

**LAKSHMI PLANUM: A DISTINCTIVE HIGHLAND VOLCANIC PROVINCE;** Kari M. Roberts and James W. Head, Dept. of Geological Sciences, Brown University, Providence, R. I. 02912

**Introduction-** Lakshmi Planum, a broad smooth plain located in western Ishtar Terra and containing two large oval depressions (Colette and Sacajawea), has been interpreted as a highland plain of volcanic origin.<sup>1-5</sup> Lakshmi is situated 3-5 km above the mean planetary radius and is surrounded on all sides by bands of mountains interpreted to be of compressional tectonic origin (Fig. 1).<sup>5-7</sup> Four primary characteristics distinguish Lakshmi from other volcanic regions known on the planet, such as Beta Regio: 1) high altitude, 2) plateau-like nature, 3) the presence of very large, low volcanic constructs with distinctive central calderas (Colette and Sacajawea), and 4) its compressional tectonic surroundings. Building on the previous work of Pronin,<sup>5</sup> the purpose of this study is to establish the detailed nature of the volcanic deposits on Lakshmi, interpret eruption styles and conditions, sketch out an eruption history, and determine the relationship between volcanism and the tectonic environment of the region. The following is revised and reprinted from a previous abstract,<sup>13</sup> intended as a review for the Flagstaff Venus Geoscience Workshop. A more detailed, thorough discussion and interpretation of features and units on Lakshmi Planum may be found in a paper to be submitted to the *Journal of Geophysical Research*, entitled "Characterization and Interpretation of Lakshmi Planum, Venus: A Distinctive Highland Volcanic Province."

**Observations and Interpretations-** On the basis of our detailed mapping we have compiled a province map (Fig. 1) that illustrates some of the basic characteristics and relationships in Lakshmi Planum. **Major shields/calderas:** Two major caldera structures (Colette, C; Sacajawea; S) and their circumferential low-shield-forming flow deposits dominate the region. Colette is 130 x 180 km, elongated in a N-S direction, is approximately 1-2 km deep<sup>4,5</sup> and is surrounded by an extensive radiating system of flows having an average width of 15 km, and lengths of 100-300 km. The shield structure surrounding Colette is about 500 x 700 km in dimension and descends about 1 km from the rim to the surrounding plains. Sacajawea is a 200 x 120 km oval-shaped depression elongated in a SW-NE direction, approximately 1.5-2 km deep, and lacks the distinct radial lobate flow patterns of Colette, although mottled deposits surrounding Sacajawea, and distinct from the undivided plains, have been mapped extending about 300 km from the center of Sacajawea. The Sacajawea shield structure (defined by the caldera and the surrounding deposits) is very low (less than 1 km from the rim to the surrounding plains). On the basis of the relative crispness and distinctiveness of the flows and structures comprising the Colette shield, it is interpreted to be younger than Sacajawea.<sup>4,5</sup> Elsewhere, we have described the characteristics and relationships of Colette and Sacajawea calderas.<sup>8</sup>

A wide range of additional structures interpreted to be **volcanic source vents** have been mapped including: 1) **domes and cones**, which range from 1-50 km in diameter and include **small cones** (<10 km diameter) scattered throughout the region; **small domes** (10-15 km in diameter) sometimes containing summit depressions and apparently preferentially located in association with structural features (e.g., inside Colette, along a rift associated with Sacajawea, and within the Ridged Terrain); and **low shields**, up to 75 km across, almost indiscernible topographically, and containing a summit pit; 2) **Diffuse halo** (Fig. 1, [1]); SE from Colette is a large, dark semicircular feature about 50 km in diameter surrounded by an elongated halo of diffuse radar-bright deposits that are apparently superimposed on the more distinct flow deposits of Colette. The diffuse character, the lack of distinctive lobate patterns, the elongation and the superposition of the deposits suggest that they may be of pyroclastic origin; 3) **Vent Complex** (Fig. 1, [2]); flanking Sacajawea to the S-SW is a very broad (~200 km diameter) radar-bright feature that lacks distinctive topographic expression in the currently available altimetry. It appears to be a localized center of volcanism, characterized by very mottled lobate flow deposits which become more continuous towards a central region containing numerous volcanic craters and domes.

