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Emplacement of long lava flows on planetary surfaces

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Abstract. Three long lava flows on Mars, Venus, and the Moon were examined in order to evaluate their possible emplacement rate and condition. On the Moon, flows of the last (phase III) effusion within the Imbrium impact basin were examined using Apollo photography. The longest phase III flow can be followed for 250 km, terminating ~400 km from the probable source vent. This flow has a width of 10 to 25 km, thickness of 10 to 30 m, and a medial channel preserved in its proximal reach, and it was emplaced on a regional slope of ~0.3°. In the Tharsis region of Mars, a well-defined set of lava flows extends north from the topographic saddle between Ascraeus and Pavonis Montes. Viking Orbiter images show one flow that can be traced for 480 km, with a width ranging from 5 to 50 km, thickness of 30 to 100 m, and a prominent medial channel in its proximal reach, and was emplaced on a regional slope of ~0.5° to ~0.1°. The Sirenia Fluctus area on Venus consists of an array of intermixed radar-bright and radar-dark lobate flows, one of which can be traced for 180 km, with a width of 5 to 20 km, and an unknown thickness (but inferred to be ~30 m), and was emplaced on the lowland plains where the regional slope is only ~0.03°. When viewed at the full Magellan resolution, this flow contains several flow margins, indicating its compound nature. Effusion rates were calculated for the simple lunar and Martian flows using published empirical and theoretical relationships, resulting in a broad range of 500 to 10^8 (Moon) and 600 to 2×10^8 (Mars) m^3/s, with most likely values of $\sim 5 \times 10^4$ to $\sim 10^5$ for both flows. The compound Venus flow would have required 494 years for emplacement at the typical Kilauea rate of ~5 m^3/s, but the thermal balance of planetary tube systems could also be consistent with a rate at least an order of magnitude larger. The distinction between simple and compound flows is important to any evaluation of flow emplacement based solely on remote sensing data.

1. Introduction

Volcanic flows of great length have been observed on several planetary surfaces [e.g., *Lopes-Gautier*, 1993]. Long lava flows on three planetary surfaces are examined here to provide constraints on the emplacement conditions experienced by these lavas. The observable flow dimensions, the topography over which the lava flowed, and the environmental conditions are compared for long lava flows on the Moon, Mars, and Venus. The results should provide a basis for comparison with long lava flows on Earth and other planetary surfaces.

The three lava flow localities chosen for this study represent distinct settings in which long lava flows have been documented with spacecraft images and photographs. Each long flow has traceable flow margins in excess of 180 km in total length, and each occurs within broader flow fields indicative of substantial local volcanic effusion. The specific sources for the three flows are not identifiable, so the observed flow lengths are minimum values only. All three flow locations occur in areas of broad volcanic plains with relatively low relief.

2. Background

Long basaltic lava flows on Earth are usually associated with localized massive volcanic effusion in areas called "large igneous provinces" (LIPs). LIPs are widely distributed on Earth, ranging in size from the enormous Ontong Java region on the east Pacific seafloor ($\sim 3.6 \times 10^7$ km^3) to the smaller but extensively studied Columbia River Basalt (CRB) group ($\sim 1.3 \times 10^6$ km^3) in the Pacific northwest of North America [*Coffin and Eldholm*, 1993]. LIPs occur as oceanic plateaus (e.g., Ontong Java), on volcanic passive margins (on continental shelves), or within continental land masses (e.g., CRB). These diverse settings lead to a wide range in the state of knowledge of each province due to the difficulty or ease with which the rocks can be accessed, but still an impressive global data set has resulted from individual studies [*Macdougall*, 1988].

Recently, a debate has arisen concerning the mode of lava emplacement within large igneous provinces, specifically within the CRB continental flood basalts. *Shaw and Swanson* [1970] provided the first quantitative estimates of CRB emplacement, relating constant effusion along feeder dikes to turbulently flowing lava powered by the hydraulic head generated along the gently sloping lava surface. Their calculations resulted in emplacement times of days to a few weeks for CRB flows, encompassing individual flow units hundreds of kilometers in length, driven in large part by the observation that very little chilled glass is preserved in CRB flows, which was interpreted to imply extremely rapid emplacement [*Shaw and Swanson*, 1970]. This approach was adopted by subsequent studies of the emplacement of long lava flows on the Moon [*Schaber*, 1973b] and Venus [*Roberts et al.*, 1992]. However, recent observations of basaltic lava flow inflation in Hawaii, caused by the rise of an initially emplaced surface through continued influx of lava, have provided a

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mechanism for the slow emplacement of what eventually becomes a thick lava flow [*Walker*, 1991; *Hon et al.*, 1994]. Field evidence cited for inflation features within the CRB [*Self et al.*, 1996, 1997] remains controversial, since many of these areas are also interpreted to be consistent with the rapid emplacement of the lava [*Swanson et al.*, 1989, pp. 21-26; *Tolan et al.*, 1989; *Reidel and Tolan*, 1992]. If the lavas were emplaced via inflation, flow units within the CRB could require years to decades for emplacement, in marked contrast to the days to weeks envisioned by the flood scenario. Hopefully, insights from long planetary flow studies can help clarify distinctions between scenarios and point to helpful evidence from other studies of long lava flows.

The issue of fast versus slow emplacement of the CRB flows was addressed during a field trip preceding the 1995 International Union of Geology and Geophysics (IUGG) meeting [*Hon and Pallister*, 1995], where participants were shown some of the controversial features while advocates for both fast and slow emplacement presented their cases. Both sides made sufficiently compelling cases to warrant further study, but both sides require additional field evidence addressing both fast and slow emplacement within the flows of the CRB flows. A Chapman Conference in 1996 specifically addressed the conditions of emplacement for long lava flows, and an associated field trip visited localities on the Undara, Kinrara, and Toomba flows, Cenozoic basalts that include some of the longest subaerial lava flows in the world [*Stephenson and Whitehead*, 1996]. Once again the issue of fast versus slow emplacement was integral to the field localities, particularly for assessing the field evidence for inflation within the long lava flows. The Australian flows displayed pahoehoe textures over essentially their entire lengths, one of which is 160 km long [*Stephenson et al.*, 1996].

Lava tubes are important in discussing possible emplacement conditions for long lava flows. Several descriptions are present within the literature for the formation of lava tubes [e.g., *Greeley*, 1971, 1987; *Peterson and Swanson*, 1974; *Hon et al.*, 1994; *Peterson et al.*, 1994]. Recent studies of the thermal effect of transport of lava through a tube illustrate the dramatic effect the insulating properties of a well-developed tube can have on the lava carried by the tube [*Keszthelyi*, 1995; *Dragoni et al.*, 1995; *Sakimoto et al.*, 1997]. In particular, tubes provide a viable mechanism for transporting basaltic lava for hundreds of kilometers within the environmental conditions encountered on all of the terrestrial planets [*Keszthelyi*, 1995]. Tube-fed lavas are inferred to have played a prominent role in the emplacement of the 120-km-long Toomba flow in North Queensland [*Whitehead and Stephenson*, this issue] and the 75-km-long Carrizozo flow in New Mexico [*Keszthelyi and Pieri*, 1993], as well as for many flows on the ocean floor [*Ballard et al.*, 1979; *Bonatti and Harrison*, 1988; Gregg and Fink, 1995]. Two ways lava tubes form in basaltic flows are roofing over of active lava channels [*Peterson et al.*, 1994; *Dragoni et al.*, 1995] and locally concentrated flow inside an inflating flow lobe [*Hon et al.*, 1994]. On planetary flows a roofed-over lava channel might be inferred from a medial (leveed) channel and aligned collapse pits. Aligned collapse pits have been cited as evidence for tube-fed emplacement on some planetary lava flows [*Oberbeck et al.*, 1969; *Carr et al.*, 1977; *Mouginis-Mark et al.*, 1988; *Sakimoto et al.*, 1997], but none of the flows described below display this distinctive pattern. The relationship between lava tubes and inflated flows is clearly relevant to a discussion of possible effusion rates associated with planetary flows, but it is unlikely that features diagnostic of inflation can be detected unambiguously using the planetary remote sensing data currently available.

