localized occurrences possibly related to individual sources such as hot spots. Later work in the Vellamo Planitia, V–12 quadrangle (Aubele, 1994, 1995) showed that many of these occurrences represented a stratigraphic unit in this region, and later this unit has been recognized in many areas on the planet (Basilevsky and Head, 1995b; Basilevsky and others, 1997; Crumpler and Aubele, 2000, Ivanov and Head, 1998, 2001a,b), including this quadrangle. Shields characterizing this unit occur in clusters, which give the unit a locally hilly texture, and as isolated outcrops in relatively smooth plains. The shields are probably volcanic in origin and are likely to be the sources of the adjacent smooth plains material. In the Lakshmi Planum quadrangle, however, there is no clear evidence for specific flow units associated with the small edifices of shield plains. The unit is widely distributed in the quadrangle but occurs predominantly in its southwestern part within the lowlands around the Lakshmi Planum upland. The area of the unit is about 0.55 x 10^6 km^2 or about 7.6% of the map area (table 3). Quite often, occurrences of shield plains material are associated with swarms of grooves that outline the structures of Omosi-Mama and Beiwe Coronae. There are almost no concentrations of shield plains material within the volcanic plateau of Lakshmi Planum, where the plains were either completely buried by younger plains materials or never formed. Some isolated clusters of shields occur as kipukas in places where subsequent plains materials embay shield plains.

Pitted and grooved plains material (unit ppg, fig. 9) has intermediate radar albedo and is characterized by numerous narrow and wide and apparently shallow depressions with scalloped edges. Sometimes, chains of pits or slightly elongated rounded depressions are seen. In places, isolated pits and low shieldlike features complicate the surface of the pitted and grooved plains material. In the Lakshmi Planum quadrangle, unit ppg occurs in four small outcrops many tens of kilometers across at the periphery of the volcanic plateau of Lakshmi in spatial association with the mountain ranges. Three occurrences of the unit are at the southern edge of the plateau near Danu Montes and the fourth occurrence is in the northwestern corner of the plateau at the conjunction of Akna and Freyja Montes. The area of the unit is about 0.07 x 10^6 km^2 or about 1.0% of the map area (table 3).

Regional plains material, lower unit, (unit rp_1 fig. 10) forms the most widespread plains unit in the quadrangle. The total area of the plains is about 2.0 x 10^6 km^2 or about 25.9% of the quadrangle (table 3). This unit is composed of morphologically smooth, homogeneous plains material of intermediate-dark to intermediate-bright radar albedo complicated by narrow, linear to anastomosing wrinkle ridges (a structural element) in subparallel to parallel lines or intersecting networks. This unit resembles the ridged unit of the plateau sequence on Mars (Scott and Tanaka, 1986), which is a plains unit defined by "long, linear to sinuous mare-type (wrinkle) ridges." In the map area, the wrinkle ridges typically are less than 1 km wide and tens of kilometers long; in some areas they may be smaller, whereas in others they are larger. The trend of wrinkle ridges often varies locally even within one site (fig. 3). The unit is interpreted to be plains material of volcanic origin that was subsequently deformed by wrinkle ridges. Volcanic edifices and sources of the plains material are not obvious. The lower unit of regional plains material covers the northern portion of the plateau of Lakshmi Planum and isolated patches of it are seen in the southern portion of the plateau. This unit is also abundant to the south of the Planum where material of the lower unit of regional plains preferentially occurs within the lowlands of Sedna Planitia. The lower unit of regional plains material is noticeably less abundant on the regional slopes of Lakshmi Planum where older and highly tectonized units are concentrated.

Regional plains material, upper unit, (unit rp_2, fig. 11) has noticeably higher radar albedo than material of the lower unit of regional plains and usually is characterized by lobate boundaries. Wrinkle ridges mark the surface of the unit (fig. 11). The largest area of this unit occurs in the southeastern, south-central, and southwestern portions of the quadrangle that correspond to the southern regional slope of the Lakshmi Planum upland. A smaller occurrence of this unit is on the northern flank of Colette Patera. This unit makes up about 0.92 x 10^6 km^2 or 12.8% of the area of the quadrangle (table 3).

Plains units that are younger than regional plains materials are characterized by morphologically smooth surfaces and often by distinctive lobate and digitate shapes and margins. Two types of the younger plains units are recognized.

Smooth plains material (unit ps, fig. 12) is characterized by uniform and low albedo and tectonically undeformed and featureless surfaces. Small patches of this unit are scattered throughout the map area, but preferentially are concentrated in its central (volcanic plateau of Lakshmi Planum), northwestern, and northeastern portions. The total area of smooth plains is about 0.31 x 10^6 km^2 or ~4.3% of the map area (table 3).

Lobate plains material (unit pl, fig. 13) comprises a significant part of the quadrangle (about 0.79 x 10^6 km^2 or 10.9%, table 3). A distinctive pattern of radar bright and sometimes radar dark flow-like features with lobate fronts characterizes this unit. The surface of the unit is almost tectonically undeformed and flow-like features embay most tectonic structures including those that deform the surface of the regional plains material, upper unit. There are three major areas where the lobate plains material occurs. The first is a large complex of lava flows, Neago Fluctūs, the source of which is in the complexly deformed zone at the southern regional slope of the Lakshmi Planum upland. The second is inside the volcanic plateau of Lakshmi Planum and represents lava flows from Colette and Sacajawea Paterae. Lava flows of Djata Fluctus to the west of Lakshmi Planum represent the third area of lobate plains material.

Impact craters and related deposits are observed in several places in the quadrangle (table 2, figs. 3, 14). Their locations are noted by symbols and they are mapped as undivided crater material (unit c) and crater flow material (unit cf). Four impact craters within the mapped area (Cotton, Stefania, Lind, and an unnamed crater at lat 55.1° N., long 350.6° E., table 2) are characterized by distinct surrounding radar dark material (Campbell and others, 1992; Ivanov and others, 1992) that partly to mostly obscures the underlying terrain. One crater (Gražina, table 2) is deformed by extensional structures related to evolution of Freyja Montes. None of the craters in the quadrangle are embayed by volcanic materials.

Structures

A variety of extensional and contractional tectonic structures (some are in distinctive belts) is observed and mapped in the quadrangle (fig. 3).

