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Flow field stratigraphy surrounding Sekmet Mons Volcano, Kawelu Planitia, Venus

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[1] Detailed mapping has revealed several stratigraphic components among lobate plains in the vicinity of Sekmet Mons volcano (44.5°N. lat., 240.5° long.), located on the northern lowland plains of Kawelu Planitia on Venus. Volcanic effusion events produced discrete lobate plains throughout the area. Superposition of flow margins between adjacent lobate plains components indicate that the effusive activity generally progressed from southwest to northeast across the Sekmet Mons area, leading to a cumulative total of 1.5 million km^2 covered by adjacent lobate plains components. Source areas for the effusion responsible for the lobate plains components occur primarily along fracture zones or from concentrations of low volcanic domes ("shield fields") instead of from single constructs. Magellan radar backscatter values from a mixture of both radar bright and radar dark flow components within the flow fields are well below values typical of clinkery a′a lava flows on Earth, but they are consistent with values from terrestrial pahoehoe flows. Detailed mapping of Strenia Fluctus (centered on 41.5° N. lat., 251.0° long.), one of the latest lobate plains units in the area, does not show a systematic trend among effusive centers that contributed to the generation of this flow field. Instead, the Strenia Fluctus flow field is a complex mixture of flows that emanated from a shield field along Mist Chasma and that flowed down a very gentle (>0.1°) regional slope to the east. A 4-km-diameter cone north of Strenia Fluctus was the source of a flow complex traceable for more than 200 km over a slope of only 0.03°. Individual flows within Strenia Fluctus are composed of intermixed lobes, similar to relationships observed on the distal portion of the 75-km-long Carrizozo basalt flow in New Mexico, which also displays abundant inflation features and a predominant pahoehoe surface texture. If the Venusian lobate plains consist of pahoehoe flows comparable to the Carrizozo flow, they were most likely emplaced at modest effusion rates ($\sim$50 to 500 m^3/s), and even with inflation the flows are likely $\leq$15 m in thickness. Under these conditions all of the lobate plains surrounding Sekmet Mons could have been emplaced in $\sim$14,000 to 1400 Earth years, assuming continuous effusion with only one source vent active at a time. At similar rates all of the lowland plains in the northern hemisphere of Venus could have been resurfaced by 15-m-thick flows through continuous single-vent effusion in $\sim$1.4 million to $\sim$140 thousand Earth years. *INDEX TERMS:* 5480 Planetology: Solid Surface Planets: Volcanism (8450); 5464 Planetology: Solid Surface Planets: Remote sensing; 5475 Planetology: Solid Surface Planets: Tectonics (8149); 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5460 Planetology: Solid Surface Planets: Physical properties of materials; *KEYWORDS:* fracture zones, pahoehoe, Strenia Fluctus, effusion rate, Carrizozo, northern lowlands

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1. Introduction

[2] The Magellan mission [*Saunders et al.*, 1992] has revealed the great complexity of the surface of Venus, which is perpetually hidden from visual observation by a dense cloud cover. Synthetic Aperture Radar (SAR) images, at 12 cm wavelength, were obtained for more than 98% of the surface of Venus during the 4 year duration of the Magellan mission. Early in the Magellan mission, volcanism was recognized as one of the major processes responsible for shaping the Venusian surface [*Saunders et al.*, 1992; *Head et al.*, 1992]. The lowlands in between the few high standing regions in the northern hemisphere of the planet have not received a great deal of focused attention to date, at least in part because the plains lacked the dramatic landforms and structures evident in other terrains on Venus. This report is an attempt to rectify the perception of a

“boring” quality that is at times associated with the Venusian lowland plains.

[3] Many topical studies of Venus geology have been undertaken in recent years through support of a planet-wide geologic mapping effort overseen by the U. S. Geological Survey [e.g., *Tanaka et al.*, 1994]. Geologic mapping of the Kawelu Planitia (V16) and Bellona Fossae (V15) quadrangles at 1:5,000,000 scale has been underway for several years [e.g., *Zimbelman*, 1994, 2002]. However, Venus map units have undergone significant revision as the Venus mappers have slowly developed consensus on a series of map units that appear to have global relevance [e.g., *Tanaka et al.*, 1997; *Basilevsky and Head*, 1998]. However, great caution must be exercised in extrapolating from regional to global map units based solely on remote sensing data [e.g., *Hansen*, 2000]. Mapping of V16 and V15 was undertaken because of the large number of volcanic flow fields, mapped here as lobate plains material, present within the Kawelu Planitia region of the northern lowland plains. Careful mapping of the superposition relations observed along flow boundaries has resulted in a more detailed picture of the relative stratigraphy of many of the flow fields in the vicinity of the Sekmet Mons volcano (44.5° N. lat., 240.5° long.), which in turn provide new insights into flow emplacement from volcanic centers on Venus and the potential contribution of volcanic units to the overall history of the lowlands.

[4] The manuscript is organized around the following topical sections: a brief description of the northern lowlands and the regional setting of the study area, stratigraphic results from mapping lobate plains components in the Sekmet Mons region, a study of the Strenia Fluctus lobate plains component within the study area, examination of an individual flow within the Strenia Fluctus field for comparison to the Carrizozo basalt flow in New Mexico, discussion of some implications for the results obtained here, and ending with the primary conclusions derived from this study. The progression is intentional, going from a regional perspective to attributes of individual flows for comparison to terrestrial analogs. Field results from terrestrial flows provide important clues to the lava emplacement that likely took place in the Venusian flow fields. The observations presented here should prove useful to future geophysical modeling of magma emplacement within the Venusian lowlands, a subject beyond the scope of the present study.

2. Background

[5] Radar systems provide our only information about the morphology and topography of the northern plains of Venus. Early Earth-based radar images showed the northern plains to be featureless areas surrounding isolated exposures of either enhanced roughness or dielectric properties [e.g., *Campbell et al.*, 1976; *Campbell and Burns*, 1980]. The Pioneer Venus Orbiter obtained the first global topographic data set for Venus, which showed that large portions of both the northern and southern hemispheres were lowland plains relative to scattered radar bright highlands areas [*Pettengill et al.*, 1979, 1980]. The Venera 15 and 16 spacecraft provided SAR images of Venus from 30° to 90° N latitude, with a spatial resolution of 1 to 2 km/pixel, which revealed a complex array of lineations and isolated volcanic centers throughout the northern lowland plains [*Barsukov et al.*, 1986; *Sukhanov et al.*, 1989]. The large antenna at Arecibo, Puerto Rico, attained increasing spatial resolution data of Venus as detector technology steadily improved [*Campbell et al.*, 1989], along with multipolarization information about the Venusian surface. The Magellan mission finally provided near-global coverage of SAR images with a spatial resolution of ~120 m/pixel, revealing the great complexity of both the lowland plains and the highland areas [*Saunders et al.*, 1992]. Early Magellan results for volcanic terrains concentrated on numerous volcanic centers discovered in the SAR images [e.g., *Head et al.*, 1992], along with huge fields of intermixed volcanic flows given the Latin descriptive name ‘Fluctus’ [e.g., *Roberts et al.*, 1992; *Crumpler et al.*, 1997]. Detailed study of the Magellan data set has led to the identification of more than 1700 volcanic and magmatic centers across Venus [*Crumpler and Aubele*, 2000]. Most research on Venus volcanism has focused on the various volcanic centers as opposed to the broad lowland plains between these centers.

