

**FORMATION AND EVOLUTION OF LAKSHMI PLANUM (V-7), VENUS: ASSESSMENT OF MODELS USING OBSERVATIONS FROM GEOLOGICAL MAPPING.** 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>Department of Geol. Sci., Brown University, Providence, USA (James\_Head@brown.edu).

**Introduction:** Lakshmi Planum is a high-standing plateau (3.5-4.5 km above MPR) surrounded by the highest mountain ranges on Venus [1-6]. Lakshmi represents a unique type of elevated region different from dome-shaped and rifted rises and tessera-bearing crustal plateaus. The unique characteristics of Lakshmi suggest that it formed by an unusual combination of processes and played an important role in Venus geologic history. Lakshmi was studied with Venera-15/16 [7-10,5,11] and Magellan data [12-14], resulting in two classes of models, divergent and convergent, to explain its unusual topographic and morphologic characteristics. Divergent models explain Lakshmi as a site of mantle upwelling [10,15-18] due to rising and subsequent collapse of a mantle diapir; such models explain emplacement of a lava plateau inside Lakshmi and, in some circumstances, formation of the mountain ranges. The convergent models consider Lakshmi as a locus of mantle downwelling, convergence, underthrusting, and possible subduction [19,11,20-29]. Key features in these models are the mountain ranges, high topography of Lakshmi interior, and the large volcanic centers in the plateau center. These divergent and convergent models entail principally different mechanisms of formation and suggest different geodynamic regimes on Venus.

Almost all models make either explicit or implicit predictions about the type and sequence of major events during formation and evolution of Lakshmi and thus detailed geological mapping can be used to test them. Here we present the results of such geological mapping (the V-7 quadrangle, 50-75N, 300-360E; scale 1:5M) that allows testing the proposed models for Lakshmi.

**Material units:** Eleven material units make up the V-7 quadrangle. (1) Tessera (t), exposed inside and outside Lakshmi appears to be the oldest material because it is embayed by most of the other units in the map area. (2) Densely lineated plains (pdl) postdate tessera and form one of the oldest units; patches occur outside Lakshmi Planum. (3) Ridged plains (pr) postdate pdl and occur outside Lakshmi. (4) Shield plains (psh) display abundant small shield-shaped features interpreted to be small volcanoes; embays the previous ones and occurs predominantly within lowlands around Lakshmi. (5) Pitted and grooved material (pgm) displays small pits and is cut by broad and shallow grooves with scalloped edges; occurs inside Lakshmi in association with mountain ranges. (6) Lower unit of regional plains (rp<sub>1</sub>) has smooth surface, cut by wrinkle ridges; the most widespread unit that occurs inside and outside of Lakshmi Planum. (7) Upper unit of regional plains (rp<sub>2</sub>) is also deformed by wrinkle ridges but has lobate boundaries and higher radar albedo than regional plains; occurs both inside and outside Lakshmi. (8) Lobate plains (pl<sub>2</sub>) is

characterized by lobate flows that embay most tectonic structures including wrinkle ridges; form fluctūs outside Lakshmi and surround Colette and Sacajawea Paterae inside the plateau. (9) Smooth plains (ps) have uniform and low radar albedo, embays wrinkle ridges; largest occurrence is in southern portion of Lakshmi. (10) Impact craters (c) and (11) crater outflow deposits (cf) are peppered throughout the quadrangle without any preferential concentrations.

**Structures:** Extensional structures. In places, fractures and graben are closely spaced and obscure underlying terrain; form belts (groove belts, gb) that extend for hundreds of kilometers mostly within the southern regional slope of Lakshmi where they cut pdl and pr and are embayed by shield plains and regional plains. Contractional structures. Wrinkle ridges mildly deform shield plains and regional plains; broader and more linear ridges dominate ridged plains (pr), which are largely equivalent to the ridge belts of [13,30]. The most important occurrences of contractional structures are mountain belts (unit mt) that surround the interior of Lakshmi and consist of densely spaced ridges 5-15 km wide, tens of km long. Regional plains usually embay the ridges.

**Sequence of major events during evolution of Lakshmi Planum:** Various plains units heavily embay fragments of tessera in all localities inside and outside Lakshmi. The consistent relationships of embayment and the complex and unique surface deformational pattern suggest that tessera represents the oldest material. Tessera distribution patterns suggest more extensive presence under younger plains units, forming basement.