**Plains units** dominate the surface of Lakshmi and are interpreted to be volcanic on the basis of their embayment relationships, their flatness and uniform albedo, and their association with volcanic source vents. **Undivided Plains units** (PU) are characterized as smooth low-albedo plains in which individual flow features are not seen in either Venera 15/16 or Arecibo data. They cover a large part of Lakshmi, and may be derived from the major shields, from the numerous domes and cones, or from presently buried sources. **Grooved Plains** (PG) occur in a single patch about 150 km to the north of Sacajawea and are typified by very finely spaced furrows or grooves arranged in sweeping curvilinear sets trending generally N-S but frequently curving to the NE or NW. This system of faults<sup>5</sup> appears to be extensional in origin, and is embayed by Sacajawea deposits and undivided plains. **Ridged Plains** (PR) are defined by faint bright lineaments on plains material arranged in subparallel sets that follow the borders of the planum or trend S-SE across it. On the basis of the ridge-like nature of some of these bands, and their association with the compressional deformation in the surrounding orogenic belts, we have interpreted them to be of compressional origin. The parallelism of many of these ridged units with the adjacent orogenic belts, and the general tilting of the ridged plains away from the mountains, strongly suggest that the plains have been involved in at least the latter phases of deformation producing the orogenic belts.

**Structural features and units** occur within the plains, as well as dominating the surrounding mountains. **Ridged Terrain** (RT) is characterized by a very rough-textured system of ridges and grooves and is concentrated in east central Lakshmi where, in at least one occurrence, the ridges and grooves are arranged in rhomboidal sets with the small angle subtending about 35° and the bisectrix oriented about N35°W. Virtually all other units are superposed on or embay RT, and we thus concur with Pronin<sup>5</sup> that this unit is representative of an episode of deformation early in the history of Lakshmi. Adjoining Sacajawea to the SE is a system of linear features interpreted by Pronin<sup>5</sup> to be fault scarps with characteristics similar to graben, at least one of which contains a volcanic dome. This may be a flanking rift zone similar to those occurring on

Hawaii. In addition, a series of domes and cones appear to be arrayed in a preferred orientation, trending E-SE along a line connecting Colette and Sacajawea.

#### Conclusions-

1) **Volcanic style:** The range of deposits and structures mapped in Lakshmi Planum indicates that the region is dominated by at least three styles of volcanism: a) centralized effusive, very large low shield structures (>500 km) with numerous long flows and extremely large calderas<sup>8</sup> (100-200 km); b) distributed effusive, with a wide range of source vents most typically forming cones and domes in the 1-50 km diameter size range; although dispersed throughout Lakshmi, many are localized along structural trends; on the basis of their radar characteristics, most mapped effusive deposits appear to be relatively smooth at scales of decimeters to meters; c) possible pyroclastic, represented by the Diffuse Halo; if further mapping confirms a pyroclastic origin, this would imply the presence of volatile-rich magmas on Venus.<sup>9</sup>

2) **Sequence and Geologic History:** Formation of the Ridged Terrain was followed by emplacement of plains which were subsequently deformed to produce the Grooved Plains N of Sacajawea. Sacajawea was formed and its related deposits embayed the Grooved Plains and Ridged Plains. Although brighter than those of Sacajawea, the deposits of the Vent Complex appear truncated by the large caldera; we thus interpret it to be older than Sacajawea. Colette and its associated flows were formed subsequent to Sacajawea, but it is not known if activity in the two structures overlaps in time. The Diffuse Halo appears to postdate Colette. Ridged Plains appear to have formed throughout the history of Lakshmi, apparently deforming in response to compressional deformation and regional tilting in the adjacent mountain ranges. Ivanov et al<sup>10</sup> have argued that the radar brightness (decimeter to meter scale roughness) associated with fresh impact crater haloes is lost by a smoothing process after about 120-250 my. If this is true, and bright units on Lakshmi have a similar roughness, then this may imply that at least some of the volcanism occurred relatively recently.