Extensional structures

Long linear fractures and some paired and inward-facing scarps mapped as sharp grooves interpreted to be grabens are seen in the eastern-central portion of the map area. These grabens form the complex of Rangrid Fossae at the southeastern edge of Lakshmi Planum. The grabens are several hundreds of kilometers long, oriented in the northwest direction, and produce a large set of parallel curvilinear structures that are slightly bent toward the west. Almost all structures of Rangrid Fossae are significantly broader at their southern ends and become progressively narrower northward. The southern ends of the grabens often have the shape of broad elongated depressions with scalloped edges or chains of pits. Morphologically, these depressions and pit chains resemble those that characterize the surface of pitted and grooved plains material (unit ppg).

In many places, the extensional structures such as fractures and grabens are so closely spaced that they tend to obscure underlying terrain and their presence takes on a defining character of the terrain. These concentrations are characterized by numerous short and long curvilinear subparallel lineaments that are usually wide enough to be resolved as fractures and grabens. These occurrences form linear belts (groove belts, unit gb; fig. 15) that consist of individual swarms of extensional structures. The belts can be many hundreds of kilometers long and a few hundreds of kilometers wide. Individual swarms of grabens are typically tens of kilometers wide and are characterized by slightly higher topography relative to the surrounding plains. In detailed mapping at the F-Map scale, remnants of pre-existing plains can be seen between the neighboring tectonic features but cannot be mapped at the 1:5 M scale. Orientations of grooves in the belts are generally parallel to the trend of the groove belts as a whole.

Groove belts are concentrated in the southern half of the quadrangle; one of the most distinctive belts extends along the southern and western regional slopes of Lakshmi Planum from the area to the south of Clotho Tessera almost to Atropos Tessera (fig. 3). Groove belts (unit gb) are distinguished from densely lineated plains material (unit pdl) by their belt-like form, a lower density of tectonic features, and the character of the fractures (more distinctly recognizable grabens in groove belts). The belts also appear to be relatively distinctive stratigraphically. The structures of the belts are mostly embayed by shield plains material (unit psh) and by the lower unit of regional plains material (unit rp_1). Thus, these plains units represent the upper stratigraphic limit for the groove belts. The lower limit of the belts is established by material and deformation of densely lineated plains material (unit pdl) and ridged plains material (unit pr) that are consistently cut by groove belts.

Apparently, there are two types of groove belts in the map area. The first, which outlines Lakshmi Planum from the south, does not show association with coronae. The second type of belt, which runs from the southern edge of the quadrangle in a northerly direction, both connects two large coronae (Beiwe and Omosi-Mama Coronae) and forms their rims. The association of coronae and zones of extensional structures (corona/groove belt chains) on Venus has been mapped and described in many regions (Baer and others, 1994; Ivanov and Head, 2004a, 2006).

Contractional structures

Several types and scales of contractional features are observed within the quadrangle (fig. 3). Wrinkle ridges are widespread in the quadrangle and are so important in the broad regional plains that they in part define and characterize material of the plains (fig. 10). These features are mapped in a representative sense in terms of density and trend by individual wrinkle ridge symbols. There is no single predominant trend of wrinkle ridges in the quadrangle. Wrinkle ridges are common structures within the southwestern part of the map area where shield plains material and both units of regional plains material are the most important. In contrast, there are almost no wrinkle ridges in the southern portion of the volcanic plateau of Lakshmi Planum where relatively young plains units (ps and pl) are predominant. Thus these units appear to form an upper stratigraphic limit for the wrinkle ridges development within the map area.

Broader and less sinuous ridges dominate ridged plains material (unit pr, fig. 7). The general trends of these ridges are also represented in the units by symbols. Ridged plains material is largely equivalent to the ridge belts of Squyres and others (1992). Basilevsky and Head (1995a,b) described a structure (ridge belts, RB), which was a belt consisting of a cluster of densely spaced ridges 2–5 km wide and a few tens of kilometers long.

The most important occurrences of contractional structures in the map area are mountain belts (unit mb, fig. 16) surrounding the volcanic plateau of Lakshmi Planum. Densely packed ridges that are 5–15 km wide and tens to a few hundreds of kilometers long characterize all belts. There are four mountain belts: Danu, Akna, Freyja, and Maxwell Montes. Danu Montes, which are about 100 km wide and reach elevation about 1 km above the surface of the plateau of Lakshmi Planum, extend for about 1000-1200 km along the southern margin of Lakshmi (fig. 3). Ridges at the inner side of this belt (with respect to Lakshmi Planum) are embayed by material of the lower unit of regional plains material of the plateau (fig. 17*A*).

Akna Montes represent a shorter (about 800–900 km), wider (about 200 km), and higher (about 3 km above the surface of the plateau) mountain range, which is slightly convex toward the plateau of Lakshmi (fig. 3). Some of the innermost ridges of Akna Montes with respect to the plateau appear to be embayed by materials of the lower unit of regional plains material from the Lakshmi interior (fig. 16). The surface of the plains, however, is tilted toward the mountain belt and deformed by wrinkle-type ridges that are parallel to the trend of the belt. At the outer side, the belt of Akna Montes is in contact with an extensive exposure of material of densely lineated plains in Atropos Tessera. Materials of this unit appear to be additionally deformed by long and broad ridges that continue the general trend of ridges in Akna Montes.

The mountain belt of Freyja Montes (figs. 1 and 3) forms the northern and northeastern boundary of Lakshmi Planum. This belt is wide (about 300 km) and high (about 3 km above the surface of Lakshmi) and characterized by complicated structures consisting of several domains with their own pattern of deformation. As in the case of Akna Montes, there is some evidence for embayment of structures of Freyja Montes by material of the lower unit of regional plains from the Lakshmi Planum side. The surface of the plains is tilted toward the belt and deformed by broad and low ridges that are parallel to the general orientation of Freyja Montes (fig. 17*B*).

The mountain range of Maxwell Montes is at the eastern edge of Lakshmi Planum and is the highest mountain construct on Venus (about 12 km above mean planetary radius). Within the map area, only the westernmost extension of Maxwell is seen. Relations of ridges of the range with the plains of the Lakshmi interior appear to be ambiguous and do not provide strong evidence suggesting relative ages of these units.