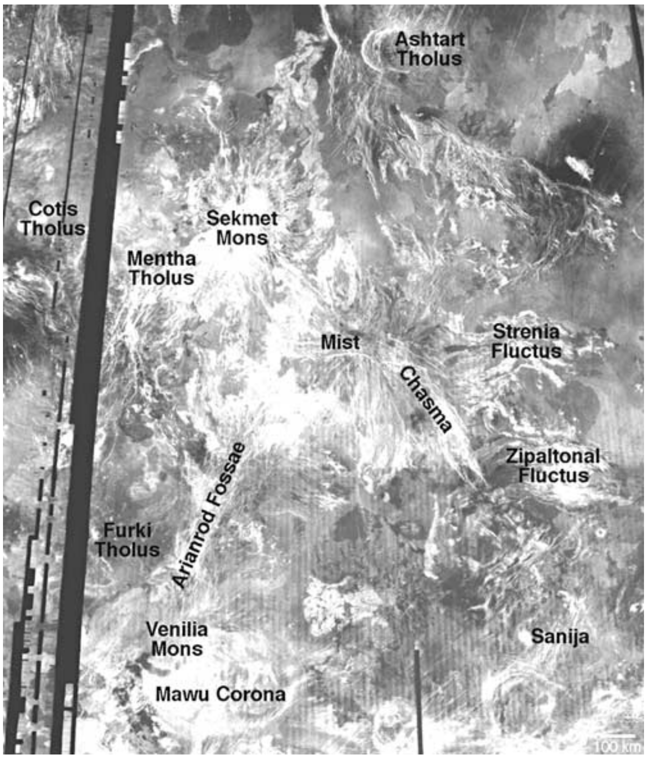

Figure 1. Magellan Synthetic Aperture Radar (SAR) image mosaic of volcanic flow fields in western Kawelu Planitia, Venus. The area shown corresponds to 30° to 50°N. lat., ~232° to ~256° long. The flow fields are superposed on surrounding lowland plains and older units (see Figure 2). North is to the top; 225 m/pixel; sinusoidal projection. Magellan compressed once C1-MIDRs 45N244 (top) and 30N243 (bottom).

[6] The general setting for the study region investigated here is in northern Kawelu Planitia, which is located west of the Beta and Asteria Regio highlands, and east of the Bellona Fossae elevated rift zone. The area mapped for this study corresponds to 30° to 50° N. latitude and approximately 230° to 260° longitude (Figures 1 and 2). Most of

Figure 2. Lobate plains materials (light gray) in western Kawelu Planitia near Sekmet Mons. Radar dark plains, typically at the distal end of lobate flow fields, are shown in dark gray. Both lobate plains and dark plains are superposed on the regional plains (white) and other older units (see Figure 3). Tesserae, the oldest stratigraphic units in this region, occur as isolated blocks (black). 1-km topographic contours (white lines) are shown for the Sekmet Mons volcanic construct, the largest relief feature in the mapped area. Contours indicate the 6052, 6053, and 6054 radius levels obtained from Magellan altimetry data, as published by *U.S. Geological Survey* [1998]. Coronae and other structural features are shown schematically. Fields of small shields (dotted pattern) are concentrated near the intersections of fracture zones; several shield fields are the source for lobate plains flow fields. Contacts are dashed where the precise location is unclear. Area covered by map corresponds to Magellan SAR mosaic in Figure 1. Table 1 lists lobate flow unit names and areas.

the study region is at or below the 6052 km radius elevation level, which is 1 km above the zero datum for elevation [*U.S. Geological Survey*, 1998]. The central volcano Sekmet Mons, discussed below, has the greatest vertical relief for any landform within the study area; Venilia Mons, another volcanic center, is the only other area with more than 1 km of relief. Various coronae (circular to ovoid structural features interpreted to be associated with mantle upwellings) [e.g., *Stofan et al.*, 1992], fossae (zones of concentrated tectonic extension), flucti (volcanic flow fields), chasma (large rift valleys), tholi (volcanic domes), and a few impact craters have been given provisional names in this area by the U.S. Geological Survey (selected feature names are shown in Figure 1). The lowland plains of Kawelu Planitia typically display less than a few hundred meters of relief in Magellan altimetry, and regional slopes on the plains are generally on the order of 0.1° over length scales greater than hundreds of km [*U.S. Geological Survey*, 1998]. The lowland plains typically display no distinctive attributes in remote sensing data sets such as dielectric constant, radar cross section (reflectivity), and roughness at radar wavelengths [*Campbell et al.*, 1997].

[7] Systematic geologic mapping of Venus was initiated under the Venus Data Analysis Program of NASA, and when that program ended, mapping was continued under the Planetary Geology and Geophysics Program of NASA. There was a considerable learning curve for all of the Venus mappers as they jointly struggled to determine specific attributes of material units that could be derived from the SAR images and the supporting remote sensing data. In particular, changes in Magellan SAR image brightness can be due not only to variations in surface texture on Venus, but also due to changes in the incidence and emission angles that vary regularly along the elliptical Magellan orbit [*Tanaka et al.*, 1994]. In spite of these challenges, the systematic mapping has revealed several terrain types that appear to occur throughout much of the Venusian surface [*Johnson et al.*, 1999; *Chapman*, 1999; *McGill*, 2000; *Bender et al.*, 2000; *Rosenberg and McGill*, 2001; *Ivanov and Head*, 2001]. There is considerable debate at present as to whether or not mapped material units can be related stratigraphically beyond a local region [e.g., *Basilevsky and Head*, 1995, 1998; *Hansen*, 2000], and great caution should be exercised in making correlations beyond reaches where mapped units are in physical contact with each other. The question of the continuity of a discrete map unit is particularly applicable to what many mappers refer to as the 'regional plains'; lowland plains lacking unique or distinctive characteristics observable in the SAR and remote sensing data.

[8] The current project was undertaken to assess the volcanic contribution to regional plains development, the presumed (but currently untestable) origin for much of the regional plains materials. The question of the volcanic resurfacing of large portions of Venus factors into models for planetary evolution and modification [e.g., *Phillips and Hansen*, 1998; *Solomon et al.*, 1999; *Phillips and Bullock*, 1999], as well as the inferred global resurfacing event that led to the current paucity of impact craters across the entire planet [*Phillips et al.*, 1992; *Schaber et al.*, 1992]. Any improvement in constraints that can be applied to the lowland plains should assist in the testing and refinement of various global models for Venus.

3. Sekmet Mons and Vicinity

[9] Sekmet Mons volcano (44.5° N. lat., 240.5° long.) is the largest topographic landform within the 3.9 million km^2 of the northern lowland plains encompassed by the study area (Figures 1 and 2). The Sekmet Mons construct (the summit of which is indicated by '+' in Figure 2) is an irregularly shaped region ~240 km in diameter (at the

Table 1. Lobate Plains in the Vicinity of Sekmet Mons[a]

Unit	Area, 10^4 km^2	Associated Feature Name (where available)
laf	13.0	Arianrod Fossae
lat	5.1	Ashtart Tholus
lft	14.5	Furki Tholus
lmc	21.0	Mist Chasma
lsf	11.1	Strenia Fluctus
lsm	42.5	Sekmet Mons
lvm	13.0	Venilia Mons
lzf	9.1	Zipaltonal Fluctus
l1	5.7	
l2	3.2	
l3	1.9	
l4	6.2	
l5	4.5	
l6	0.6	
l7	2.0	
l8	10.0	
l9	2.5	
l10	2.9	
l11	1.2	
Total	170.0	

[a] See (Figure 2).

