

**MAPPING OF THE V-7 QUADRANGLE: SEQUENCE OF EVENTS DURING FORMATION OF LAKSHMI PLANUM, VENUS.** M. A. Ivanov<sup>1,2</sup> and J. W. Head<sup>2</sup>. <sup>1</sup>Vernadsky Institute, RAS, Moscow, Russia, mikhail\_ivanov@brown.edu; <sup>2</sup>Brown University, Providence, RI, USA, james\_head\_iii@brown.edu

**1. Introduction** The key feature of the Lakshmi Planum quadrangle (V-7, 50-75° N, 300-360° E) is the volcanic plateau of Lakshmi Planum, which represents a unique class of highlands on Venus. The surface of Lakshmi Planum stands 3-4 km above mean planetary radius, MPR, and is surrounded by the highest Venusian mountain ranges that are 7-10 km high. Lakshmi Planum and its mountain surroundings are among the most intriguing features on Venus [1-7]. There are two alternative models of formation of the complex of Lakshmi Planum. In the first, this feature is considered as a result of mantle upwelling, formation, and collapse of a large dome [8, 6, 9, 10]. In the second model, formation of Lakshmi Planum is explained by a mantle down-welling and collision of terrains against a foreland of the core region of Lakshmi [11-16]. The sequence of events during formation of Lakshmi plays the crucial role in the assessment of both models. For example, the collapse of a large dome would result in formation of chaotically oriented contractional structures in the interior of the plateau, suppressed volcanism there, and the general progression of events in the direction from inside out. The alternative model would be consistent with the opposite direction of the geologic activity, the older relative age of the mountain ranges, and younger volcanic activity in the central area of the plateau.

In our mapping, we used traditional methods of unit definition [17,18] appropriately modified for radar data [19]. We defined units and mapped relations between them and tectonic structures using F- and C1-MIDR's images and altimetry data. The background for our mapping approach is described in [19-23]. In this paper we describe the set of mapped units and structures and outline the apparent sequence of events during formation of Lakshmi Planum.

**2. Material units and structures** Although we have mapped tectonic structures independently of geologic units, sometimes the structures become a part of the definition of a unit. For example, tessera is analogous to Aureole member 4 of the Olympus Mons Formation on Mars [24]. In recently published Venus maps, the same approach was successfully applied for mapping of several quadrangles [25-28]. Here we summarize the stratigraphic units and structures and their relations.

**2.1. Units** Tessera (t) appears to be the oldest material because it is embayed by most of the other units in the map area. Tessera is deformed by at least two sets of intersecting ridges and grooves, and is a result of tectonic deformation of some precursor terrain [3,4,29,30]. In the V-7 quadrangle, tessera is exposed inside and outside Lakshmi Planum. Densely lineated plains (pdl) postdate tessera and form one of the oldest units. It has relatively flat surfaces and is cut by dense swarms of lineaments (fractures). Typically small patches of pdl occur outside Lakshmi

Planum. Ridged plains (pr) are commonly deformed by relatively broad (2-5 km wide) ridges tens of kilometers long. In the V-7 quadrangle this unit is not abundant and occurs in the southern portion of the map area outside Lakshmi. Shield plains (psh) are characterized by abundant small shield-shaped features (2-20 km) interpreted to be small volcanoes. The unit is widely distributed in the quadrangle but occurs predominantly within the lowlands around Lakshmi Planum and is absent inside the plateau. Material of psh embays all previous units. Pitted and grooved material (pgm) is cut by narrow, wide, and shallow grooves with scalloped edges. In places, isolated pits and low shield-like features are seen. The unit pgm occurs in four small areas at the periphery of the interior of Lakshmi in spatial association with the mountain ranges. Regional plains (rp) form the most widespread unit. The surface of it is smooth, homogeneous, and typically cut by wrinkle ridges. The sources of the unit are unknown. Regional plains occur both inside and outside Lakshmi Planum and cover majority of the quadrangle. Lower unit of lobate plains (pl1) is also deformed by wrinkle ridges but has lobate boundaries and higher radar albedo than regional plains. The largest area of this unit is outside Lakshmi and smaller occurrence of it is on the northern flank of Colette Patera inside the plateau. Smooth plains (ps) are characterized by uniform and preferentially low albedo. Material of unit ps embays wrinkle ridges. Small patches of ps are scattered throughout the map area. The largest occurrence of the unit is in the southern portion of Lakshmi Planum. Upper unit of lobate plains (pl2) is characterized by lobate flows that embay most tectonic structures including wrinkle ridges. There are three major occurrences of the unit: Negao Fluctus and Djata Fluctus outside Lakshmi and Colette and Sacajawea Paterae inside the plateau. Impact craters (c) and crater outflow deposits (cf) are peppered throughout the quadrangle without any preferential concentrations.