Stratigraphic Relations of Units

The material units and structures mapped within the Lakshmi Planum quadrangle commonly reveal relations of superposition (embayment) and crosscutting that either clearly display or strongly suggest relative ages among the units. Relations between the apparently oldest units in the map area, tessera material and densely lineated plains material, are shown in figure 18 in an area to the northeast of Lakshmi Planum where the large massif of Itzpapalotl Tessera is in contact with fragments of densely lineated plains material. Later plains materials broadly embay these highly deformed materials. This means that both tessera and densely lineated plains are at the bottom of the stratigraphic column. The surface of tessera material (unit t) is rough due to numerous chaotically oriented ridges and grooves. The most prominent of these are broad troughs oriented to the northwest, the floors of which are covered by dark plains material. The troughs cut both tessera and densely lineated plains materials and, thus, are relatively young structures. Densely lineated plains (unit pdl) occur as elongated massifs, the surface of which is deformed by densely packed, north-northwest-trending short and narrow lineaments. The surface of these materials appears to be smoother and structures that deform tessera material appear to be abutted at the northeastern edge of the massif of the unit pdl (fig. 18). The difference in the character, density, and orientation of structures suggests that densely lineated plains material was emplaced when tessera material was already in place and deformed. Some of the lineaments that cut the surface of densely lineated plains material cross the contact between the two units and are seen within tessera material. These relations suggest that material of the unit pdl was superposed on the surface of tessera material and covered some of the tessera structures and, thus, is younger. The tectonic deformation, however, continued and structures that deform the surface of the unit pdl material have added complexity to the tessera surface. This additional complication of the tessera surface, the presence of the long broad troughs, and the example of Atropos Tessera (fig. 6) indicate that the tessera-forming deformation continued subsequent to the emplacement of younger materials.

Vast plains units, such as shield plains material and the lower unit of regional plains material, embay ridged plains material (unit pr, fig. 19) and, thus, appear to provide the upper stratigraphic level for the ridged plains material. The lower level of this unit is poorly determined. Direct relations between ridged plains material and either tessera material or densely lineated plains material cannot be established because the units are not in contact with each other within the map area. The simpler pattern of deformation may suggest, however, that ridged plains material was deformed later than the units t and pdl and did not accumulate as much deformation as tessera and densely lineated plains materials. Elsewhere on Venus, units that have morphology similar to that of ridged plains material within V–7 quadrangle appear to be about at the same stratigraphic level as densely lineated plains material or slightly higher (Ivanov and Head, 2001a, 2005, 2006). This may be circumstantial evidence that in the Lakshmi Planum quadrangle, unit pr is also near the bottom of the regional stratigraphic column. This apparent stratigraphic position of ridged plains material is supported by the observation that structures of groove belts appear to cut the surface of the ridge plains material in places (fig. 19) and appear to be embayed by units psh and rp_1 materials (figs. 19, 20).

Relations between groove belts and shield plains material are much more clear and consistent throughout the map area (fig. 20). In the area shown in figure 20, a large fragment of a groove belt is in contact with a broad field of shield plains material. The density of structures that form the belt varies across the scene and wide gaps between swarms of grooves are covered by shield plains material, which appears to be tectonically undeformed. In places, shield plains material abuts the grooves. These relations clearly indicate that emplacement of shield plains material occurred after formation of the majority of grooves that form the belt. Some of the grooves, however, cut through the surface of unit psh and appear to deform shields (fig. 20). This suggests that development of grooves continued after emplacement of shield plains material, but at much lower rate.

Throughout the map area, consistent relations of embayment occur between shield plains material (unit psh) and the lower unit of regional plains material (unit rp_1, fig. 21). In many areas within the quadrangle, the shield plains material occurs as tight clusters of small shieldlike structures, which is a characteristic feature of this unit elsewhere on Venus (Crumpler and Aubele, 2000; Addington, 2001). Clusters of shields form equidimensional fields tens of kilometers across surrounded by wrinkle ridged plains material as shown in figure 21. The clusters may have slightly different radar albedo and internal pattern of deformation that is absent within surrounding regional plains. There is no evidence for flows emanating from any of the shields and superposed on the surface of surrounding plains. The density of shields is sharply diminished across the cluster boundaries and only a few small isolated edifices are seen between neighboring clusters.

These relations between the shield plains material unit and the lower unit of regional plains material strongly suggest that the shields (clustered or individual) represent kipukas of a unit (shield plains material, unit psh) heavily flooded by younger regional plains material (Ivanov and Head, 2004b). Kreslavsky and Head (1999) have shown detailed quantitative examples of such relations that illustrate how isolated shields become smaller and less dense away from the contact, suggesting embayment by younger plains units. Although these relative ages are typical within the map area, one cannot rule out the possibility of partly contemporaneous emplacement of shield plains material and the lower unit of regional plains material. To account for this uncertainty, these two units are shown partly overlapping in the Sequence of Map Units.

Regional plains material units rp_1 and rp_2 are deformed by a pervasive network of wrinkle ridges and, thus, predate the episode(s) of ridge formation (fig. 22). The upper unit of regional plains material is typically brighter in SAR images and, in places, this unit is characterized by lobate boundaries resembling lava flows and internal flowlike features. Outside Lakshmi Planum, occurrences of the upper unit of regional plains material apparently extend along local depressions and tend to outline local highs on the surface of the lower unit of the regional plains material. Inside Lakshmi, northern flows from Colette Patera are superposed on vast featureless regional plains material and also are cut by wrinkle ridges, thus representing the upper unit of regional plains material (unit rp_2). This apparent topographic position and more distinctive flows within the upper unit of regional plains material suggests that unit rp_2 generally postdates, but may be locally correlative with, the lower unit of regional plains material (unit rp_1).

Consistent relations exist between the upper unit of regional plains material (unit rp_2) and lobate plains materials (unit pl, fig. 23). In each locality where these units are in contact, lobate plains material is almost tectonically undeformed and clearly embays structures of wrinkle ridges. In the example shown in figure 23, the surface of the upper unit of regional plains material is cut by a system of subparellel wrinkle ridges oriented northwest. The ridges deform the surface of unit rp_2 that displays faint internal flowlike and channellike features. More bright flows of lobate plains material (unit pl) spread over the surface of unit rp_2 and mostly lack wrinkle ridges. This means that volcanic activity responsible for the emplacement of the lobate plains material began near terminus of wrinkle ridge formation. However, the distal portion of the larger flow of the unit pl appears to be deformed by a wrinkle ridge (fig. 23). This relation implies that, as in the case of groove belts and shield plains material, the majority of wrinkle ridges formed before emplacement of the lobate plains material but some of the ridges still continued to form after its deposition. Relations between regional plains material that cover the northern portion of Lakshmi Planum with lobate plains material and smooth plains material are similar to those observed outside the Planum. In each locality inside Lakshmi where these units are in contact the lobate and(or) smooth plains materials show almost no tectonic structures and embay wrinkle ridges.