6052 km radius level) with ~2 km of vertical relief, broad topographic ridges extending N40W and N40E from the summit, and with modest flank slopes ranging from ~1.0° to 1.3° and averaging 1.1° [*U.S. Geological Survey*, 1998]. The volume of a uniform right vertical cone of 120 km radius and 1.1° slope is 35,000 km^3, with a maximum relief of ~2.3 km. The topographic ridges associated with the highest part of the central construct are consistent with the orientation of fracture zones extending away from the volcano (Figure 2), which indicates structural control of the effusive vents. The summit of Sekmet Mons has a concentration of small domes that are interpreted to be individual volcanic vents [*Crumpler et al.*, 1997, Figure 9]. Lobate plains units (light gray in Figure 2), defined as planar regions with digitate landforms having lobate margins, merge with the construct-associated flows that radiate from the summit of Sekmet Mons. The lobate digitate forms around Sekmet Mons and on all other mapped lobate plains units are interpreted here to be lava flows which consist of both radar bright and radar dark components. Flow orientations (arrows in Figure 2) can be inferred from the digitate patterns within each of nineteen discrete lobate plains units (Table 1 and Figure 2). The flow orientations within the study area are generally consistent with the local gradient inferred from the regional topography [*U.S. Geological Survey*, 1998]. Separate lobate plains units are identified by named features within the unit where possible, and simply by number where no named feature is nearby (see Table 1).

[10] Lobate plains materials comprise 43.1% of the total map area (shown in light grey in Figure 2); they are all superposed on the slightly more abundant regional plains (white, 44.4% of map). The regional plains lack any significant distinguishing characteristic, a property that has been described globally [e.g., *Basilevsky and Head*, 1998] but which is difficult to demonstrate to be a single material unit of global extent [e.g., *Hansen*, 2000]. The only unit stratigraphically younger than both the lobate plains and the regional plains is associated with a few impact craters (c, 0.2% of map). An intriguing unit superposed on the regional plains but consistently superposed by the nearest lobate plains materials are radar dark plains (dark gray, 4.0% of map). These dark plains always occur at the distal margins of lobate plains, which raises the possibility that the dark plains may be an early effusive phase, perhaps more fluid and far reaching than the subsequent lobate flows, and thus dark plains materials could potentially underlie much of the lobate plains areas.

[11] Lobate plains units appear to emanate from a variety of local sources. Sekmet Mons is the apparent source for the largest single area of associated flows (lsm in Table 1); other mapped lobate plains units are associated with Venilia Mons (a volcanic construct with a large summit caldera), the intersection of major fracture zones (e.g., unit lmc associated with Mist Chasma), individual coronae (e.g., unit l4), and concentrations of numerous small volcanic edifices (e.g., the "shield fields" of *Aubele and Slyuta* [1990] and *Aubele et al.* [1992]; unit laf associated with Arianrod Fossae). This diversity of apparent sources may reflect variations in eruptive style, but it is perhaps more probable that they represent different stages within a continuum of features related to effusive eruptions on Venus. For example, shield fields or rifting associated with fracture zones often may accompany the initiation of eruptive activity, but only rarely does the activity continue at one location long enough to build a construct such as Sekmet Mons. A similarity of eruptive processes for the individual lobate plains units is consistent with analysis of radar backscatter values from both radar bright and radar dark flows within different lobate plains units in this area [J.R. Zimbelman, V16 map in review with the U.S. Geological Survey]. Radar backscatter values for any lobate plains unit in the Sekmet Mons area are consistently well below the values associated with clinker-covered a′a flows on Earth, but are quite consistent with the values obtained from glassy pahoehoe flows [*Campbell and Campbell*, 1992]. Several coronae surround the lobate plains complex but these structures are rarely the source of identifiable lobate flows at this locality, consistent with an earlier assessment that concluded the coronae in the Kawelu Planitia region were relatively old structures [*Chapman and Zimbelman*, 1998].

[12] Careful mapping of lobate plains materials and the superposition or truncation relations at flow field margins has revealed a relative stratigraphy between various units (Figure 3a). The relative stratigraphy for the lobate plains units includes the important assumption that the margins of each flow field are representative of the dominant effusive activity from that volcanic center, something that at present can not be tested independently with available data. Stated another way, the relative stratigraphy between lobate plains units assumes that the distal portions of each flow field are accurate proxies for the dominant effusion from each center. It is quite probable that most lobate flow fields consist of flows emplaced over a range of ages, the uncertainty of which is represented graphically by the diagonal contact lines in the flow field boxes (Figure 3a). Most lobate plains superposition relations are clearly visible in optimally stretched Magellan SAR images; cases where the relative relationship is suggestive but not conclusive are indicated by dashed contacts in the map (Figure 2) and dashed lines in the stratigraphic chart (Figure 3a).

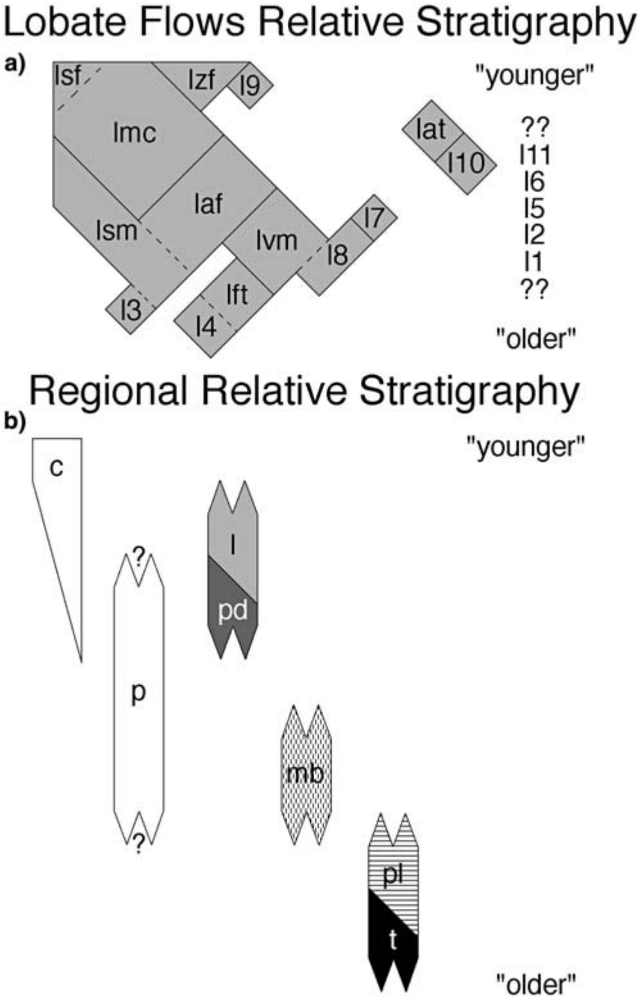

Figure 3. Relative stratigraphy of units in the vicinity of Sekmet Mons, as mapped in Figure 2. (a) Lobate flow relative stratigraphy is indicated schematically; vertical location indicates relative stratigraphic position at flow field contacts, but the uncertainty of individual flow field ages is illustrated by the diagonal contacts. Solid lines indicate a clear stratigraphic relationship exists; dashed lines indicate less certain contact relationships. Lobate plains not in contact with lobate flow units in the Sekmet Mons area lack relative stratigraphic control and are shown at right, in a vertical position consistent with the nearest lobate flow unit for which there is stratigraphic control. See Table 1 for lobate flow unit designations. (b) Relative stratigraphy of units in the Sekmet Mons region. Units: c, crater material; l, lobate plains material; pd, dark plains material; p, plains material; mb, mountain belt material; pl, lineated plains material; t, tessera material. The precise stratigraphic bounds of the regional plains (p) are not constrained by the available data.