The transition from the smooth, ropy texture of pahoehoe lava to the clinkery rubble of an aa flow is clearly related to effusion rate for Hawaiian flows [*Rowland and Walker*, 1990]. However, this transition is also closely related to the rate of shear experienced by the lava and its volatile content [*Kilburn*, 1990, 1993]. The presence of pahoehoe or aa surface textures is difficult to determine using current planetary image data, although the use of variable rod lengths in measuring the margins of lava flows shows great promise for distinguishing between the fractal nature of these flow types [*Bruno et al.*, 1992, 1994]. Flow texture is strongly influenced by the environment into which the flow is emplaced, along with the effusion rate of the flow [*Griffiths and Fink*, 1992a, b; *Gregg and Fink*, 1995, 1996], so the pahoehoe-aa transition will not be used here to infer effusion conditions. A more fundamental issue is the distinction described by *Walker* [1971] as "compound" or "simple" lava flows. Compound flows consist of multiple flow fronts and margins emplaced as the flow advances by near-simultaneous effusion from many locations along the front, often highly intermixed within the broader confines of the flow outline. By contrast, simple flows are emplaced behind a single advancing front, and they can display a medial channel which supplied the active snout during emplacement if conditions allowed the channel to drain once effusion stopped. The distinction between compound and simple flows can provide a clue to the flow emplacement, and some of these characteristics are resolvable with existing planetary data.

3. Three Planetary Examples of Long Lava Flows

The lava flows examined here are found on broad volcanic plains on the Moon, Mars, and Venus. The associated flow fields occur in very different physical environments, ranging from a dense carbon dioxide atmosphere (Venus) to a vacuum (the Moon), and yet they all display comparable overall dimensions and plan views. In this section we describe the characteristics of a long flow within each field, as well as the general aspect of the field in which it occurs. Basic parameters for the long flow identified on each planet are summarized in Table 1.

3.1 Mare Imbrium, Moon

The large impact basins on the Earth-facing side of the Moon are flooded with basaltic lava that was sampled by five of the six Apollo landings [*Vaniman et al.*, 1991]. Mare Imbrium includes some of the last lavas erupted onto the basin floor, with many clear flow margins and occasional leveed channels on flows that are traceable for hundreds of kilometers [*Schaber*, 1973a, b; *Schaber et al.*, 1976]. The early phases of the Imbrium eruptions generated lava flows that extend 1200 and 800 km (for phases I and II, respectively) from the vent area [*Schaber*, 1973a, b]. The last eruptive episode (phase III) generated flows that traveled 400 km (Figure 1) and are traceable close to the inferred source vent near the Euler-β feature located at 22°50'N, 31°20'W [*Schaber*, 1973a].

Table 1. Characteristics of Long Lava Flows on Three Planetary Surfaces

	Region		
	Mare Imbrium	Tharsis Montes	Strenia Fluctus
Planet	Moon	Mars	Venus
Figure	1	3	6, flow 1
Location			
Latitude, °N	26 to 32.5	5 to 12.5	39.5 to 41
Longitude, °	21 to 28 W	108 to 111 W	250 to 252 E
Dimensions			
Length, km	250	480	180
Width, km	10 to 25	5 to 50	5 to 20
Length/Width	10:1 - 25:1	10:1 - 96:1	9:1 - 36:1
Thickness, m	10 to 30	30 to 100	30?
Area, km^2	4800	8800	2600
Volume[a], km^3	48-144	260-880	78
Average slope, °	0.3	0.3	0.03
Environment			
Surface temperature, K	~100 to ~360	~150 to ~290	~750
Atmosphere	vacuum	carbon dioxide	carbon dioxide
Atmospheric pressure[b], bars	0	~0.004	~90,000
Surface gravity, m/s^2	1.62	3.74	8.87

[a]Area multiplied by range of thicknesses.
[b]One bar pressure = 10^6 dyn/cm^2 = 10^5 N/m^2.

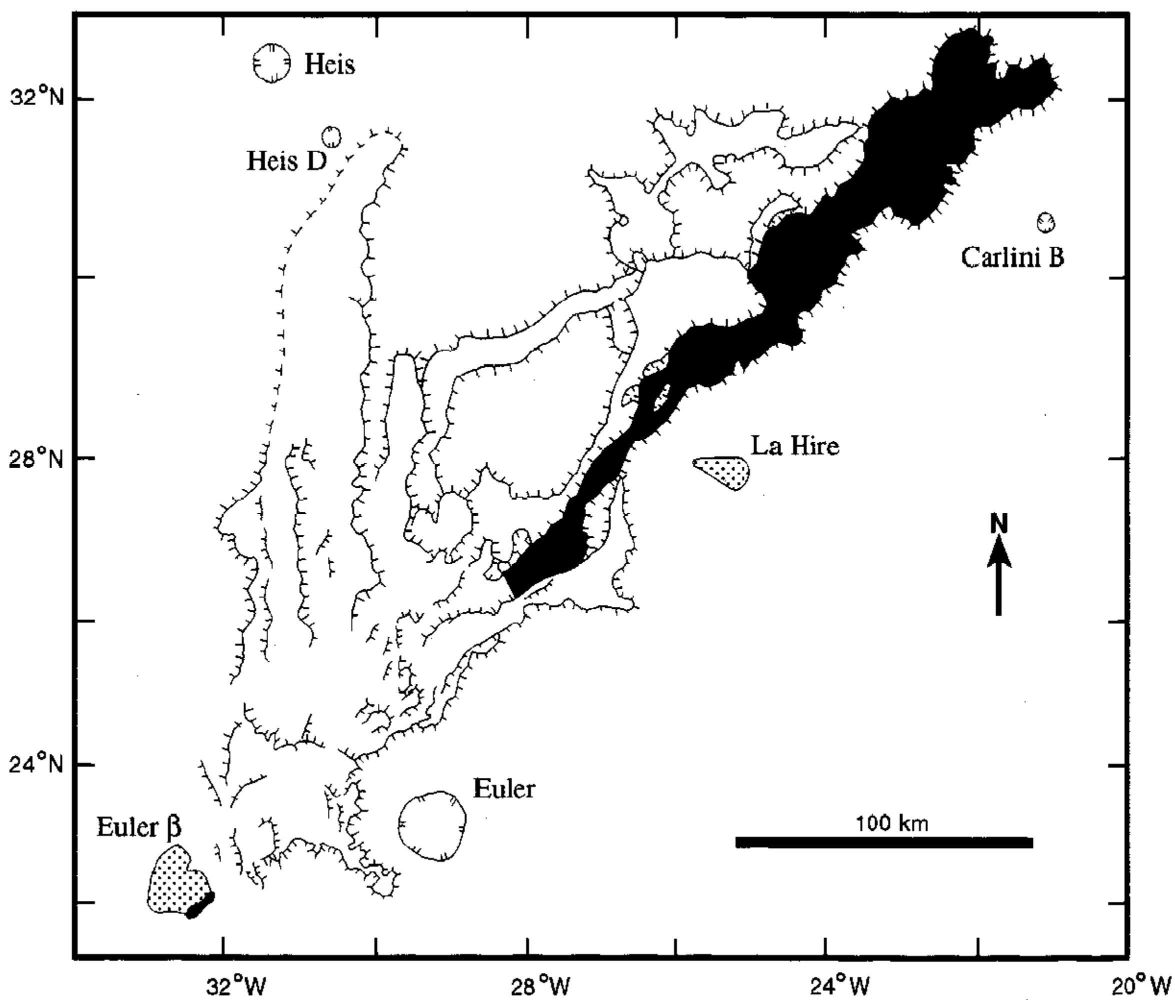

Figure 1. Flow margins of phase III lava flows in Mare Imbrium on Earth's Moon [after *Schaber*, 1973a, Figures 30-15 and 30-21b]. Large impact craters and hills (pattern) are shown for reference. The flows progresses to the north-northwest from a vent area inferred to be along the southeastern margin of the Euler-ß feature at 22°50'N, 31°20'W [*Schaber*, 1973b]. The flows are interpreted to be compound within 120 km of the source vent [*Schaber et al.*, 1976]. Shaded flow represents the longest simple flow traceable beyond the compound flow region; see Table 1 for dimensions.