The deformational episodes that have formed the mountain ranges around Lakshmi have stratigraphic constraints from both stratigraphically below and above. The lower stratigraphic limit for Akna Montes appears to be provided by the additionally deformed densely lineated plains material in Atropos Tessera (fig. 6) where the surface of the plains is deformed by broad arches parallel to the general strike of ridges in Akna. The lower unit of regional plains material within Lakshmi Planum embays ridges of Danu and Akna Montes (figs. 16, 17*A*) but the surface of the plains is tilted away from the Akna Montes mountain range. This suggests that the long wavelength warping of the plains continued until the shorter wavelength deformation that produced ridges of the range had ceased. The warping of the plains may indicate the late-stage gravitational readjustment of the bulk of the mountain range. Emplacement of the upper unit of regional plains material and lobate plains material inside Lakshmi Planum appears to be controlled by the tilted surface of the lower unit of regional plains material. Thus, the episodes of young volcanism may indicate the upper stratigraphic limit of the warping. The massif of Freyja Montes displays more ambiguous relations with the lower unit of regional plains material (fig. 17*B*). Although some structures of the range appear to be embayed, suggesting that the short wavelength deformation of Freyja is mostly older than emplacement of the lower unit of regional plains material, the surface of the plains sometimes displays broad and low ridges resembling those that form the Freyja massif (fig. 17*B*). Some of these broad ridges apparently control the distribution of wrinkle ridges and, thus, predate them. These relations suggest that the short wavelength deformation responsible for the formation of the ridges of the Freyja massif mostly took place before emplacement of the lower unit of regional plains material but some deformation occurred after formation of the unit and before formation of wrinkle ridges. The surface of the lower unit of regional plains material adjacent to Freyja Montes is tilted away from the mountain range suggesting, as in the case of Akna Montes, that broad warping of this material occurred after emplacement and deformation by wrinkle ridges.

Geologic History

The area of Lakshmi Planum quadrangle (western Ishtar Terra, figs. 1, 2) is a unique area on Venus where the highest mountain ranges surround a high-standing volcanic plateau (for example, Barsukov and others, 1986). Extensive studies of this region using Venera-16/16 and Magellan data have resulted in two groups of models put forth to explain the unusual topographic and morphologic characteristics of western Ishtar Terra. The first group includes models that explain Lakshmi as a site of mantle upwelling (Pronin, 1986, 1990, 1992; Grimm and Phillips, 1990). In this model, formation of Lakshmi Planum initiated in its central area due to rising and subsequent collapse of a mantle diapir (Pronin, 1986, 1990, 1992). In the modified model (Grimm and Phillips, 1990), a diapir was considered to have impinged at the base of a thickened block of lithosphere. Models from the other group consider the planum as a locus of mantle downwelling, convergence, underthrusting, and possible subduction (Head, 1986, 1990; Head and others, 1990; Roberts and Head, 1990; Bindschadler and others, 1990; Lenardic and others, 1991; Hansen and Phillips, 1993, 1995; Keep and Hansen, 1994; Ansan and others, 1996; Marinangeli and Gilmore, 2000). For both groups of models, the understanding of the progression of large-scale deformation is important. Thus, the main goal of the geological mapping, establishing of the sequence of events, should help constrain the models of formation and evolution of the western Ishtar Terra. Here we discuss stratigraphic positions of units, their temporal correlation, and the implied geologic history of the region. We also examine the sequence of tectonic deformation and its interpretation as well as the evolution of volcanic and tectonic styles.

Lakshmi Planum quadrangle is made up of the western side of Ishtar Terra, the eastern portion of which represents one of the largest tessera regions on Venus, Fortuna Tessera (Ivanov and Head, 1996). Smaller massifs of tessera populate western Ishtar and occur to the south (Moira and Clotho Tesserae) and to the north (Itzpapalotl Tessera) of Lakshmi Planum. Outcrops of tesseralike material, which is deformed by several sets of tectonic structures, occur also inside Lakshmi Planum where it is heavily embayed by the material of lower unit of regional plains material. The largest of these outcrops are seen in the eastern part of the plateau and smaller fragments of tessera material occur in its northwestern part. Such a pattern of areal distribution suggests that tessera material forms the older basement of the plateau. The complex and unique deformational pattern of the surface, which is not repeated within the other tectonized units, suggests that tessera material outside and inside Lakshmi Planum are among the oldest units within the map area. This interpretation is in accord with the stratigraphic position of tessera material elsewhere on Venus (Ivanov and Basilevsky, 1993; Ivanov and Head, 1996; Hansen and others, 1997; Phillips and Hansen, 1998). Although exposures of tessera material make up only about 9 percent of the map area (table 3), the likely extent of tessera in the subsurface may significantly increase the total amount of tessera material within the V–7 quadrangle. It is important to emphasize that the distinctive pattern of deformation seen in tessera material is not visible on the surface of ridges that compose the mountain ranges. Their surfaces appear to be morphologically smooth as if these structures were produced by the deformation of morphologically smooth plains-forming material. Thus, tessera material was probably not significantly involved in the later deformation that produced the mountain ranges and could compose an ancient craton-like massif as the basement of the plateau of Lakshmi. Such a massif is the key feature of almost all downwelling models of Lakshmi formation (for example, Head, 1990; Roberts and Head, 1990; Hansen and Phillips, 1995) and some upwelling models (Grimm and Phillips, 1990).

Volcanic plains material that has been densely fractured (unit pdl) appears to be younger than tessera material (fig. 18) where these units are in contact. The deformation patterns in densely lineated plains material is simpler than in tessera material and consists of very dense and unidirectional lineaments. The role of extension in the formation of the structural pattern of unit pdl is evident. Fragments of densely lineated plains material are locally elevated and irregularly shaped and predominantly populating the western part of the quadrangle outside of the mountain belts that surround Lakshmi Planum. The largest massif of the unit occurs in the Atropos Tessera area where the surface of the unit pdl is additionally deformed by broad ridges and to some degree resembles pattern of deformation of tessera material (fig. 6). The pattern of deformation of this unit indicates areas of limited extension and possible shear that occurred in the map area roughly contemporaneous with continuing tessera deformation. There are no outcrops of densely lineated plains material inside Lakshmi Planum but they may be completely covered by a composite layer of later plains units. The alternative is, of course, that the specific tectonic regime responsible for formation of the pattern of deformation of unit pdl never operated inside Lakshmi.