[13] Discrete lobate plains units in the vicinity of Sekmet Mons are sufficiently numerous and in contact with enough of their neighbors to reveal possible relative time horizons within the effusive emplacement across the region (Figure 3a). The inferred time horizons (e.g., units laf and l7 are younger than units lsm, lvm, and l8 that together may represent a time equivalent eruption series) indicate a trend of effusive activity that moved generally from west to east (and less consistently from south to north) across the region. This general trend is graphically illustrated by the progression of lobate plains stratigraphy from upper left to lower right (Figure 3a). Seven surrounding lobate plains units are not in contact with the central twelve units. The isolated lobate plains units are shown at positions consistent with the relative stratigraphy of the lobate plains units nearest to them (right side, Figure 3a), but there is no constraint on where each of these surrounding units actually falls within the relative stratigraphy of the Sekmet Mons complex.

[14] The cumulative area covered by the twelve lobate plains units in contact with each other is 1.5 million km^2, equivalent to an area about one tenth that of South America. The effusive activity recorded by the Sekmet Mons complex of units thus approaches continental scale, independent of the thickness of the various flows. If the possible correlation horizons within the flow field complex (Figure 3a) are time equivalent (something that can not be demonstrated, but which is at least a reasonable hypothesis), then the areas of various lobate plains units should provide a clue to the eruptive output. The size of the individual boxes in Figure 3a is roughly proportional to the mapped areal coverage of each unit (Figure 2 and Table 1). If areal coverage of units can be treated as a proxy for the magnitude of effusive activity, then the enormous area affected by the flows may have resulted from a Gaussian-like distribution of effusion; limited eruptions mostly in the west and south, followed by extensive effusion in the central region, with limited final eruptions mostly in the east and north. This possible association of eruptions in time and space would suggest that the mantle sources for the magma might have migrated with time, or that the crust of Venus may have shifted with respect to more deep-seated mantle sources. Either possibility could influence concepts of mantle motion within Venus.

[15] Several outcrops of materials older than the regional plains occur as isolated topographic highs surrounded by either lobate plains or regional plains (Figures 2 and 3b). Mountain belt material (vertical dashed lines, 2.4% of map) is present only near the northern edge of the study area, and much more extensive outcrops of these deformed mountainous regions are present in the Pandrosa Dorsa quadrangle to the north [*Rosenberg and McGill*, 2001]. Lineated plains (horizontal lines, 3.5% of map) consist of plains with a dense pattern of lineations, usually with one principal orientation. The lineated plains are often, but not always, in close association with tesserae (black, 2.4% of map), which display two or more lineation trends. Both the lineated plains and the tesserae outcrops are consistently embayed by both the regional plains and lobate plains units, but there is at present no conclusive way to prove that widely separated patches of either of these units are of an equivalent age. The jagged lines on the top and bottom of most boxes in Figure 3b are intended to illustrate this general uncertainty, the greatest of which is for the regional plains (where "?" have been added to the jagged lines in Figure 3b). While the time uniformity of the regional plains can not be demonstrated or reasonably assumed, it would also be misleading to suggest that the lineated plains and the tesserae are younger than either the dark plains or the lobate

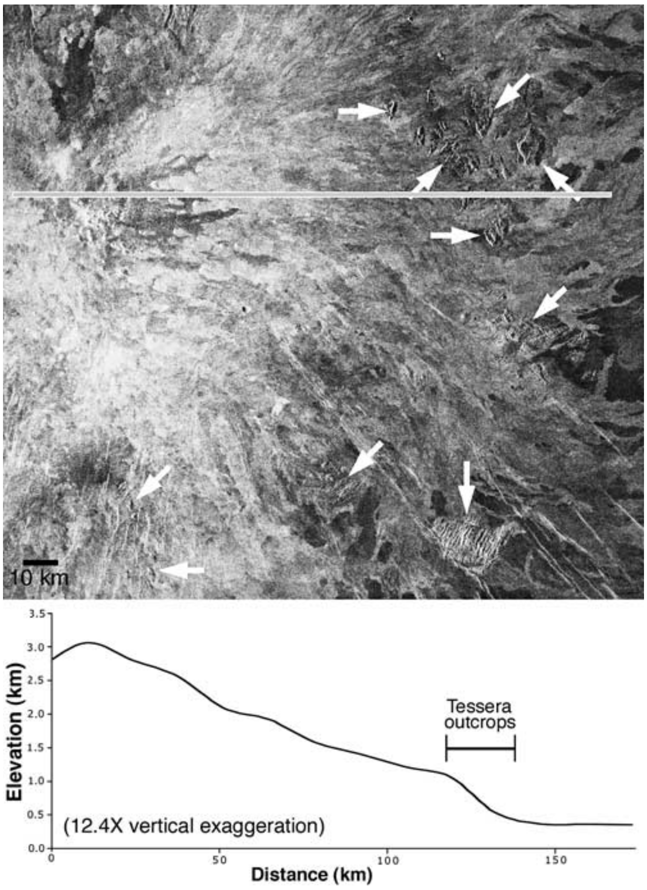

Figure 4. Lobate flows in the immediate vicinity of Sekmet Mons, indicating flow radial to the summit area, which contains numerous small domes. Small knobs and isolated patches of tesserae materials (arrows), exposed in a band concentric to Sekmet Mons, are surrounded by the radially oriented flows. North is to the top. Gray line indicates the location of the topographic profile shown at the bottom, derived from Magellan GTDR altimetry data. Image is a portion of Magellan SAR full resolution F-MAP 42N246, centered on 44.2°N. lat., 241.1° long.

plains that are consistently superposed on these units throughout the study area.

[16] There are several small (generally <10 km long) outcrops of tessera terrain embayed by, but not completely buried beneath, lava flows from Sekmet Mons. There is a large area of tesserae inliers west of the summit of Sekmet Mons (Figure 2), as well as some isolated tessera remnants east and south of the volcanic construct (Figure 4). Only the larger blocks show two prominent lineation orientations, but associations of small inliers show elongations that indicate two or more trend orientations (i.e., upper right of Figure 4), so that a tessera interpretation is preferred over that of lineated plains for these remnant knobs. The remnant features are not observed within 90 km of the summit of Sekmet Mons, are best expressed at distances of 110 to 140 km from the summit, and occur >150 km from the summit in a large area northwest of the volcano summit at the end of a topographic ridge aligned with the trend of the Mist Chasma fractures to the southeast (Figure 2). The tessera outcrop pattern south and east of the Sekmet Mons summit (Figure 4) is roughly concentric to the volcanic construct, and the outcrops occur close to the break in slope between the construct and the adjacent flow apron. This pattern may be consistent with predictions for a flexural arch around a volcanic load on a relatively thin lithosphere, but it is even closer to the predictions from an uplift model where buoyant crustal underplating or intralithospheric intrusion tends to counteract subsidence induced by edifice-building extrusive flows [*McGovern and Solomon*, 1997, 1998]. Evidence consistent with the uplift model (with subsurface loading, low deflections and no major arch) is supportive of a relatively thin lithosphere at this location (P. McGovern, personal communication). These observations suggest that Sekmet Mons should be a target for more detailed geophysical modeling in the future.