**2.2. Structures** Extensional structures. In many places, extensional structures are closely spaced and obscure underlying terrain. These concentrations consist of numerous fractures and graben and form linear belts (groove belts, gb) that are many hundreds of kilometers long and a few hundreds of kilometers wide. Groove belts are concentrated within the southern regional slope of Lakshmi Planum where they cut the units pdl and pr and are embayed by shield plains and regional plains.

Contractional structures. Several types and scales of contractional features are observed within the quadrangle. Narrow and sinuous wrinkle ridges are seen throughout the quadrangle but more abundant in vast areas of regional plains. Broader and more linear ridges dominate ridged plains (pr),

which are largely equivalent to the ridge belts of [31-32].

The most important occurrences of contractional structures in the map area are mountain belts (unit mt) surrounding the interior 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 such belts. Danu Montes (~100 km wide, ~1000-1200 km, and ~4-5 km high) border the southern edge of Lakshmi. Regional plains embay the ridges of Danu Montes on both sides of the mountain range. Akna Montes to the W of Lakshmi is a shorter (~800-900 km), wider (~200 km), and higher (~6-7 km) mountain range, which is slightly bent inside, toward plateau of Lakshmi. Regional plains of the Lakshmi interior embay the innermost ridges of Akna Montes. At the outer side, ridges of Akna Montes deform the surface of pdl. Freyja Montes border Lakshmi Planum from the N and NE. This belt is wide (~300 km) and high (~6-7 km) and is characterized by complicated structure consisting of several domains with their own pattern of deformation. The massif of Freyja Montes appears to be embayed by regional plains of the Lakshmi interior. The northern edge of the belt is outside of the map area. Maxwell Montes are at the eastern edge of Lakshmi Planum. Within the map area, only the western most extensions of Maxwell are seen. Relationships of structures of Maxwell with the plains inside Lakshmi appear to be ambiguous and do not provide strong evidence suggesting relative age of these units.

**3. Discussion and conclusions** The major goal of our mapping in the V-7 quadrangle was to establish the sequence of events during formation and evolution of Lakshmi. The main issues that we addressed in our study were: When the mountain ranges formed? What is the nature of the Lakshmi interior? How do the interior and exterior regions of Lakshmi compare to each other? What is the general sequence of events during formation and evolution of Lakshmi Planum? There are three major physiographic provinces in the map area: the interior of Lakshmi Planum, the surrounding mountain ranges, and the exterior of Lakshmi. The sets of units and structures and their stratigraphic relationships are similar within the interior and exterior. This implies that similar processes in similar sequences have operated there and allows broad temporal correlations among mapped features. There is no compelling evidence suggesting when the mountain ranges formed relative to each other. It is possible, however, to establish range of stratigraphic ages for the mountain belts as a class of features. The youngest unit deformed by structures of the mountain belts (Akna Montes) is pdl of Atropos Tessera. This unit establishes the lower stratigraphic limit of the belts formation. The oldest unit embaying structures of the ranges are regional plains inside and outside Lakshmi. Thus, the mountain crown of Lakshmi was formed relatively early on in the geologic history of the region.

The interior of Lakshmi has relatively simple stratigraphic record. The oldest units exposed there is tessera, which is heavily embayed by regional plains. Large and small outliers of tessera are seen in many places of the interior suggesting that the thickness of regional plains is small. An important feature of the interior is the absence of ridge belts that indicates virtual lack of contractional deformation there. Thus, the interior of Lakshmi appears to represent initially a tessera-like plateau that was and geologically stable during formation of the mountain ranges. The youngest activity within the interior is related to volcanism and formation of the young plains ps, pl1, and pl2 sourced by Colette and Sacajawea Paterae.

The exterior of Lakshmi displays abundant units and structures that predate regional plains (t, pdl, gb, pr, psh) suggesting that both volcanism and tectonics were concentrated predominantly outside the plateau during the earlier stages of the geologic history of the region. After formation of regional plains, volcanism through a few centers to the southeast and west of Lakshmi played the major role in the geologic history. The sequence of events during formation of the Lakshmi Planum and its surroundings suggests that these features began near the beginning of the observable geologic record. The general progression of events appears to be oriented from outside in rather than in the opposite direction, which is consistent with the formation of the complex of Lakshmi Planum and the mountain ranges due to large-scale horizontal convergence, underthrusting, imbrication, and folding [13,14,16,33].

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