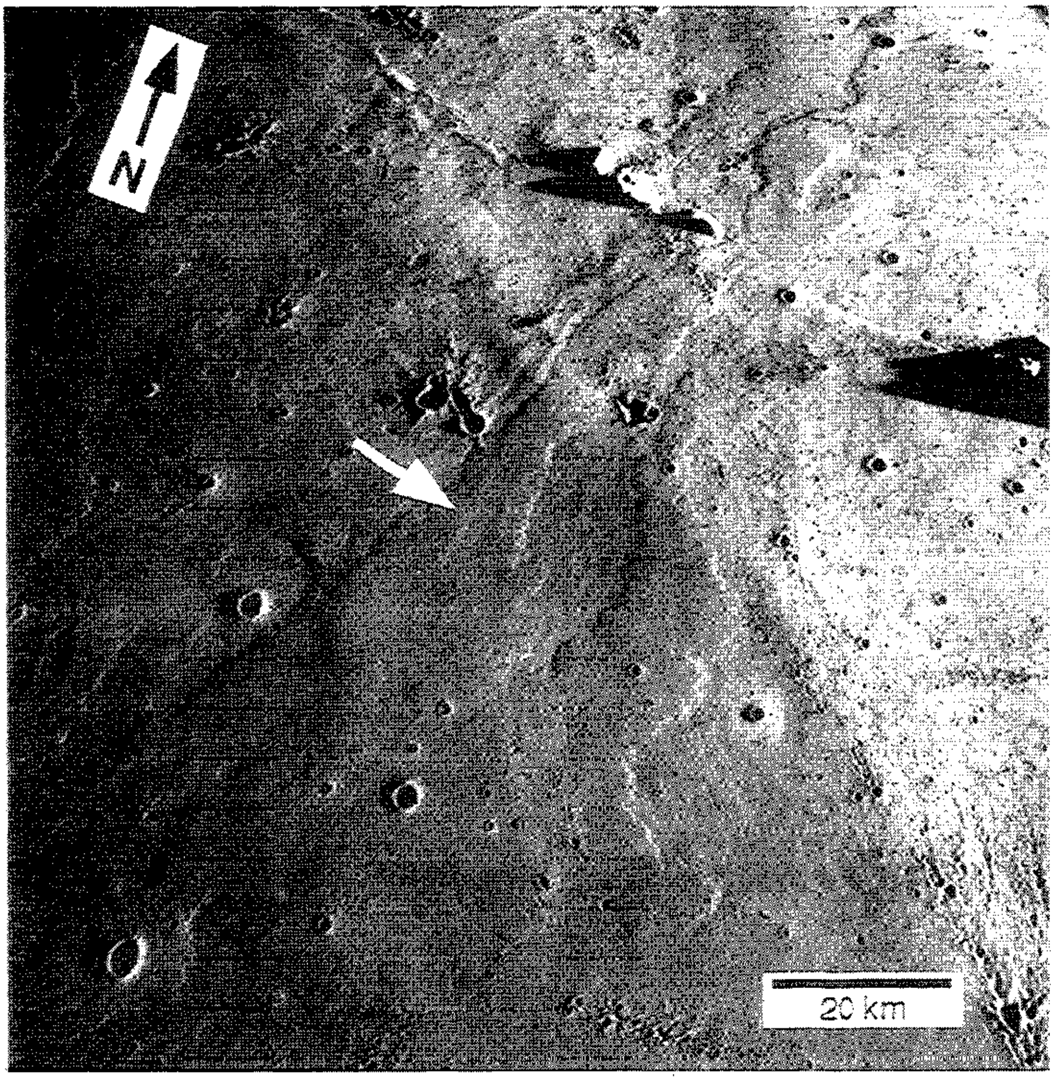

Figure 2. The phase III lava flows in Mare Imbrium photographed at very low solar incidence angle (2°) during the Apollo 15 mission. The flows traveled north-northwest. La Hire mountain is at right center. A portion of the longest traceable flow (shaded in Figure 1) passes through the center of the frame, including a leveed medial channel (arrow) representing about one half of the flow width in this area. Photogrammetric analysis in *Schaber et al.* [1976] indicate flow margin heights in this region range from 7 to 36 m, reduced from the 12 to 53 m reported by *Schaber* [1973b]. Portion of Apollo 15 metric camera photograph AS15-M3-1557.

Excellent low-illumination Apollo photography provides good documentation of the morphology of these latestage lunar mare flows. Flow margins and medial (leveed) channels (Figure 2) were recorded in photographs obtained at solar illumination angles of from 4° to 2°, which highlight these subtle features [*Schaber*, 1973a, b].

The ubiquitous impact craters on the Imbrium flows indicate that they have been subjected to a prolonged history of cosmic bombardment. No Apollo samples were obtained from this area of the Moon, but the cratering record suggests that these flows are among the youngest materials emplaced onto the lunar surface, with probable exposure ages of from 2.5 to 3.0 b.y. [*Schaber et al.*, 1976]. The Imbrium lava flows show distinct differences from other mare materials at infrared and ultraviolet wavelengths [*Whitaker*, 1972], consistent with color ratio images of relatively young terrains elsewhere on the Moon. Laboratory analyses of lunar-like materials have documented the relatively low viscosity (5-9 Pa s at 1250°C [*Weill et al.*, 1971]; 1 Pa s = 10 poise) and high bulk density (2950 kg/m^3 [*Murase and McBirney*, 1970]) of lunar basalts, as compared to typical terrestrial basalts. The Apollo samples provide the only rheological properties available at present that are directly applicable to lava flows observed on planetary surfaces, as well as the only case in which we are certain that the specific planetary lavas are basaltic in nature.

Observed flow widths for the phase III lavas range from 5 to 25 km for flows >150 km from the inferred vent. The phase III flows attain a combined width of ~120 km at a distance of ~120 km from the vent area (Figure 1). *Schaber et al.* [1976] infer that the proximal phase III flows were emplaced as compound, overlapping flows. Consequently, we will restrict our discussion to the longest "simple" phase III flow (shaded in Figure 1) that attained the greatest distance from the vent area of any of the phase III lavas. This flow can be traced for

250 km with a variable width of from 10 to 25 km, resulting in a length/width aspect ratio of from 10:1 to 25:1. A subtle medial channel is present on the proximal reach of this flow, corresponding to about one half of the flow width in the channeled reach (Figure 2). Photogrammetric measurements of the phase III flow heights initially ranged from 10 to 63 m [*Schaber*, 1973b], but later analysis reduced this range to 10 to 30 m [*Schaber et al.*, 1976].

The lunar environment is notable in that it is now and likely has been for billions of years, a nearly perfect vacuum. Thus cooling of lunar lava flows has been by radiation and conduction, without the convection component available for flows emplaced within an atmosphere or on the ocean floor. Solar illumination generates surface temperatures from ~100 to ~360 K throughout the lunar day, equal to its 29-day orbital period around Earth. The relatively small size of the Moon results in a low value for the acceleration of gravity (1.62 m/s^2) as compared to that on Earth (9.80 m/s^2). Topography within the Imbrium basin is very subdued, with an average slope from the source region to the basin center estimated to be between 1:100 (0.57°) and 1:1000 (0.06°) [*Schaber*, 1973b]. The longest phase III flow can only be followed to ~120 km from the vent area, where slopes are likely to be considerably less than the maximum value near the source. Recent laser altimetry from the Clementine spacecraft [*Zuber et al.*, 1994] show that the distal phase I flows in the Imbrium basin are topographically higher than the basin center, suggesting that significant basin subsidence took place subsequent to the emplacement of the phase I and II Imbrium lava flows.