4. Strenia Fluctus

[17] The Strenia Fluctus lobate plains material (unit lsf) was mapped in greater detail in order to assess the potential for additional stratigraphic information within individual flow fields as was obtained from the regional mapping of adjacent flow fields. Strenia Fluctus was chosen because it is one of latest effusion events in the region (see Figure 3a), it was included within a previous investigation of long planetary lava flows [*Zimbelman*, 1998], and because the field displayed numerous radar bright and radar dark flow components throughout the entire field (Figure 5). As was mentioned earlier, the radar backscatter cross section from both radar bright and radar dark components within the flow field suggest a pahoehoe texture everywhere; no flow component, not even the brightest ones, has a surface texture that is as rough as typical a′a flows on Earth [*Campbell and Campbell*, 1992]. Flow components were identified in optimally stretched SAR data and separated into individual flows on the basis of superposition relationships with adjacent flow components and continuity of SAR textural detail along the various components.

[18] Thirteen individual flow components were identified within the Strenia Fluctus lobate plains (Table 2 and Figure 6). Note that the detailed map does not encompass all of the Strenia Fluctus unit shown in Figure 2, so that the total area of the flow components given in Table 2 is less than the total area listed in Table 1. It is difficult to trace individual flow components close to the shield field that is the source of the Strenia Fluctus effusion, so the area mapped in Figure 6 covers all terrain where relative stratigraphic information could be determined. As with many of the lobate plains units around Sekmet Mons, radar dark plains (unit pd in Figure 2) are present at the distal edge of several flow components, and it is reasonable to infer that these materials are probably found beneath most of the flows that comprise the field. Some individual flow components within the composite field are nearly as radar dark as the distal dark plains; these four components (numbers 2, 8, 11, and 13 in Figure 6) are shown with a gray fill darker than that used for the majority of the flow components but lighter than the distal dark plains. Where three of the dark lobate plains components (numbers 2, 8, and 13) are in contact with the distal

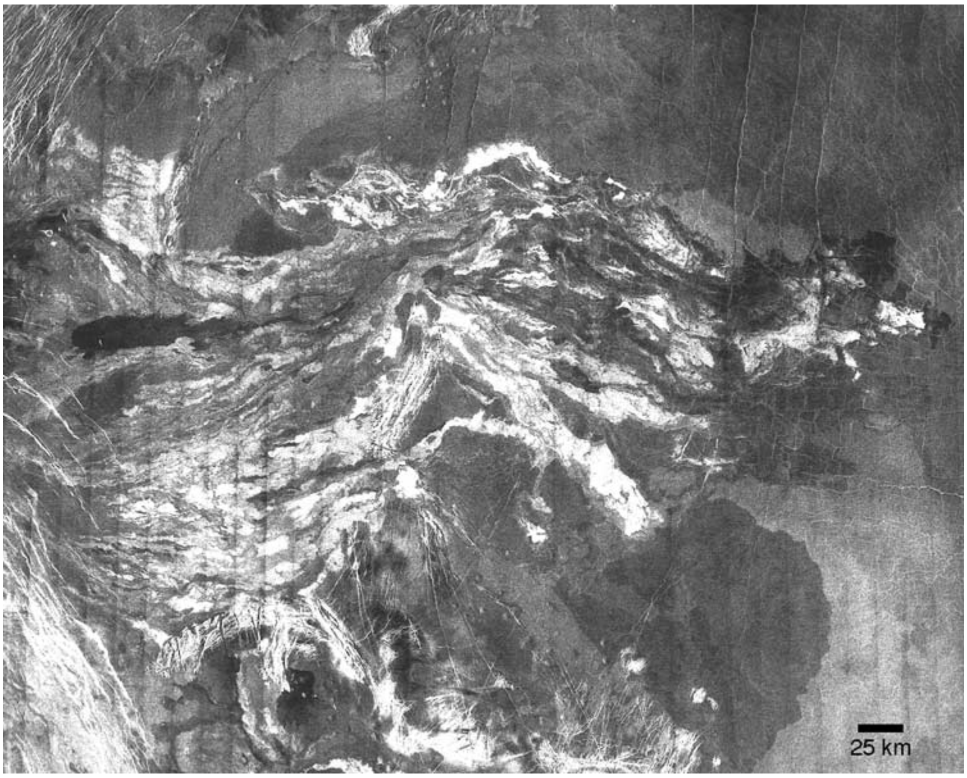

Figure 5. Strenia Fluctus lobate plains. Various flow components have differing radar reflectance properties, but all radar cross sections are consistent with pahoehoe flows on Earth and less than values typical of terrestrial a′a flows [*Campbell and Campbell*, 1992]. Flows extend east down a very gentle slope from numerous small shields near the Mist Chasma fracture zone, off the left side of the image (see Figure 2). Geologic interpretation of this area is shown in Figure 6. North is to the top. Portion of Magellan SAR full resolution F1-MIDR 40N25, 38.5° to 42.5°N. lat., 247.6° to 254.0° long.

dark plains, the latter consistently have a lower backscatter than the individual flow components. This result is consistent with the interpretation derived from the regional mapping that the distal dark plains could represent a very fluid early phase of the effusion. However, it now appears that comparable very smooth-textured flows occur throughout the course of the flow field development, and not only during an early phase. The lobate plains components are superposed on all other units in the immediate area, as discussed at the end of this section.

[19] The relative stratigraphy of the thirteen Strenia Fluctus flow components (Figure 7) does not show the same kind of spatial trend that is observed between the discrete flow fields (Figure 3a). As with the regional mapping, the relative stratigraphy is indicated by boxes with numerous diagonal lines to represent the uncertainty inherent in the assumption that the margin of a flow component accurately reflects the majority of the flow emplacement. The assumption is less restrictive here than it was for contacts between flow fields because there is greater confidence that an individual flow feature is being tracked. However, in the next section it will be shown that the flow components mapped here are likely compound flows themselves, so there remains uncertainty as to how long (within the duration of the entire flow field effusion) a particular flow was active, and whether or not there were reactivation pulses that might make use of transport systems from an earlier eruption from the same vent area. The relative stratigraphy for the entire Strenia Fluctus field appears to be analogous to the distributive nature of a prolonged eruption from a fairly restricted vent location, resulting in a complex interfingering of various flows, as was documented during the Mauna Ulu [*Swanson et al.*, 1979] and Puu Oo [*Wolfe et al.*, 1988] eruptions on Kilauea volcano in Hawaii. There is no evidence either in the complex flow unit patterns (Figure 6) or in the

Table 2. Strenia Fluctus Lobate Plains Components[a]

Unit	Area, 10^3 km^2
1	4.8
2	9.5
3	8.9
4	1.9
5	9.7
6	6.2
7	5.0
8	8.5
9	10.5
10	3.4
11	1.5
12	19.5
13	6.6
Total	96.0

[a]See (Figure 6).