A less deformed plains unit (ridged plains material, unit pr) was emplaced either contemporaneously or, in part, following the formation of the tessera and densely lineated plains materials. Although no evidence exists for sources, the smooth surface of the deformed material of the unit strongly suggests that it is of volcanic origin. This unit makes up a very small fraction of the map area (about 0.4%, table 3) and, thus, does not appear to be areally important. Small fragments of the unit occur within the deformational zone along the southern regional slope of Lakshmi Planum southeast of Clotho Tessera. The most important features of ridged plains are ridges that are several kilometers wide. Elsewhere on Venus, these ridges are usually compose prominent ridge belts (Kryuchkov, 1990; Frank and Head, 1990; Squyres and others, 1992; Ivanov and Head, 2001a,b, 2006). The belts have significant relief, reaching several hundred meters (Ivanov and Head, 2001b), and thus represent significant zones of compression. The lack of prominent ridge belts within the V–7 quadrangle suggests that compressional environments outside Lakshmi occurred locally and in rather small areas.

The major contractional structures within the map area are concentrated in the mountain ranges surrounding the plateau of Lakshmi Planum (for example, Barsukov and others, 1986). The ranges consist of densely packed parallel ridges that are 5–10 km. They form compact and high-standing zones mapped as mountain belts (unit mb). There is a general consensus that the belts were formed under large compressional stresses (Pronin, 1986, 1992; Grimm and Phillips, 1990, 1991; Head, 1986, 1990; Head and others, 1990; Roberts and Head, 1990; Bindschadler and others, 1990; Hansen and Phillips, 1993, 1995; Marinangeli and Gilmore, 2000). Relations of mountain belts with the other material units and structures suggest that formation of the morphologically distinctive, short-wavelength structures of the belts (an orogenic phase) took place after emplacement and deformation of tessera and densely lineated plains materials but mostly before emplacement of the lower unit of regional plains material. The long-wavelength component of the deformation is probably related to the later evolution of the belts and is manifested by broad tilting of plains at the contact with the mountain ranges. This tilting continued after the emplacement of the lower unit of regional plains material. This broad warping is similar to the situation at large tessera regions where materials of plains units are tilted away from the tesserae (Head and Ivanov, 1996; Ivanov and Head, 1996), interpreted to be the consequence of late epeirogeny of regions of thickened crust. The warping of the plains occurs at Akna and Freyja Montes but not at the base of Maxwell Montes (Suppe and Conors, 1992) and Danu Montes.

The most extensive zone of groove belts that outlines the southern regional slope of Lakshmi Planum apparently formed approximately contemporaneously with the deformation of the orogenic phase of the mountain belts. The structures of the southern branch of groove belts that outline some coronae in the southwestern corner of the map area do not display clear relations with the other occurrences of the belts. These structures, however, mostly predate both shield plains and the lower unit of regional plains materials and, thus, appear to have about the same stratigraphic position as the other occurrences of groove belts.

Another distinctly different plains unit (shield plains material, unit psh) was emplaced in many parts of the map area after emplacement and deformation of ridged plains material and the first orogenic phase of formation of the mountain belts. The lack of extensive development of contractional features such as arches and ridges within the areas of unit psh implies that regional compressional stresses significantly waned before emplacement of this material. Presently exposed occurrences of shield plains material are seen preferentially in the southwestern and northeastern parts of the map area in close spatial association with groove belts.

Clusters of small shields characterizing the unit have slightly different radar albedo than surrounding regional plains and often are outlined by clear curvilinear to sinuous contacts that outline individual shields at the boundaries of the clusters (fig. 21, see also Aubele, 1994). There is no evidence for flows either emanating from the shields or superposed on the surface of surrounding plains. The density of shields is sharply diminished across the cluster boundaries and only a few small isolated edifices are seen between neighboring clusters. All these criteria collectively suggest that the clusters of shields and shield plains material largely predate emplacement of the vast lower unit of regional plains material (Ivanov and Head, 2004b).

The abundant shield volcanoes and inter-shield plains that are characteristic of this unit are noticeably different from the volcanic style of subsequent plains units and indicate widespread local and shallow magma sources during the emplacement of shield plains. Shield plains material embays densely lineated plains material (fig. 21) and, due to a lack of the broad ridges, is likely younger than the deformation characteristic of the ridged plains material.

Two reasons may explain the close association of shield plains material with groove belts. First, groove belts form local highs and the topographic position of shield plains material on flanks of the belts could be an important factor in the present areal distribution of unit psh where it survived flooding by the lower unit of regional plains material (Ivanov and Head, 2001b, 2004b). This is consistent with broad embayment of shield plains material by later regional plains materials and the areal distribution of outcrops of unit psh suggests that the shield plains material probably underlies a significant part of regional plains, at least within the lowlands surrounding Lakshmi Planum from the south. Second, the association of unit psh with groove belts may have genetic links. The most extensive areas of unit psh in the western part of the map area are associated with groove belts that form rims of two coronae (Beiwe and Omosi-Mama) that may be the surface manifestations of mantle diapirs (for example, Stofan and others, 1992) and serve as volcanic centers. The belts may represent the initial tectonic phase of interaction of the diapirs with lithosphere and shield plains material may correspond to the later volcanic stage of evolution of the diapirs. This interpretation is partly supported by the fact that the association of groove belts and shield plains material is less typical within the deformational zone of groove belts to the south of Lakshmi where corona and coronalike features are absent (fig. 3).

Shield plains material is absent in the interior of Lakshmi Planum suggesting that it either never formed there or was completely covered by younger plains materials. The first interpretation appears to be more favorable because outcrops of the tesseralike units embayed by the lower unit of regional plains material are exposed within Lakshmi Planum (fig. 3) but fields of shield plains material are not associated with any of them. Small fragments of pitted and grooved plains material (unit ppg), which vaguely resemble outcrops of unit psh and probably have been formed due to distributed volcanic eruption (fig. 9), occur along the inner edge of the mountain ranges. This unit is superposed on ridges of the ranges and is embayed by unit rp_1. Thus, it formed approximately contemporaneously with shield plains material outside Lakshmi. The unit ppg indicates small pulses of volcanic activity within Lakshmi after the waning of the orogenic phase of the mountain ranges and before and (or) concurrent with the emplacement of the lower unit of regional plains material on the surface of the Planum.