Densely fractured plains (pdl) appear younger than tessera; the largest massifs of pdl occur in Atropos and Itz'papatotl Tesserae where plains are further deformed by broad ridges and to some degree resemble the tessera deformation patterns. The ridges are generally conformal to the strike of Akna/Freyja Montes and occur within large areas of densely lineated plains adjacent to the mountain ranges. The ridges are clearly related to the orogenic phase of formation of mountain belts [10,16-19,11,20-23,25,26,29]. Shield plains and regional plains embay mountainous ridges both outside and inside Lakshmi Planum, which implies that the orogenic phase was shifted toward earlier stages of the observable geological history of Ishtar Terra. Shield plains were emplaced after the main phase of mountain belt formation and before regional plains, but exclusively outside of the plateau.

The lower unit of regional plains (rp<sub>1</sub>) postdates shield plains; occurrences are concentrated S of Lakshmi Planum (Sedna Planitia) and in the interior of Lakshmi. The thickness of unit rp<sub>1</sub> is small because outliers of older units occur within the broad regional plains. Youngest units in Ishtar, smooth/lobate plains, are su-

perposed on regional plains and undeformed by tectonic structures; they were emplaced after cessation of tectonic activity. Smooth/lobate plains form extensive lava aprons around Colette and Sacajawea Paterae, representing the latest volcanic activity inside Lakshmi Planum.

**Testing models of Lakshmi Planum formation:** Detailed geological analysis thus allows both definition of material units and tectonic structures and establishing the sequence of major events during its formation and evolution, and testing the suite of models proposed to explain the mechanisms of formation of this structure.

The interpreted nature of units and the sequence of events strongly contradict the predictions of divergent models: 1) The very likely presence of an ancient (craton-like) tessera massif in the core of Lakshmi; such a core is inconsistent with the rise and collapse of a mantle diapir [10,15,16]. 2) The absence of a rift zone in the interior of Lakshmi; these zones appear to be a natural consequence of growth of surface topography due to diapiric rise [e.g. 31]. 3) The apparent migration of volcanic activity toward the center of Lakshmi; divergent models are consistent with the opposite trend of volcanism. 4) The abrupt cessation of mountain range ridges at the edge and propagation over hundreds of kilometers outside Lakshmi in Atropos and Itzpapalotl Tesserae. Divergent models predict the opposite progression.

Convergent models of formation and evolution of Lakshmi Planum appear to be more consistent with the observations. The pure downwelling models [e.g. 23], however, face three important difficulties. 1) The possibly unrealistically long time span that can be required to produce the major features of Lakshmi [32]. 2) The strongly asymmetrical north-south topographic profile of Lakshmi and striking difference in the height and thickness of the mountain belts to the north-west and north (Akna and Freyja Montes) and to the south of Lakshmi (Danu Montes). The pure downwelling models would require formation of more symmetrical structures. 3) The absence of radial contractional structures (arches and ridges) in the interior of Lakshmi. These structures represent the necessary result of the downwelling models.

Convergence models are most consistent with observations and explain the structure by collision and underthrusting/subduction of lower-lying plains with the elevated and rigid block of tessera [20-22]. These models are capable of explaining formation of the major features (for example, mountain belts) and the sequences of events and principal trends in evolution of volcanism and tectonics. To explain the pronounced longitudinal asymmetry of Lakshmi, however, these models have to consider major axes of collision to be at the N and NW of the plateau in Atropos and Itzpapalotl Tesserae.

A plausible scenario for formation/evolution of Lakshmi Planum consists of the following stages: **Stage 1:** Pre-deformational configuration of western Ishtar; a layered suite of low-lying lava plains surrounded a tessera craton. **Stage 2:** Compression from the N led to deformation of plains against the tessera massif foreland and formation of higher mountain ranges; displacement

of the craton may have caused formation of Danu Montes. **Stage 3:** Continued underthrusting finally caused limited uplift of N mountain ranges and the N portion of Lakshmi Planum, creating the Lakshmi asymmetry; two different events may have followed, one with and one without delamination [33]. **Stage 4a:** In the beginning of delamination, fertile mantle flowed toward the base of the massif, melted, and led to emplacement of  $rp_1$  in the Lakshmi interior. **Stage 5a:** During more mature stages of delamination, the deepest portion of the slab would start to melt to form the youngest lava plains at Colette and Sacajawea Paterae. **Stage 4b:** If no delamination occurs then formation of unit  $rp_1$  could be due to broad melting of the underthrust slab as it crosses the melting isotherm. **Stage 5b:** As underthrusting proceeded, the relatively colder slab deflected the isotherm downward and new deeper portions of the slab melted, producing the younger lavas near Lakshmi Planum center.

When either delamination or continued underthrusting waned, the thicker crust of the northern mountain ranges rose epirogenically, which led to additional elevation of the ranges and the northern portion of Lakshmi.

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