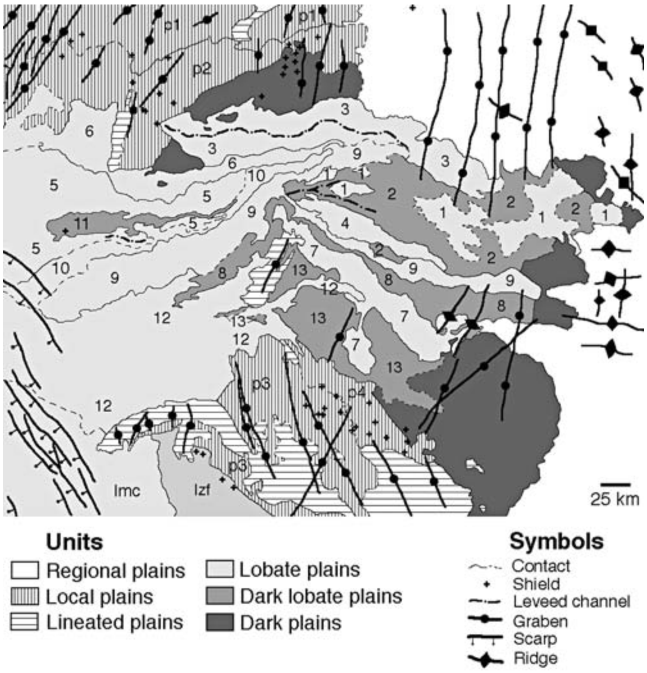

Figure 6. Lobate plains components in Strenia Fluctus, numbered according to mappable subunits. Light and medium gray tones illustrate the approximate relative radar brightness of the lobate components; see Table 2 for unit areas. Radar dark plains occur at the distal end of some lobate plains components, both of which are superposed on regional plains (white). Isolated outcrops of stratigraphically older lineated plains form local obstructions to flow paths. Portions of the regional plains can be locally subdivided into four plains units older than the regional plains (labeled as units p1 to p4); see text for a discussion of these units. Contacts are dashed where the precise location is unclear. Relative stratigraphy of lobate plains units is shown in Figure 7. Area covered by map corresponds to Magellan SAR image mosaic in Figure 5.

preserved contact relationships (Figure 7) to indicate any systematic variation in the apparent sources for the flow components, which are inferred to be a field of dozens of small (<6 km diameter) shield volcanoes near Mist Chasma, west of the area shown in Figure 6.

[20] There are two notable exceptions in Strenia Fluctus to the general rule that individual flow components can not be traced to their source vent. Flow component 3, on the northern margin of the flow field, can be traced to a single 4-km-wide dome. The flow can be traced for nearly 200 km along a regional slope that Magellan altimetry indicates is only $\sim 0.03°$ [*Helgerud and Zimbelman*, 1993]. The unit 3 flow has complex textural variations along its length and a medial channel is visible on the proximal 120 km of the flow. There are clear superposition relationships between the unit 3 flow and both the underlying surrounding plains and with flow units 6 and 9 that truncate features on the unit 3 flow. Flow unit 11 also may have emanated from a single partially destroyed cone ('+' on west side of flow 11 in Figure 6), that produced a 150-km-long flow that narrows distally, confined between the margins of earlier flows, with a planform very similar to 130-km-long Undara basalt flow in Australia [*Zimbelman and Stephenson*, 1998]. These examples illustrate that a single vent can generate a remarkably long flow, even though the individual vents for most of the Strenia Fluctus flows are not identifiable.

[21] The Strenia Fluctus flow components are superposed on all other map units, with the exception of small portions of lobate plains units lmc and lzf (lower left of Figure 6). Structural activity was evident throughout most of the time period covered by the unit stratigraphy. For example, portions of flow component 2 traveled north within some of the graben on the regional plains, but tensional stresses were present after emplacement of the most distal flow components where other graben cut both the flows and the regional plains. Four local plains units (p1 to p4) are identified, with good contacts showing that p2 is superposed on p1, and p4 is superposed on p3. These local plains units include several individual shields, such as the source for flow component 3, but they do not have the areal density of shields described for the shield plains unit identified by *Aubele et al.* [1992]. The regional plains embay local plains units p1 and p2, so these two units may have been among the earliest effusion events in the region. Nearby exposures of lineated plains represent the lowest stratigraphic unit in the Strenia Fluctus area.

5. Individual Flow Components

[22] Some of the individual flow components that comprise Strenia Fluctus display subtle features within each component. For example, when the SAR brightness is optimally stretched to enhance the variations within flow component 7, the lineations can be mapped out to show their relationship to the overall flow (left side of Figure 8). Many of these subtle lineations appear to represent separate components of the overall flow, with an inferred direction of flow that is consistent with the trend of the entire component 7 flow. These features are interpreted to represent

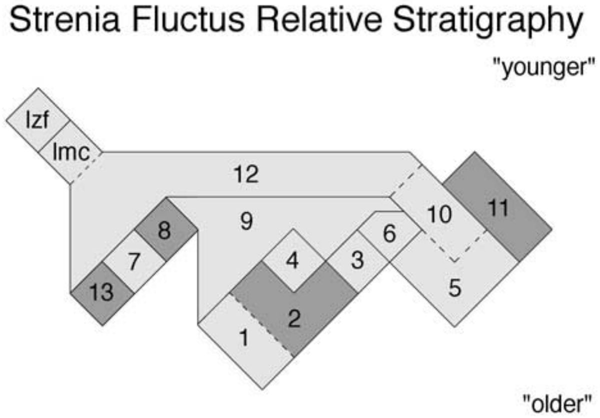

Figure 7. Relative stratigraphy of Strenia Fluctus lobate plains units (see Figure 6). Stratigraphy is based on superposition relations observed at unit margins, but the diagonal boxes illustrate the uncertainty for the actual age span encompassed by materials comprising each mapped unit. Boxes are in contact with all other flow components identified during the geologic mapping. See Table 2 for unit areas.