3.2 Tharsis Montes, Mars

The three large Martian shield volcanoes which compose the Tharsis Montes occur near the summit of the 4000-km-wide Tharsis uplift, where the Martian crust is elevated ~10 km above the surrounding terrain [*Carr*, 1981, pp. 87-95]. Each of the three shield volcanoes is approximately 200 km in basal diameter, with relief of 12 to 17 km above the surrounding summit of the Tharsis uplift [U.S. Geological Survey [*U.S. Geological Survey* (USGS), 1991]. All three volcanoes are surrounded by volcanic plains composed of numerous flows interpreted to be derived from either the volcanoes themselves or nearby unidentified vents [*Scott and Tanaka*, 1986]. A broad fan of lava flows southwest of Arsia Mons has been discussed at length in the literature, with some flows up to 700 km in length [*Carr et al.*, 1977; *Moore et al.*, 1978; *Schaber et al.*, 1978; *Scott and Tanaka*, 1981]. Another well-defined set of lava flows emanates to the northwest from the topographic saddle between Ascraeus Mons and Pavonis Mons volcanoes [*Scott et al.*, 1981a, b]. Images from the Viking Orbiter spacecraft reveal one lava flow within this field whose margins can be traced for 480 km, as well as several other adjacent flows that follow the same general trend (Figure 3). The vents for these flows cannot be identified since subsequent lava flows have buried the proximal portions of all of thge visible flows.

The 480-km-long lava flow (Figure 3, shaded) shows some important variations in basic morphology and dimensions over its traceable length. The proximal portion of the flow is gently sinuous with a medial channel, flanked by natural lava levees, that accounts for about one half of the flow width (Figure 4). Shadow measurements indicate that the proximal flow margins are ~30 m thickness. The proximal flow width is quite uniform at ~5 km. The leveed medial channel implies that at least this portion of the flow likely was fed by a river of lava comparable to the channel-fed aa flows common in Hawaii [*Lipman and Banks*, 1987; *Rowland and Walker*, 1990].

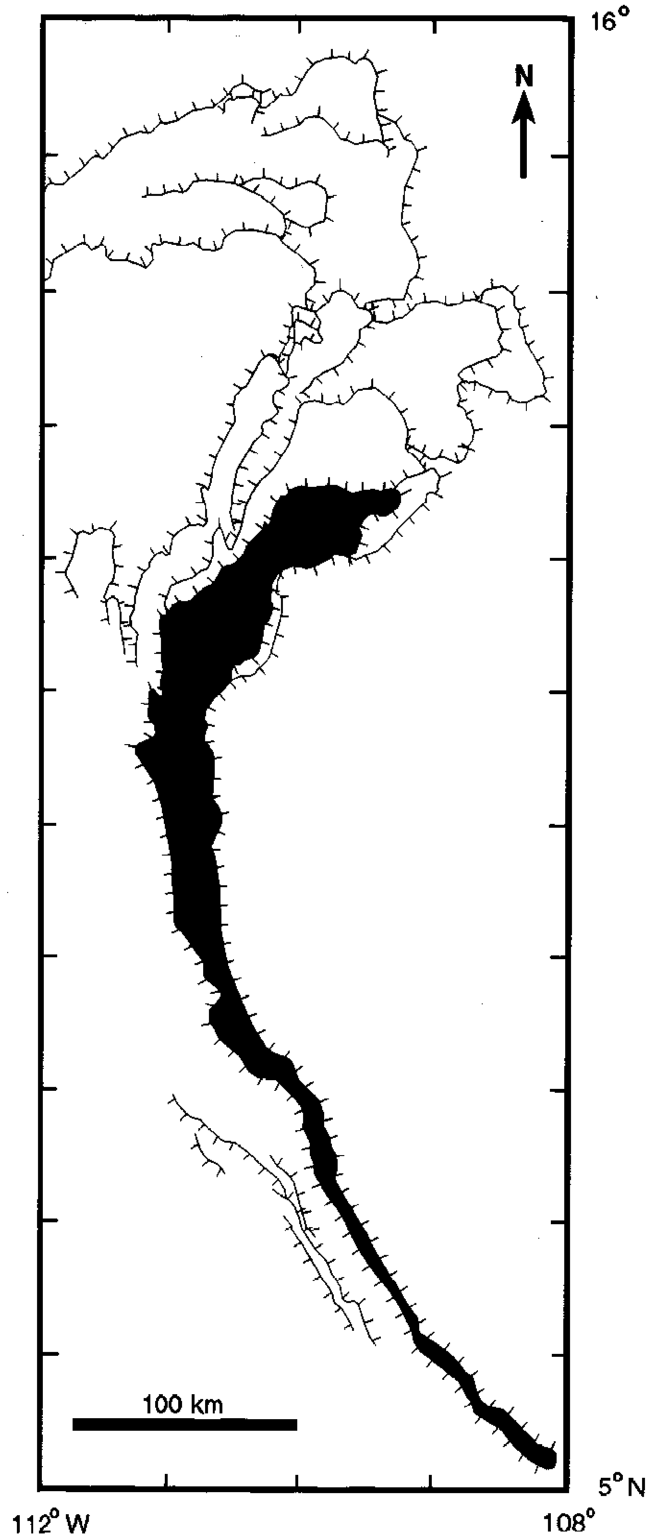

Figure 3. Flow margins visible northwest of the topographic saddle between Ascraeus Mons and Pavonis Mons on Mars. Shaded flow has margins that can be traced for 480 km down the northwestern flank of the Tharsis uplift; see Table 1 for dimensions.

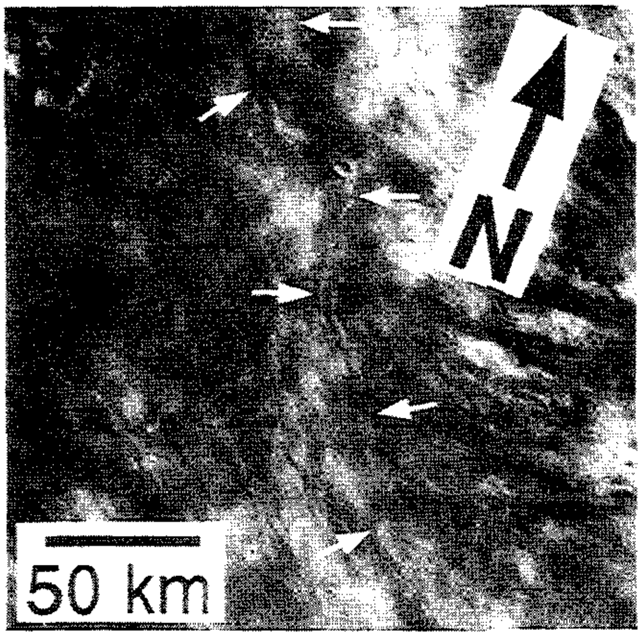

Figure 4. Proximal portion of traceable long lava flow (arrows) in the Tharsis Montes region of Mars. A leveed medial channel representing about one half of the flow width is evident along the proximal reach. Portion of Viking Orbiter image 643A51, orthographic projection, neutral gain filtered version, 270 m/pixel resolution, centered on 7.1°N, 109.8°W.

Regional topography in the proximal portion of the flow has an average gradient of ~0.5° toward the northwest [USGS, 1991]. The medial channel disappears once the flow reaches the more gently sloping (~0.1°) plains surrounding the Tharsis volcanoes (below the 5 km elevation contour, [USGS, 1991]. The flow widens to more than 30 km on the gently sloping plains, locally attaining a width of 50 km. Distal portions of the flow display broad upper surfaces lacking any distinct morphology at the 190 m/pixel resolution of the best Viking images of this area (Figure 5). Shadow measurements of margins near the terminus of the flow indicate a thickness of ~100 m. Owing to the highly variable width along the flow, length/width aspect ratios range from 10:1 for distal widths to 96:1 for proximal widths. Numerous other lava flow margins are evident surrounding the long flow (Figures 3 and 5), indicating that several episodes of lava emplacement occurred in this area [*Scott et al.*, 1981a, b]. Many of these earlier eruptions must have been longer than the flow described above, which likely was one of the last in the eruptive sequence. Here we assume these flows are approximately basaltic in composition in the absence of compelling compositional evidence.