Subsequent to the emplacement of shield plains material, the style of volcanism changed again (Head and others, 1996). Instead of abundant small shield volcanoes, the lower unit of regional plains material (unit rp_1) broadly occurring and regionally deformed by wrinkle ridges, was emplaced from sources that are poorly known. Occurrences of unit rp_1 are concentrated mostly in the southern portion of the map within the lowlands of Sedna Planitia surrounding Lakshmi Planum from the south and in the interior of Lakshmi. The wide extent of this unit and its uniform morphology suggest a high-effusion-rate mode of emplacement from a few sources. Such a volcanic style during the formation of the lower unit of regional plains material is in distinct contrast to the widespread and abundant small shield volcanoes just preceding this phase. The widespread lower unit of regional plains material appears to be relatively thin (Ivanov and Head, 2001b), because small and large outliers of older units commonly occur within the broad fields of regional plains materials.

The massive outpouring of lava during emplacement of the lower unit of regional plains material (unit rp_1) changed to more localized eruptions that produced the upper unit of regional plains material (unit rp_2). Wrinkle ridges, which belong to the same family of structures that deform lower unit of regional plains material, as well as materials of other older units, deform flow-like features characterizing unit rp_2. This means that the new radical change of volcanic style (from unit rp_1 to rp_2) occurred before the main phase of wrinkle ridge formation. On the basis of the outcrop distribution of the upper unit of regional plains material it appears that the sources of this material may have been distributed in different parts of the map area. The most abundant and the largest fields of unit rp_2 are seen in the southern portion of the map area at the base of the regional slope of Lakshmi Planum. Distinct flows of the unit rp_2 flow to the south toward the lowlands of Sedna Planitia indicating that the main topographic configuration of the region was established before emplacement of the upper unit of regional plains material. Another field of unit rp_2 is at the northern flank of Colette Patera inside Lakshmi. This occurrence of the unit probably indicates some early stages of volcanism in the interior of Lakshmi. Sacajawea Patera and its surroundings does not display lava flows that are deformed by wrinkle ridges. All visible volcanic activity of Sacajawea Patera postdates both the emplacement of the upper unit of regional plains material and its deformation by wrinkle ridges.

The youngest units in the Lakshmi Planum quadrangle, smooth plains material and lobate plains material, are undeformed by tectonic structures and obviously were emplaced after formation of the pervasive networks of wrinkle ridges. Smooth plains material (unit ps) is concentrated preferentially at the distal edges of volcanic fields to the south of Colette and Sacajawea Paterae. Such an association suggests that smooth plains material in these localities represents volcanic material. Smooth plains material is not deformed by wrinkle ridges and, thus, postdate emplacement of the upper unit of regional plains material that corresponds to the earlier phases of volcanism at Colette Patera. Lobate plains material is clearly superposed on smooth plains material and, thus, whereas unit ps may represent the middle stages of volcanism at the Paterae in the interior of Lakshmi, unit pl represents late-stage volcanism.

Lobate plains material apparently represents the youngest material in the map area. The unit is concentrated in three areas: outside the deformational surrounding of Lakshmi Planum to the west and to the southeast of it and in the interior of the planum, around Colette and Sacajawea Paterae. Outside Lakshmi, lobate plains material occurs as extensive complexes of large and interfingering lava flows (fluctūs) that suggest multiple episodes of voluminous eruptions. The larger of the fluctūs is Neago Fluctūs (fig. 1) to the southeast of Lakshmi. By its dimensions (hundreds of kilometers), and complex superposition of lava flows, Neago Fluctūs resembles Mylitta Fluctus and other complexes of lava flows in the transition zone from the elevated Lada Terra to the lowlands of Lavinia Planitia within the Mylitta Fluctus, V–61 quadrangle (Roberts and others, 1992; Bridges and McGill, 2002; Ivanov and Head, 2006). Djata Fluctus to the west of Lakshmi (fig. 1) is significantly smaller than Neago Fluctūs and is in spatial association with Omosi-Mama Corona. In contrast to large lava complexes elsewhere on Venus, for example, Mylitta Fluctus, the source of which is Jord Corona (Roberts and others, 1992), and Juturna and Cavillaca Fluctūs sourced by Boala Corona, Neago Fluctūs displays no distinctive source features. This suggests that the episodes of the latest volcanic activity at the southeastern base of Lakshmi Planum may not be related directly to mantle diapirs manifested by coronae. These episodes also appear to be not persistent enough to build significant volcanic constructs. Lobate and digitate flows that make up unit pl flow along the regional slopes in both sites where the unit occurs outside Lakshmi, providing evidence that the long-wavelength topographic configuration of the exterior of Lakshmi Planum already existed before emplacement of lobate plains material. Inside Lakshmi, the unit pl occurs on the floor of Colette and Sacajawea Paterae and forms a broad apron around them. The apron extends mostly to the south of both Paterae following the regional slope of the Lakshmi surface to the south. Such a distribution of young lava material indicates that the slope was established prior to the late stage volcanism at the paterae. In places where flows from Colette Patera (unit pl) come close to Akna Montes, the flows appear to be stopped at the tilted surface of the lower unit of regional plains material. This implies that the later phases of evolution of the mountain belts (broad warping of the surrounding plains) were completed before the later stages of volcanism of Colette Patera and perhaps Sacajawea Patera as well.

Of the twenty-three impact craters in the map area (table 2), only one, Gražina (lat 72.5° N., long 337.5° E., 16.5 km), is cut by structures associated with Freyja Montes (fig. 17*B*). The other impact craters display no evidence of either tectonic deformation or volcanic embayment. This means that the short-wavelength tectonic deformation, which could be morphologically detected, and volcanic activity in the quadrangle mostly ceased before formation of the craters.