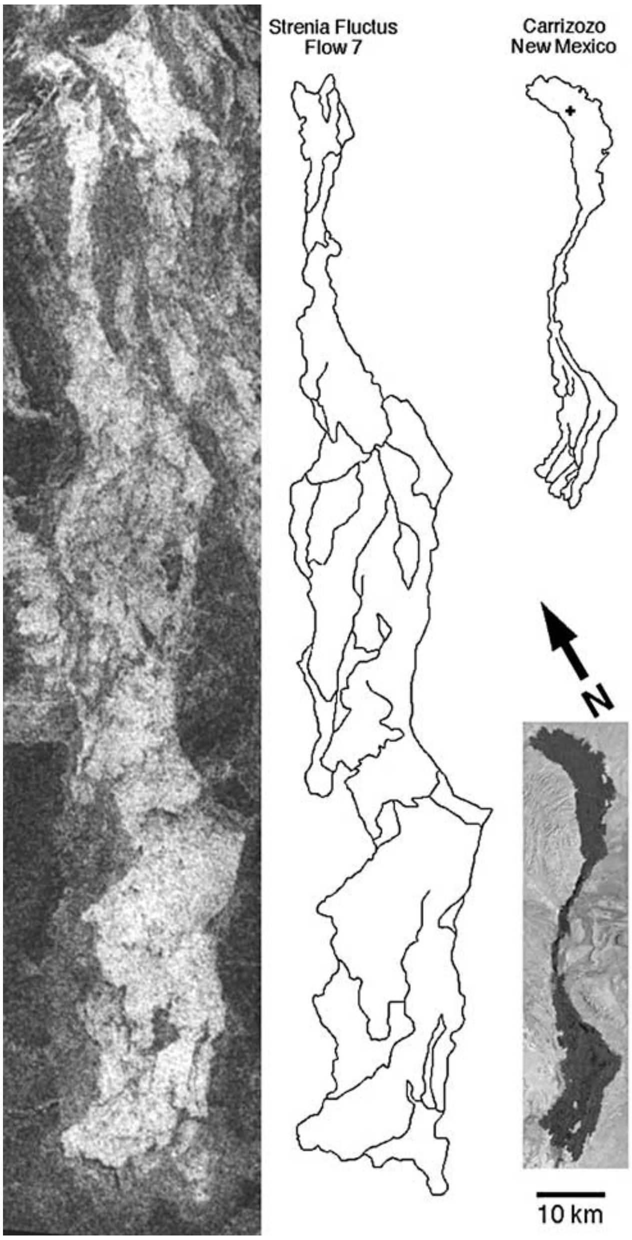

Figure 8. Comparison of a Strenia Fluctus flow unit, left, (the central portion of component 7 in Figure 7) and the Carrizozo basalt flow in New Mexico, right, shown at the same scale. The Magellan SAR image, from F1-MIDR 40N251, has been optimally stretched to highlight subtle radar brightness variations along the central portion of component 7, and rotated to show both flows side by side. The sketch to the right of the SAR image shows many overlapping flow components within the interior of the flow. The Carrizozo image (bottom right) is from a Landsat Thematic Mapper band 4 scene. Above the Carrizozo image is a sketch of multiple flow lobes in the distal portion of the flow, based on features interpreted to correspond to the margins of inflated flow components (see text). Cross shows location of Little Black Peak, inferred to be the source for the Carrizozo flow.

Figure 9. Typical tumulus within the Carrizozo flow on the north side of U.S. Highway 380, located ~10 km down flow from Little Black Peak. The tumulus surface consists of plates of pahoehoe basalt that fractured as the flow deflated as effusion ceased at the vent [*Keszthelyi and Pieri*, 1993; *Zimbelman and Johnston*, 2001]. A Differential Global Positioning System traverse was obtained across this tumulus and several adjacent tumuli (see Figure 10). Survey rod is 1.85 m tall. JRZ photo, 11/12/99.

separate flow lobes within the component 7 flow, making this a ‘compound’ flow as defined by *Walker* [1972]. It is not coincidental that the length/width ratios of most of the flow lobes within component 7 are generally consistent with the ~10:1 aspect ratio of the entire component; flow component 7 consists of a series of intermixed flow lobes emplaced either adjacent to or on top of each other. The radar reflectivity for all parts of flow component 7 is well below the value typical of a′a flows on Earth [*Campbell and Campbell*, 1992], so that all of these flow lobes are likely pahoehoe in surface texture. Component 7 is not unique with regard to multiple flow lobes; many of the other components of Strenia Fluctus show comparable relationships under extreme enhancement, and other flow fields throughout the Sekmet Mons region also show similar subtle internal features.

[23] A compound pahoehoe flow origin for most of the flow components within Venusian flow fields lends itself to comparison with a well-preserved compound pahoehoe basalt flow in central New Mexico, near the town of Carrizozo (right side of Figure 8). The Carrizozo flow is the longest subaerial lava flow within the continental United States, and it has received previous attention as an analog to planetary flows [*Keszthelyi and Pieri*, 1993]. The individual flow lobes which comprise the Carrizozo flow are not readily apparent in Landsat data, but recent field investigations have identified several lobes in the distal portion of the flow field (Figure 8) [*Zimbelman and Johnston*, 2001]. The Carrizozo flow is almost entirely pahoehoe in its surface texture, including the distal flow margins, with numerous tumuli (Figure 9) oriented parallel to the flow direction that are indicative of substantial inflation during flow emplacement [*Keszthelyi and Pieri*, 1993; *Zimbelman and Johnston*, 2000, 2001]. The tumuli on Carrizozo are similar to some of the lava rise features identified on inflated long basalt flows in eastern Australia [*Whitehead and Stephenson*, 1998]. *Keszthelyi and Pieri* [1993] made several attempts to

estimate the effusion rate for Carrizozo from various published models but with inconsistent results; they finally assumed an effusion rate typical of current eruptions at Kilauea (~5 m^3/s), leading to a possible emplacement duration of several decades. Detailed topography derived from Differential Global Positioning System (DGPS) measurements at Carrizozo reveal elevations of the highest points that are generally within 2 m of a common elevation level (~1603 m) across the eastern 2 km of the flow (Figure 10). These observations are interpreted to indicate inflation of the flow within discrete lobes that can be identified today by their elevation properties [*Zimbelman and Johnston*, 2001]. Unfortunately, comparable topographic data are not available for the flows on Venus, but Carrizozo can still provide clues to the probable emplacement of compound pahoehoe flow fields.

[24] The planform of the Carrizozo flow is distinct in the narrow reach that comprises the central one third of the flow (Figure 8). While this portion of the flow does lie within a broad valley that was the course of an earlier river or stream, the narrow 'neck' does not appear to be the result of topographic confinement of the lateral width of the flow field. The most distinctive element of the narrow neck region is a single large tumulus along the central axis of the flow, interpreted to be the surface expression of a lava tube [*Keszthelyi and Pieri*, 1993]. DGPS data in the narrow neck region provide evidence in support of a collapsed lava tube coincident with the medial tumulus [*Zimbelman and Johnston*, 2001]. The dimensions of the inferred tube, along with the gentle regional slope, constrain the likely upper limit of flow through the narrow neck to be ~800 m^3/s, which would allow the emplacement of the entire flow field in a period of a few months [*Zimbelman and Johnston*, 2002]. Even without evidence for medial lava tubes for the flow lobes on Venus, Carrizozo provides useful insights into how a single lobate planform can be generated in a compound flow field emplaced under minimal shear conditions, preserving pahoehoe surface texture at great distances from the source vent.

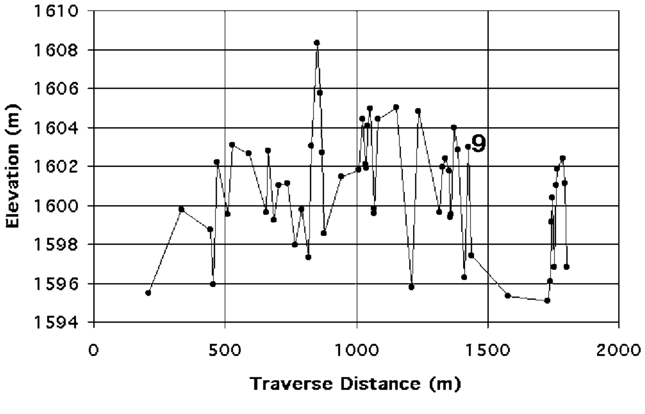

Figure 10. Segment of a Differential Global Positioning System (DGPS) traverse across northeastern portion of the Carrizozo lava flow. Data are from a traverse that followed the northern side of U.S. Highway 380 across the eastern portion of the flow. The Trimble 4800 DGPS system provided data with ~2 cm horizontal and ~4 cm vertical precision [*Zimbelman and Johnston*, 2001]. Tumulus in Figure 9 is the topographic peak labeled 9.