The precise age of the Martian flow cannot be determined, but the flows surrounding the Tharsis Montes are from the early Amazonian to late Hesperian eras which are relatively late in the stratigraphic sequence of terrain units identified on Mars [*Scott and Tanaka*, 1986]. The Martian atmosphere likely has not varied greatly in overall composition during the last half

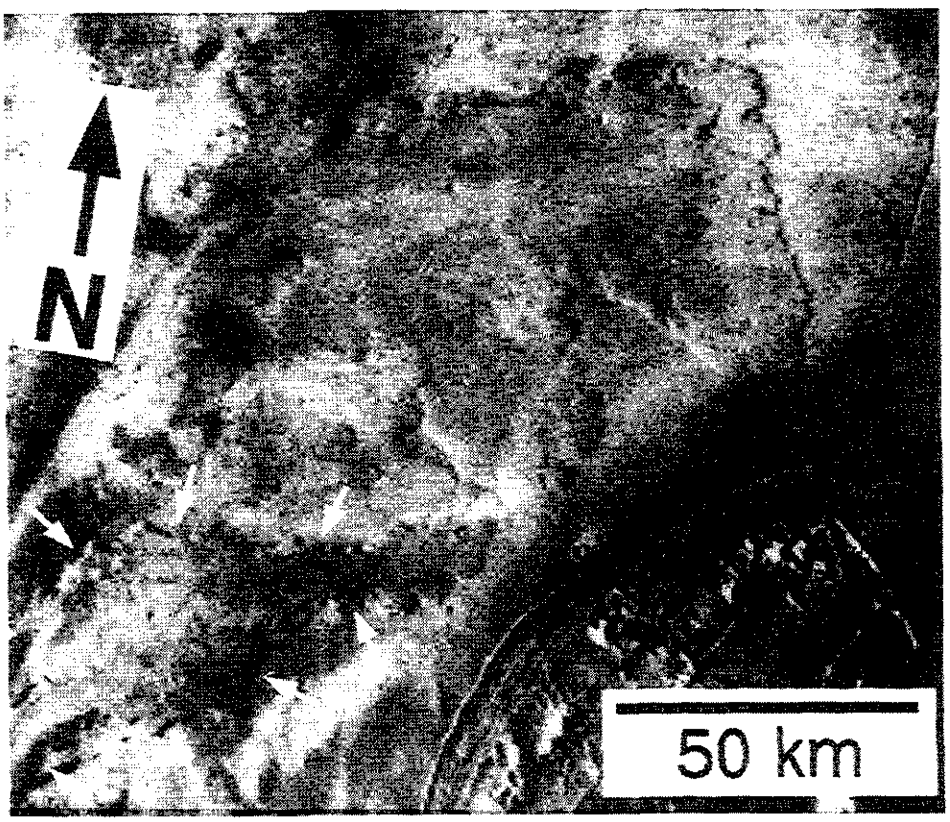

Figure 5. Distal portion of traceable long lava flow (arrows) in the Tharsis Montes region of Mars. Numerous other flow margins are also visible in this region, although the individual flows cannot be traced for lengths beyond ~100 km (Figure 3). Shadow measurements along the traceable long flow indicate flow thickness is ~100 m in the distal reach. Portion of Viking Orbiter image 516A52, orthographic projection, neutral gain-filtered version, 190 m/pixel, centered on 13.0°N, 109.1°W.

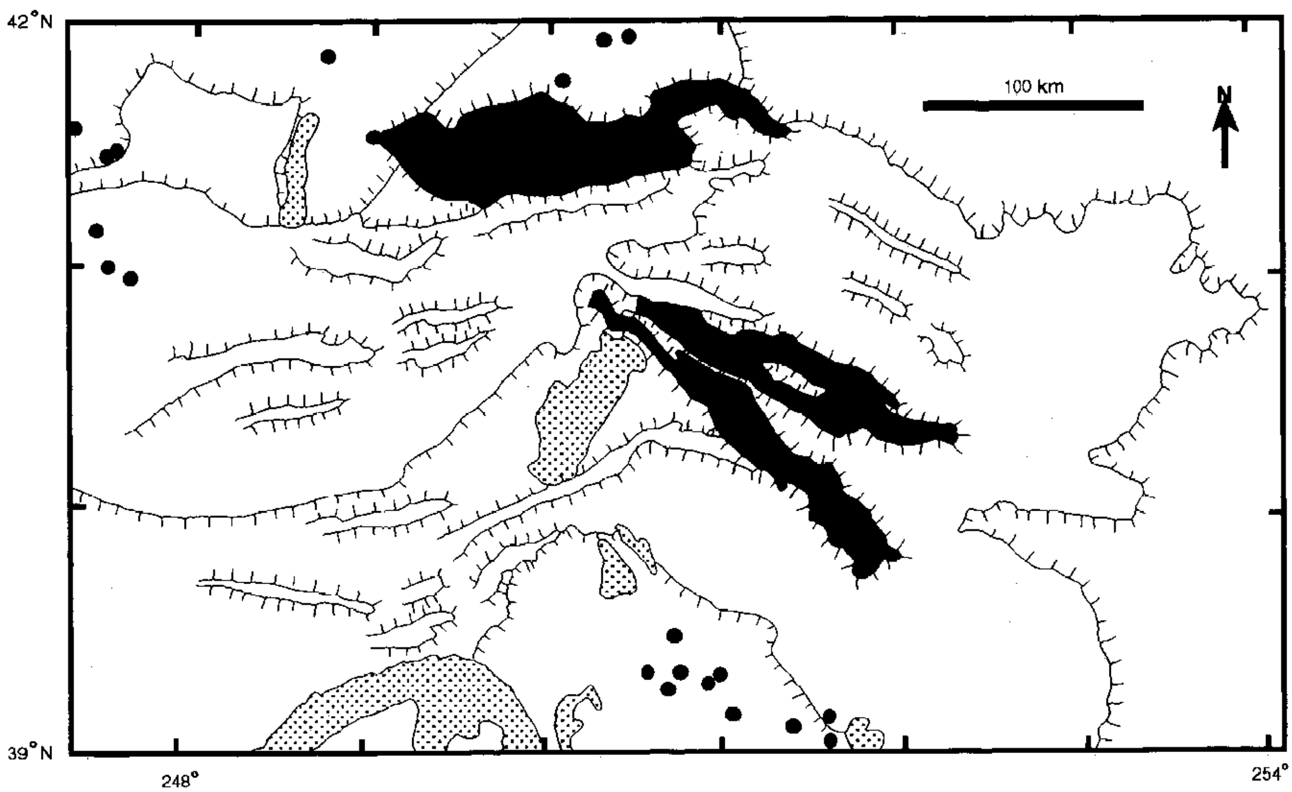

Figure 6. Flow margins visible in the Strenia Fluctus region of Kawelu Planitia on Venus. The intermixed flows have SAR reflectances that are radar-bright and radar-dark (see Figure 7). Shaded and numbered flows are discussed in the text; see Table 1 for dimensions of flow 1. Pattern indicates outcrops of intensely deformed rock (tessera) that predate the lava flows. Dots indicate individual low domes, one of which was the source of the shaded flow field 4.

of Martian history, but orbital variations could have resulted in considerable variability in total atmospheric pressure [*Pollack*, 1979]. Given the uncertainty of the precise time of the flow eruption, we will take the current atmospheric conditions to be representative of the Martian atmosphere during flow emplacement. The location of the flow field on the flank of the Tharsis uplift means that the current atmospheric pressure is reduced to about ~4 mbar (610 N/m^2). Thermal infrared measurements from the Viking IRTM experiment indicate that surface temperatures in the flow area can range diurnally from ~150 K to ~290 K [*Kieffer et al.*, 1977; *Zimbelman and Kieffer*, 1979].

3.3 Strenia Fluctus, Venus

The Magellan mission provided the first detailed views of nearly the entire surface of Venus through the use of synthetic aperture radar (SAR) imaging [*Saunders et al.*, 1992]. The lowland plains of Venus contain abundant volcanic flow features [*Head et al.*, 1992]. Several studies have focused on various aspects of the volcanic features on Venus, but the one most relevant to the current study was an analysis of the Mylitta Fluctus flow field [*Roberts et al.*, 1992]. Components of the Mylitta Fluctus flow field extend up to 1000 km from the inferred source region, representing one of the areally most extensive volcanic effusions documented on the planet [*Head et al.*, 1992; *Roberts et al.*, 1992]. Here we focus on a lava flow field more typical of those that occur throughout the Venusian lowlands.