In summary, there are clear trends in the evolution of both tectonic regimes and volcanic styles within the Lakshmi Planum quadrangle. Contractional deformation first appeared after emplacement of ridged plains material but according to the areal distribution of the unit pr it was not very abundant in the map area. The peak of contractional deformation was reached during formation of the compact mountain ranges (unit mb) before emplacement of the vast plains units. Then it significantly dropped to the level of formation of pervasive but small structures of wrinkle ridges that deform the lower and the upper units of regional plains material (units rp_1 and rp_2). Contractional structures are absent within younger plains units such as smooth and lobate plains materials (units ps, and pl). This lack of contractional structures suggests cessation of compressional stresses by the time these materials were emplaced. Thus, the most important episode of contractional deformation within the map area was shifted toward the earlier stages of the observable geological history of the Lakshmi Planum quadrangle.

Extensional deformation that overprints densely lineated plains material (unit pdl) and played a major role in the formation of groove belts (unit gb) appears to have an opposite trend. The older fractures that have shaped the surface of unit pdl material are very narrow, pervasive, and do not form belt-like concentrations. The later occurrences of extensional structures are organized into belts of broader and longer structures. The majority of extensional structures predate emplacement of the shield plains material (unit psh). After emplacement of the materials of shield plains and the lower unit of regional plains, only individual grabens appear to cut the surface of the plains. Some of the grabens form a loose system of Rangrid Fossae at the southeastern edge of Lakshmi Planum. Only minor extensional deformation is observed in either smooth plains material (unit ps) or lobate plains material (unit pl), and as such, these units appear to mark a significant waning of the extensional tectonics within the map area.

The evolution of volcanic styles is clearly seen in the stratigraphic sequence of the moderately deformed plains units (psh, rp_1, rp_2, ps, and pl) where either sources, or nature of material, or both are recognizable. The older of these units is the shield plains material (unit psh), which is characterized by small shields suggesting eruptions from distributed shallow sources (for example, Head and others, 1992) with limited supply of magma. The lack of shield plains material in the interior of Lakshmi Planum suggests that this area probably was not a favorable site for unit psh-style volcanism, which is consistent with the possible presence of a massif of thick crust and lithosphere in this area. The unit rp_1 material formed both outside and inside Lakshmi and in both localities has similar morphology and surface properties. Inside Lakshmi, possible candidates for the sources of the unit rp_1 are Colette and Sacajawea Paterae simply because these structures are the only obvious centers of volcanism within Lakshmi. If the paterae are indeed the sources of the lower unit of regional plains material in the interior of the Planum, then they began to be active when formation of the main bodies of the mountain belts (unit mb) was completed. Smooth plains material (unit ps) and both units of lobate plains material (units rp_2 and pl) manifest another distinctive change of volcanic style from the vast lava flooding to voluminous and multiple eruptions from specific sources. Such a change of volcanic activity indicates localization and possibly deepening of the sources.

The tectonic and volcanic trends and the sequence of major events established during the geological mapping of the V–7 quadrangle outline the evolution of the large-scale topography of Lakshmi Planum and put constraints on the models of its possible formation.

The presence of heavily tectonized and embayed tessera material and the lack of shield plains material in the interior of Lakshmi are consistent with and collectively suggest that initially it was a high-standing block of heavily tectonized terrain similar to large tessera massifs elsewhere on Venus (Roberts and Head, 1990, 1990; Grimm and Phillips, 1990). The presence of such a block (a craton) contradicts the model of growth and subsequent collapse of a large dome-like structure at the initial stages of evolution of Lakshmi Planum (Pronin, 1986, 1990, 1992). Pronounced asymmetry characterizes the general topographic configuration of Lakshmi Planum. The southern half of the plateau is tilted to the south and is bordered by the lowest mountain range of Danu Montes. The northern portion of Lakshmi is more horizontal and is surrounded by the significantly higher ranges of Akna and Freyja Montes. This asymmetry of the large-scale topography of Lakshmi Planum appears to be inconsistent with a model in which formation of the mountain ranges is explained by the interaction of a stationary and axial symmetric mantle plume with a block of thickened lithosphere (Grimm and Phillips, 1990). The other predictions and consequences of the divergent class of models such as the presence of rift-like zones in the Lakshmi interior, older age of volcanism relative to the mountain belts, and progression of volcanism from the center of the plateau outward, are also not supported by the observations and the established sequences of units. The morphology of the ranges provides an additional argument against the model of interaction of a plume with a thickened block of crust/lithosphere. If, as described in the model (Grimm and Phillips, 1990), the ranges grew due to outward subsurface flow that thickened crust in the region below the ranges, the surface manifestation of such a process would likely resemble a horst-and-graben structure of the mountain belts due to gravitational relaxation of the growing topography. The same type of argument apparently could be applied to the model of formation of mountain ranges by deformation “from below” (Hansen and Phillips, 1995). The morphology of the ranges, consisting of ridges with morphologically smooth surfaces separated by V-shaped structural valleys, is similar, however, to the terrestrial fold-and-thrust belts (for example, Head, 1990). About the only prediction of the divergent class of models that is supported by observations is the presence of gaps between neighboring mountain ranges. These gaps, however, are not a unique feature of the divergent models and could be explained in the framework of other models, for example, by polyphase formation of the mountain ranges (for example, Crumpler and others, 1986).

Another class of models proposed to explain the unique topographic characteristics of Lakshmi Planum considers processes of convergence. There are two groups of these models. In the first, Lakshmi Planum and its mountainous surroundings are considered as the sequential result of a continuous downwelling under Lakshmi (for example, Bindschadler and others, 1990). In the second group of models, the morphologic and topographic characteristics of Lakshmi Planum are explained by regional compression and underthrusting (for example, Head, 1986, 1990). In the framework of the downwelling model, formation of the mountain ranges is shifted toward the later stages of the process of continuous downwelling and was preceded by development of elevated topographic plateau over the locus of the downwelling (Bindschadler and Parmentier, 1989; Bindschadler and others, 1990). Although such a model is able to explain formation of the unique mountain ranges, three important characteristics of Lakshmi Planum appear to be weakly consistent with this model. First is the asymmetric topographic configuration of Planum, whereas the model might predict a more symmetrical structure (Bindschadler and Parmentier, 1989). The second is the requirement of formation of radial contractional structures in the interior of Lakshmi that predate the mountain ranges (Kiefer and Hager, 1989; Bindschadler and others, 1990). The evidence for such structures is absent. If they formed, they must have been completely flooded by later plains materials such as material of the lower unit of regional plains (unit rp_1). The layer of this material, however, appears to be relatively thin because outliers of older tectonized terrain are scattered throughout the interior of Lakshmi. Contractional structures (especially those that could be formed during persistent downwelling flow) usually have high topography of several hundred meters (Ivanov and Head, 2001b, Young and Hansen, 2005) and the thickness of the later lava plains would need to be significantly larger than the height of the ridges to completely hide them. Otherwise, the surface of the cooling plains would drape over the ridges and produce specific pattern of structures that, for example, mark impact craters buried by lava plains on the Moon and Mars (for example, Colton and others, 1972; Raitala, 1988). These “ghost” structures are also absent in Lakshmi Planum. The third is the prediction of radial normal and strike-slip faults during the latest stages of evolution of the downwelling system. These tectonic features have not been found within Lakshmi Planum.