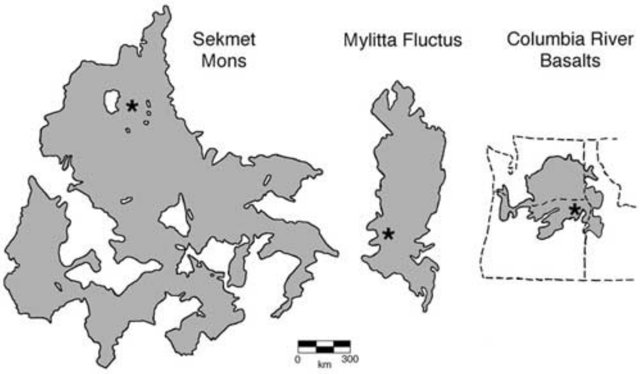

Figure 11. Comparison of area covered by three volcanic flow fields, shown at the same scale. Sekmet Mons (asterisk) and associated flow fields (left). The area shown, ~1.5 million km^2, does not include the radar dark plains shown in Figure 2. Mylitta Fluctus (center) is one of the largest individual flow fields on Venus [*Roberts et al.*, 1992]. Asterisk indicates the inferred source area for most of the flows in this field. Columbia River basalts (right) are shown in relation to state boundaries for Washington, Oregon, and Idaho, in the continental United States. CRB flows originated from dikes in eastern Oregon, near the Idaho border (asterisk).

6. Discussion

[25] The observations of lobate flows in the Sekmet Mons region lead to a hypothesis that flow field emplacement on Venus was more the result of moderate effusion than of enormous lava floods. Effusion rates <1000 m^3/s are far greater than a typical Kilauea eruption rate (~5 m^3/s) [*Rowland and Walker*, 1990] but comparable to the 1984 Mauna Loa eruption rate [*Lipman and Banks*, 1987], and still much less than that proposed for the Mylitta Fluctus flow field on Venus (>10^6 m^3/s) [*Roberts et al.*, 1992]. A similar difference of opinion exists for the proposed emplacement of the Columbia River Basalt (CRB) flows on Earth, where slow emplacement of inflated pahoehoe flow fields [e.g., *Self et al.*, 1996] is contrasted with the rapid emplacement of a turbulent flood of lava [*Shaw and Swanson*, 1970; *Reidel*, 1998]. The area covered by the Sekmet Mons flow fields is greater than that of either the Mylitta Fluctus flows on Venus or the CRB flows on Earth (Figure 11), although the Sekmet Mons flows clearly emanate from widely separated vents whereas the other two fields originate from vents within a more restricted region. The large length/width aspect ratio (>10) for Venusian flows on shallow (~0.05°) regional slopes is a useful constraint on the effusion conditions, even if each component is itself comprised of numerous flow lobes. *Miyamoto and Sasaki* [1998] carried out a series of computer simulations under a variety of assumed cooling properties and conditions, concluding that the width of the final flow was a sensitive indicator of the magnitude of the effusion. The relatively long and narrow flow components on Venus might prove to be helpful in the debate over the emplace-

ment of large igneous provinces on Earth, where pristine flow morphology is usually very difficult to observe.

[26] Information derived from study of the Carrizozo flow can be used to obtain estimates of the duration of effusive activity in the Sekmet Mons region. It is not possible to constrain the thickness of flows on Venus with the Magellan SAR data, except in cases of unusually thick flows [e.g., *Moore et al.*, 1992], but the similar gravitational accelerations on Venus and Earth make it a reasonable assumption to use flow thicknesses on Earth as an indicator of probable flow thickness on Venus. The inflated distal portion of the Carrizozo flow, 75 km from the vent, is 11 to 13 m thick [*Zimbelman and Johnston*, 2001]. Assuming a uniform 15 m thickness for the flows on Venus, the total area of the Sekmet Mons flows in contact with each other (1.5 million km^2) leads to a total volume of 23 million m^3 (this number does not allow for possible burial of flows by later effusion, and thus is at best a lower limit). There is no information on whether dispersed flow fields on Venus were active at the same time, but if we assume eruption was continuous with only a single vent area active at any one time, the total flow volume provides a lower limit to the effusion duration. Assuming constant effusion rates of 50 [e.g., *Keszthelyi*, 1995] to 500 (comparable to the rate inferred for the tube section of the Carrizozo flow [*Zimbelman and Johnston*, 2002]) m^3/s, the Sekmet Mons flow fields would have been emplaced in 450 to 45 billion seconds (14,000 to 1400 Earth years), respectively. Any hiatus between eruptions would obviously extend this period, but it can still be considered as a lower limit consistent with the other assumptions involved.

[27] The Sekmet Mons flows represent ~1% of the area of the northern lowlands on Venus, taken to be locations below the 6052 km radius, which covers roughly two thirds of the entire northern hemisphere [*U.S. Geological Survey*, 1997]. Using the same assumptions outlined above (again including continuous eruption but with only one vent area active at any one time), all of the northern lowlands could have been resurfaced by 15-m-thick flows in 1.4 million to 140 thousand Earth years at 50 to 500 m^3/s effusion rates, respectively. The northern plains resurfacing estimate ignores the volume of individual constructs, but even allowing for an increase of a factor of five in total volume (and therefore duration), a lower limit of ~5 million Earth years is still fairly short on a geologic timescale. Effusion at modest rates, consistent with the pervasive presence of a pahoehoe-like surface texture on the Venusian plains [*Campbell and Campbell*, 1992], is capable of accomplishing nearly global resurfacing without the need to resort to enormous flood-like effusion rates.

[28] The well preserved nature of the Venusian flow fields is related to the young age inferred for the exposed surface of Venus (generally <500 million years), derived from the global paucity of impact craters as compared to the other terrestrial planets [e.g., *Phillips et al.*, 1992; *Schaber et al.*, 1992]. The cratering record on Venus has been used to infer a global resurfacing event fairly late in the history of the planet, which has also been related to models of the interior of Venus [e.g., *Phillips and Hansen*, 1998] and the relationship of the surface and interior to atmospheric conditions [e.g., *Solomon et al.*, 1999]. The stratigraphic information recorded between the various components of the Sekmet Mons flow fields, along with the distributed nature of the source regions for the various fields, can be interpreted to indicate that a series of discrete mantle plumes caused the effusive activity, generally progressing from the southwest to the northeast across the region. If similar trends can be documented elsewhere on Venus, a global pattern of plume activity eventually may become available as a constraint for future geophysical models.

7. Conclusions

[29] Geologic mapping has identified several distinct and discrete components of lobate plains near Sekmet Mons volcano. Contact relations at the distal margins of the lobate plains components indicates that effusion generally progressed from southwest to northeast in the Sekmet Mons area. Components of the Strenia Fluctus flow field have a complex superposition pattern, indicating multiple source vents within a shield field near to Mist Chasma. Individual flows within Strenia Fluctus consist of multiple lobes, much like components in the compound inflated basalt flow near Carrizozo, New Mexico, where field relationships support a relatively low inferred effusion rate. Assuming 50 to 500 m^3/s effusion (consistent with the Carrizozo results), 15 m flow thickness, and continuous eruption from only one vent at a time, the Sekmet Mons flow fields would have required ~14,000 to 1,400 Earth years for emplacement. At the same range of effusion rates and with the same assumptions, ~1.4 million to 140 thousand Earth years would allow for the resurfacing of all of the northern lowland plains, a period that is relatively short on geologic timescales. This is consistent with the concept of a rapid global resurfacing event that could have reset the cratering age ~500 million years ago.

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