The Kawelu Planitia region includes numerous volcanic flows, most of which emanate from concentrations of small volcanic domes [*Zimbelman*, 1994]. Recently one flow field in Kawelu Planitia was given the provisional name of Strenia Fluctus (Figure 6). The Strenia Fluctus flow margins lose their identity approaching the source domes (off the left margin of Figure 6), but individual flow components can be traced for nearly 200 km. The flows consist of intermixed radar-bright and radar-dark lobate units, where the SAR image brightness is a complex interaction of the radar signal with surface roughness elements and the dielectric properties of those surfaces (Figure 7). Several radar-bright flow segments can be traced for >100 km, with widths that range from 5 to 20 km. When viewed at full resolution, each of these radar-bright flows are seen to consist of numerous superposed margins indicative of a compound flow (inset, Figure 7). A prominent ~150-km-long radar-dark flow (left center, Figure 7) is ~16 km wide at its proximal (upslope) reach but it narrows to ~2 km width down slope, where it flowed between previously emplaced flows; this flow is comparable in planform and scale to the Toomba flow in North Queensland, Australia [*Stephenson and Whitehead*, 1996]. Both the radar-bright compound flows and the radar-dark flows in Strenia Fluctus are consistent with quantified studies of radar backscatter in the Magellan images that indicate most flow features on Venus have surface roughness comparable to pahoehoe flows on Earth; only the very brightest flows on Venus have roughness approaching that of terrestrial aa [*Campbell and Campbell*,

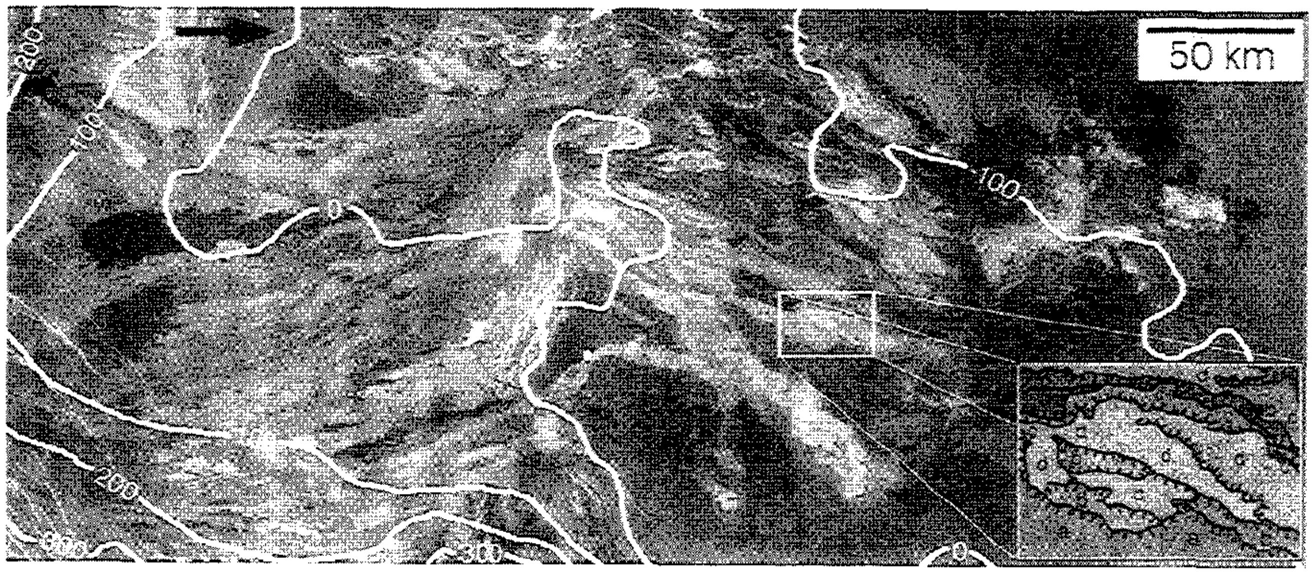

Figure 7. Strenia Fluctus lava flows on the lowland plains of Kawelu Planitia, Venus (compare with Figure 6). Superimposed contours are elevations in meters above 6250 km radius, derived from Magellan radar altimetry measurements. The radar-bright flows at center (flows 1 to 3 in Figure 6) consist of numerous overlapping flow lobes when viewed at full resolution and optimized contrast (see inset, where letters indicate relative superposition with "d" on top and "a" on bottom). Black arrow indicates a 2-km dome that is the source for a flow complex (flow 4 in Figure 6) that traversed a regional slope of 0.03°. A radar-dark flow at the left center starts with a width of ~16 km but narrows to a width of ~2 km between previously emplaced flows; this flow is comparable in planform and length to the Toomba flow in North Queensland, Australia. Portion of Magellan C1-MIDR 45N244, tiles 46, 47, and 48. Inset is from portions of F-MIDR 40N251, tiles 21, 22, 29, and 30.

1992]. Here we again assume an approximately basaltic composition in the absence of composition data.

For comparison with long flows on other planets, we focus here on the radar-bright compound flows in Strenia Fluctus (flows 1 to 3 in Figure 6). Three bright flows extend southeast past an outcrop of faulted tessera terrain, and their sources are buried beneath subsequent flows. All three flows are compound in nature when examined at full resolution and optimized contrast. These flows extend down a regional slope of 0.05° to 0.03° (contours, Figure 7), which corresponds to a vertical drop of <1 m per kilometer traversed [*Helgerud and Zimbelman*, 1993]. The longest of the three flows (flow 1, Figure 6) extends 180 km with a variable width ranging from 5 to 20 km, resulting in length/width aspect ratios that range from 9:1 to 36:1. It is very difficult to obtain good estimates of flow thickness from Magellan SAR images of Venus. Flow margins produce no observable radar "shadow" unless the flows are exceptionally thick [e.g., *Moore et al.*, 1992]. Estimates of the interaction of flows with topographic obstacles suggests that flows on the lowland plains are likely 10 to 30 m in thickness [*Roberts et al.*, 1992].

A single 2-km-diameter dome (arrow, Figure 7) is the source of a complex array of radar-intermediate to -bright flows (flow 4, Figure 6) that extend ~160 km down a regional slope of 0.03°. This example of a point source for an extensive flow field is somewhat rare among the complex volcanics of the Venusian lowlands. It seems more likely that the compound flows in Strenia Fluctus are the distal portions of a (now buried) flow complex perhaps analogous to the phase III lavas on the Moon. The Venusian lavas seem to be capable of maintaining a compound flow structure long distances from their proximal areas.

The atmosphere of Venus is composed primarily of carbon dioxide, with a perpetual cover of clouds formed by the condensation of sulfuric acid droplets. The cloud cover and the infrared properties of carbon dioxide combine to make an effective greenhouse, maintaining the surface temperature at ~750 K across the Venusian plains. The atmosphere is substantially thicker than that of Earth, with a surface pressure of ~90 bars (9×10^6 N/m^2) for the lowland plains. The elevated temperatures and pressures should have had an influence on the cooling of lava flows, but the surprising result is that forced convection in the thick atmosphere could make lava flows lose heat more effectively than a comparable subaerial flow on Earth [Head and Wilson, 1986].