3) **Relation to Tectonic Deformation:** There is abundant evidence for the synchronicity of volcanism and tectonism (elongation of calderas, rift zones adjacent to calderas, association of domes and cones with preexisting structure, Grooved Plains, Ridged Plains of various ages and orientations, etc.). Further analysis is required to determine the sequence of deformation in the adjacent orogenic belts and its link to Lakshmi volcanic history, but it tentatively appears that the center of volcanism has migrated from east to west during the history of Lakshmi. 4) **Distinctiveness of Lakshmi Planum:** Our studies further emphasize the unique nature of Lakshmi Planum in terms of its compressional tectonic environment, altitude, and presence of large low shields with extremely large calderas. No other such volcanic province has yet been identified on Venus.

5) **Origin of Lakshmi Planum:** On the basis of the presence of distributed regional compressional deformation surrounding Lakshmi Planum,<sup>6-7,11-12</sup> the sense of tectonic transport in toward Lakshmi from the north<sup>11</sup> and the east,<sup>12</sup> the evidence for crustal thickening in Freyja and Maxwell Montes in excess of several tens of kilometers,<sup>11-12</sup> and the topographic elevation of the plateau itself, we interpret Lakshmi Planum to be the locus of convergence and crustal thickening, and the volcanic activity there to be linked to melting associated with processes of convergence and crustal thickening. This model is in contrast to that of Pronin,<sup>5</sup> who attributes the volcanism to a large hot spot upwelling below Lakshmi, and spreading laterally to cause the surrounding deformation.

**References:** (1) H. Masursky, *et al.* (1980) *JGR*, **85**, 8232; (2) V. Barsukov, *et al.* (1986) *JGR*, **91**, D378; (3) A. Basilevsky, *et al.* (1986) *JGR*, **91**, D399; (4) E. Stofan *et al.* (1987) *Earth, Moon*, **38**, 183; (5) A. Pronin (1986) *Geotectonica*, **4**, 26 (in Russian); (6) Campbell *et al.* (1983) *Science*, **221**, 644; (7) Crumpler *et al.* (1986) *Geology*, **14**, 1031; (8) Magee and Head (1988) *Lunar Planet. Sci.*, **XIX**, 711; (9) Head and Wilson (1986) *JGR*, **91**, 9407; (10) B. Ivanov, *et al.*, (1986) *JGR*, **91**, D413; (11) Head (1988) *Lunar Planet. Sci.*, **XIX**, 467; (12) Vorder Bruegge and Head (1988) *Lunar Planet. Sci.*, **XIX**, 1220, (13) Magee and Head (1988) *Lunar Planet. Sci.*, **XIX**, 713.

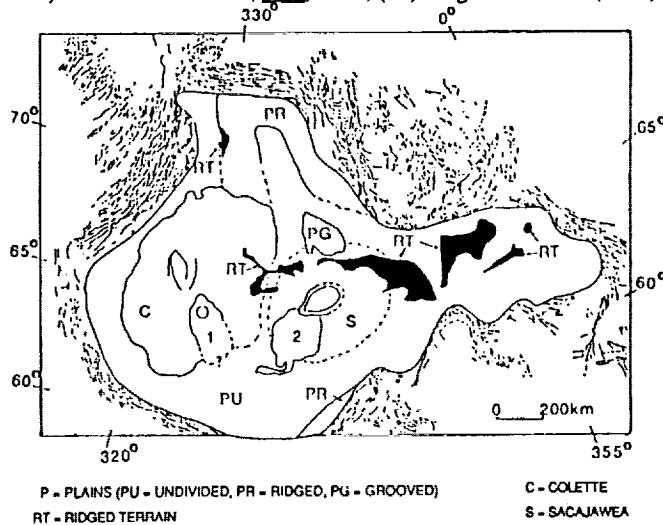


Figure 1. Province map of Lakshmi Planum. See text for explanation. Lines outside of Lakshmi Planum indicate structural trends in adjacent deformed terrain.