The convergence models that explain formation of Lakshmi Planum due to regional compression, underthrusting/subduction, and orogenesis due to collision with the edges of an ancient crustal (tessera-like) plateau (Crumpler and others, 1986; Head, 1986, 1990; Roberts and Head, 1990, Head and others, 1990) appear to be more consistent with the basic characteristics of western Ishtar Terra. These models explain the concentration of contractional structures at the periphery of Lakshmi and can account for the prominent asymmetry of this structure if the major axes of the convergence were at the northern and northwestern edges of the planum. These models are partly based on the obvious presence of heavily deformed terrain flooded by the later plains materials within the interior of Lakshmi Planum (for example, Roberts and Head, 1990). This terrain (the tessera material unit) clearly predates formation of the mountain ranges. The smooth surface of the ridges that form the ranges suggests that (1) the central tessera massif had not been significantly involved in formation of the ranges, and (2) it was mostly the material of plains units that was deformed to produce the ridges of the mountain belts.

The sequence of volcanic activity and progression of tectonic deformation play a key role in these models. Volcanism is predicted to largely postdate formation of the mountain belts with its younger phases shifted toward the center of Lakshmi Planum. This progression of volcanic events is consistent with the model in which the slabs subducting under the central craton of Lakshmi progressively melt at different depth [Ivanov and Head, 2008]. This is in complete agreement with the observations that material of the lower unit of regional plains (unit rp_1), the oldest recognizable plains unit in the interior of Lakshmi, covers the majority of the interiors and followed the orogenic stage of the evolution of the mountain ranges. The younger plains units (materials of smooth plains, unit ps, and lobate plains, unit pl) occur at the center of Lakshmi around Colette and Sacajawea Paterae.

Another requirement of the regional compression and underthrusting/subduction models is the outward sequence of deformation. The Atropos Tessera area appears to illustrate such a progression of contractional deformation at the northwestern flank of Lakshmi Planum. There, the broad ridges, which conform to the general strike of Akna Montes, deform older, densely lineated plains material and make the surface of this material resemble the complexly deformed surface of tessera. The ridges extend over distances of hundreds of kilometers and occur within the majority of Atropos Tessera. On the other side of Akna Montes, inside Lakshmi, the ridges abruptly stop near the base of the mountain range. Such an asymmetry of the distribution of the ridges on both sides of Akna suggests that the ridges preferentially formed outside Lakshmi and, thus, may indicate outward progression of deformation.

Thus, the results of the geological mapping of the V–7 quadrangle and established sequence of events in this region mostly contradict the divergent models of formation of Lakshmi

Planum and apparently are in poor agreement with the important predictions of the downwelling models. The results of the mapping are consistent with the predictions, major features, and consequences of the models explaining formation of the unique topographic and morphologic characteristics of Lakshmi Planum due to large-scale compression and underthrusting/subduction of plains units from the north against an ancient crustal block in the core of Lakshmi.

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Table 1. List of volcanic and volcano-tectonic centers in the Lakshmi Planum quadrangle (V–7), Venus (modified from Crumpler and Aubele, 2000).

[—, no official name has been assigned]

Feature name	Latitude (deg N.)	Longitude (deg E.)	Diameter (km)
Lava fields (fluctūs)			
Djata Fluctus	66.5	307	230x100
Neago Fluctūs	50	347	>600
Coronae			
—	68	346	230–250
Omosi-Mama Corona	64.5	306.0	480
Beiwe Corona	53.5	307	180x400
Xilonen Corona	51	321	250x200
Ashnan Corona	50.2	357.0	300
Paterae			
—	74.5	315	100
Colette Patera	66	323	600
Sacajawea Patera	64.5	335	225x150
Siddons Patera	61.5	340	70
Steep-sided dome			
—	60	324.5	25
Arachnoid			
—	54.5	326.5	280

Table 2. List of impact craters within the Lakshmi Planum quadrangle (V–7), Venus (modified from Schaber and others, 1998).
[—, no official name has been assigned to this feature]

Crater name	Latitude (deg N.)	Longitude (deg E.)	Diameter (km)
Gražina	72.448	337.474	16.5
Wanda	71.244	323.145	21.7
Osipenko	71	321	30
Rita	70.97	334.8	8.3
Cotton	70.758	300.197	48.1
Ivka	68.206	303.831	14.9
Magda	67.041	329.675	10.1
Zlata	64.63	333.918	7
Sigrid	63.555	314.394	16.1
Lyudmila	62.128	329.672	14.1
Berta	62	322	20
Tamara	61.63	317.315	11.9
Akhmatova	61.349	307.885	41.4
Volyana	60.636	359.938	5.3
Magnani	58.616	337.208	26.4
Kartini	57.793	333.039	23.4
—	55.1	350.6	4.3
Sévigné	52.625	326.474	29.6
Stefania	51.29	333.313	11.7
Lotta	51.06	335.909	11.8
Bahriyat	50.3	357.5	5
Lind	50.22	355.027	25.8
Aftenia	50	323.9	7

Table 3. Area of units mapped in the Lakshmi Planum quadrangle (V–7), Venus.

Unit label	Area (km^2)	Area (%)
cf	4,000	0.0
c	23,000	0.3
pl	787,000	10.3
ps	313,000	4.1
rp_2	923,000	12.0
rp_1	1,986,000	25.9
ppg	71,000	0.9
psh	549,000	7.2
gb	1,020,000	13.3
mb	459,000	6.0
pr	28,000	0.4
pdl	425,000	5.5
t	620,000	8.1
data gaps	455,000	5.9
TOTAL	7,663,000	100