4. Estimates of Effusion Rates

Effusion rates have been calculated for volcanic flows on planetary surfaces based on the inferred cooling properties of a laminar liquid-filled channel [e.g., *Hulme*, 1974, 1976; *Dragoni et al.*, 1986; *Wilson and Head*, 1983; *Pinkerton and Wilson*, 1994] or turbulently emplaced massive flows [*Shaw and Swanson*, 1970]. The calculated effusion rates generally tend to be very large. The Mare Imbrium lavas (phases I to III) have calculated effusion rates of ~10^6 m^3/s based on application of the *Shaw and Swanson* [1970] turbulent model [*Schaber*, 1973b; *Schaber et al.*, 1976]. Individual flow units within the Mylitta Fluctus flow field on Venus have estimated effusion rates that range from 8100 to 3×10^7 m^3/s based on turbulent flow equations [*Roberts et al.*, 1992, Table 4]; these researchers favor values toward the high end of the range, resulting in extremely rapid emplacement (of the order of days

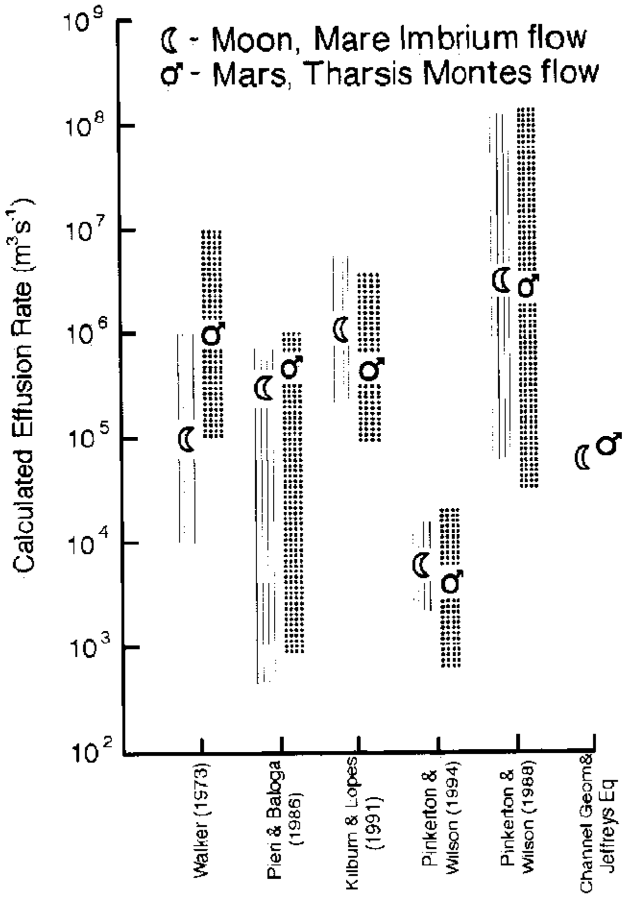

Figure 8. Calculated effusion rates for individual long flows on the Moon and Mars. Calculations used equations given in papers cited at bottom. Symbols plot at location representative of medial values; patterns (lined, Moon; dots, Mars) show the range resulting from uncertainties in flow dimensions. The channel geometry calculation assumes Newtonian flow in a channel one-half of the oberved flow dimension at medial channel locations.

to weeks) for flows that extend up to 1000 km. Plains-forming flows in the Venus lowlands also have estimated effusion rates of 10^5 to 10^6 m^3/s [*Head and Wilson*, 1986], based on the critical Grätz number associated with conductive cooling of a channelized flow. Extrapolation of the flow length versus effusion rate data of *Walker* [1973] results in a 1.5 x 10^6 m^3/s effusion rate for the Rosa Member of the Columbia River Basalt Group [*Shaw and Swanson*, 1970; *Roberts et al.*, 1992]. More moderate effusion rates have been obtained for some individual flows on Mars: *Hulme* [1976] used expressions for the flow of a Bingham fluid down an inclined plane to derive an effusion rate of 470 m^3/s for a leveed flow on Olympus Mons. Empirical relations derived for simple flows on Earth led *Lopes and Kilburn* [1990] to obtain effusion rates of 700 to 10^5 m^3/s for 18 flows on Alba Patera (~10^4 m^3/s for most flows).

Such calculated effusion rates are often many orders of magnitude larger than effusion during historic Hawaiian eruptions, which generally are < 400 m^3/s [*Rowland and Walker*, 1990]. The ongoing activity on the flank of Kilauea volcano since 1983 averaged ~5 m^3/s over 7 years of monitoring [*Rowland and Walker*, 1990, Figure 3], where the eruptions consisted initially of several episodes of (proximal) pahoehoe and (distal) aa effusion separated by varying periods of inactivity [*Wolfe et al.*, 1988]. Subsequent to 1986, the Kilauea eruption involved nearly continuous eruption of basalt at ~3.5 m^3/s from the Kupaianaha vent to generate a complex patchwork of tube-fed pahoehoe flows that formed the Kalapana flow field [*Mattox et al.*, 1993]. These flows reached the sea as pahoehoe lava, as well as providing many examples of the inflation of pahoehoe flows through the continued influx of fluid basalt into a stagnant flow, with the lava transported to the active front through tubes of varying size [*Hon et al.*, 1994]. The recent Hawaiian effusive activity is consistent with the effusion rate observed during the 1969-1974 eruption of Mauna Ulu [*Swanson et al.*, 1979; *Tilling et al.*, 1987], rates calculated from the volume of lava emplaced during the 1919-1920 eruption of Mauna Iki [*Rowland and Munro*, 1993], and the calculated long-term supply rate to Kilauea [*Holcomb*, 1987]. The Hawaii eruption rates are in contrast to fissure eruptions like the 1783-1785 Laki eruption on Iceland, where maximum effusion rates are estimated to be ~9 x 10^3 m^3/s from fissures 2.2 to 2.8 km in length, which translates to an effusion rate of 3.1 to 3.9 m^3/s per meter of fissure length [*Thordarson and Self*, 1993].

The measured dimensions of the three planetary flows will now be used to evaluate the effusion rates likely responsible for these flows. In applying published relationships relating flow dimensions to effusion rate, we first subdivide the three flows into two categories. The lunar and Martian flows have visible characteristics consistent with a simple flow while the intermixed flow fronts evident in the Venusian flow imply that it is a compound flow. This division is based on features visible in data currently available; it is possible that new information could change the inferred style of emplacement for any of the flows. Most published relationships were derived for simple flows, and these relationships will be applied only to the lunar and Martian flows. *Keszthelyi and Pieri* [1993] discuss problems resulting from applying flow relationships for simple flows to a compound flow. The basic ratioinale for each approach is summarized below, with the computed results tabluated in Figure 8. The reader should consult individual references for the details of each method.

4.1 Simple Flows

Walker [1973] compared flow length to average effusion rate for basalt flows on Hawaii, where the longest subaerial flow is ~60 km. Extrapolating his plot to include the lunar and Martian flows, their observed lengths imply effusion rates of ~10^5 (Moon) and ~10^6 (Mars) m^3/s (Figure 8). These values could vary by at least an order of magnitude and still fall within the envelope defined by *Walker's* [1973] data. This extrapolation assumes Hawaiian emplacement conditions are accurate analogs to the planetary environments and can be scaled up by several orders of magnitude without introducing significant errors. *Malin* [1980] suggested that the Hawaii data provided a better correlation between flow length and total erupted volume. However, *Pinkerton and Wilson* [1994] determined that Malin's correlation actually is consistent with *Walker's* [1973] relationship if tube-fed flows and short-duration eruptions are excluded.

Pieri and Baloga [1986] used data from the Kilauea eruptions that began in 1983 to obtain a correlation between the planimetric area of the flow (A) and effusion rate (Q). They showed that both theoretical modeling and measurements of flows from various volcanoes can show considerable variation in Q/A from volcano to volcano, but the ratio is reasonably consistent (1 to 120 m^3/km^2) for eruptions on a given volcano. Applying this Q/A range to the lunar and Martian flows, we obtain effusion rates of 5×10^2 to 6×10^5 (Moon) and 9×10^2 to 10^6 (Mars) m^3/s (Figure 8). This empirical relationship again relies primarily on Hawaii data and their applicability over many orders of magnitude. However, planimetric area is readily measured from remote sensing data, so it can provide an alternative to extrapolating *Walker's* [1973] Q/L relationship. Q/A for the lunar and Martian flows overlaps the Walker extrapolation only at the upper end of the Q/A range (Figure 8).

Kilburn and Lopes [1991] documented flow dimensions for aa and block flows on a variety of volcanoes, obtaining a statistically significant relationship between the flow emplacement time and the maximum values of length and width for the flow field. If the volume is assumed to be emplaced over the derived emplacement time, the lunar and Martian flows imply effusion rates of 2×10^5 to 6×10^6 (Moon) and 10^5 to 4×10^6 (Mars) m^3/s (Figure 8). Unlike the above methods, this calculation is based on measurements from a variety of lava types and volcanoes rather than assuming a Hawaii eruption style. Here we have applied a relationship developed for a field of simple flows to individual long planetary flows.

Pinkerton and Wilson [1994] used the Grätz number to determine when conductive cooling of lava in a central channel causes a flow to stop. The lunar and Martian flows both display proximal medial channels. Applying the Grätz number expression to the planetary flows results in effusion rates of 200 to 7000 (Moon) and 600 to 2000 (Mars) m^3/s (Figure 8). The principal assumption here is that flow is halted exclusively by conductive heat loss. Additional heat loss mechanisms could cause a flow to stop in a shorter distance than by conduction alone, while heat input (as from the latent heat of crystalization [*Crisp and Baloga*, 1994]) could extend the total flow length. Interestingly, effusion rates obtained from the Grätz number are at least an order of magnitude smaller than those obtained from other methods (Figure 8).

Pinkerton and Wilson [1988] derived a relationship for effusion rate in volume-limited flows, as defined by *Guest et al.* [1987] for flows that stop when effusion terminates at the vent, that is proportional to the term (volume / length x height)^3. Given the uncertainties in all three parameters for the planetary flows, derived effusion rates range widely from 6×10^4 to 10^8 (Moon) and 4×10^4 to 2×10^8 (Mars) m^3/s; average dimensions for both flows are consistent with an intermediate result of ~10^6 m^3/s (Figure 8). The applicability of this method is dependent on identifying volume-limited flows, and it includes some of the same conduction cooling assumptions involved in the Grätz number method.

An effusion rate estimate can be made that is independent of the methods discussed thus far. If the channelized reaches of the lunar and Martian flows are assumed to have been active at approximately one-half the flow width and thickness at their medial channel locations, the cross-sectional area of the active channels would have been 5×10^4 (Moon) and 3.8×10^4 (Mars) m^2. If we can constrain the likely flow velocity within these channels, we can obtain an estimate of the effusion rate. The Jeffreys equation [*Williams and McBirney*, 1979, p. 122] provides the flow velocity for a Newtonian fluid within a broad flow (assuming the channel is sufficiently wide to ignore drag at the walls). Apollo compositions indicate the lunar lavas likely had bulk densities of 2950 kg/m^3 [*Murase and McBirney*, 1970], as compared to typical terrestrial (nonvesicular) densities of 2600 kg/m^3 [*Lopes and Kilburn*, 1990]. Lunar lavas also likely had viscosities of 5-9 Pa s [*Weill et al.*, 1971], as compared to a typical fluid basalt viscosity of ~20 Pa s [*Kilburn and Lopes*, 1991]. Here we will assume the typical terrestrial values for density and viscosity for the Martian lava.

The 1984 eruption of Mauna Loa provided excellent observations of effusion in an active channelized aa basalt flow [*Lipman and Banks*, 1987; *Moore*, 1987]. Lava in the 1984 channel 10.5 km from the vent was measured at 1-2 m/s over an average slope of ~3° with a flow thickness of ~5 m [*Moore*, 1987]. If we take the average flow thicknesses to be 20 m and 30 m for the channelized reaches of the lunar and Martian flows, respectively, and a slope of 0.3° for both planets, then the Jeffreys equation allows us to scale Newtonian flow on the two planets to that on Hawaii. The result is that flow velocity should be ~86% (Moon) and ~140% (Mars) of the measured Mauna Loa 1984 flow velocity, or 0.9 to 1.9 (Moon) and 1.4 to 2.8 (Mars) m/s. Applying these velocities to the assumed cross-sectional areas of the active channels, these flows should have transported 4 to 9×10^4 m^3/s (Moon) and 5 to 11×10^4 m^3/s (Mars). These effusion estimates are broadly consistent with the intermediate values obtained by other methods (Figure 8). The assumed channel cross-sectional areas would require large flow velocities to transport ~10^6 m^3/s; ~20 m/s (Moon) and ~27 m/s (Mars).

4.2 Compound Flows

Keszthelyi and Pieri [1993] argue that inflation features and a predominant pahoehoe surface on the Carrizozo flow indicate emplacement at a rate comparable to currently observed tube-fed flows in Hawaii (~5 m^3/s), requiring 27 years to emplace the flow. For comparison, the Toomba flow (12 km^2) also displays numerous features interpreted to indicate flow inflation [*Whitehead and Stephenson*, this issue], requiring 76 years for emplacement at the above rate [*Stephenson et al.*, 1996]. This rate would require 494 years to produce the Venusian flow volume. Had the lunar and Martian flows also been emplaced at the Kilauea tube-fed effusion rate, they would have required 304 to 911 years (Moon) and 1646 to 5570 years (Mars). Keszthelyi [1995] examined the thermal budget for tube-fed flows in a variety of planetary environments, concluding that effusion rates of several tens of cubic meters per second could support the emplacement of flows many hundreds of kilometers in length. Thus the above emplacement times could be reduced by a factor of 10 and still be consistent with tube-fed effusion.

5. Discussion

The effusion rate estimates and associated emplacement times obtained above illustrate the importance of evaluating whether a flow is compound or simple in origin. Most published empirical and theoretical relationships are derived from simple flows fed by a single medial channel or with a front that advances uniformly under the influence of the lava within the snout. Some planetary flows, such as the Venus flows in Strenia Fluctus, do not fit this condition and instead display characteristics that suggest a compound origin. At present, there is no direct evidence that conclusively demonstrates whether compound planetary flows involve slow

Figure 9. The Toomba basalt flow, Queensland, Australia, has been undercut by the Burdekin River to expose the flow textures on the bottom of the flow ~115 km from the vent area. Rather than a rubble zone typical of aa flows, the flow bottom consists of numerous intertwined pahoehoe toes, each 20 to 50 cm in width and up to 1 m in length. The flow surface in this area displays typical pahoehoe-like textures, although erosion has somewhat subdued their appearance. Photo by J. R. Zimbelman on July 14, 1996.

effusion or rapid emplacement. In this situation, we favor the approach of *Keszthelyi and Pieri* [1993] to infer relatively modest effusion rates.

The Australian long lava flows provide unequivocal evidence that the basaltic lavas such as the Toomba flow were emplaced under conditions that produced meter-scale pahoehoe-like toes at its base, ~110 km from the vent (Figure 9). The surface of the Toomba flow near its distal end consists primarily of a pahoehoe sheets, including broad stretches lacking relief beyond that of cracks and squeeze-ups between the pahoehoe slabs (Figure 10). The distal parts of the Toomba flow also include many lava rises and pressure ridges

Figure 10. Surface of the Toomba basalt flow, Queensland, Australia, near the terminus of the ~120 km flow, at a locality appropriately calld "Flat Rocks" [*Stephenson and Whitehead*, 1996]. The flow surface here consists of broad pahoehoe exposures with crustal rafting sutures. There is no evidence either at the surface or at the flow margins for a'a clinkers. The distal ~30 km of the Toomba flow follows the Burdekin River closely, where the flow likely was confined within the former river valley. Photo by J. R. Zimbelman on July 14, 1996.

that uplifted pahoehoe surfaces into tumuli ridges [*Whitehead and Stephenson*, this issue; *Stephenson et al.*, 1996]. These features argue strongly for the low effusion rate typical of pahoehoe flows. It seems reasonable to assume that the Venus flows were emplaced in a manner roughly similar to that of the Toomba and Carrizozo flows. The downslope narrowing of the radar-dark flow in Figure 7 also may be analogous to emplacement of the distal portions of the Toomba flow within the confines of the Burdekin River. On Venus the distal portion of the radar-dark flow is constrained between previously emplaced lavas.

The effusion rates for the simple lunar and Martian flows might be expected to be closer to the middle of the wide range of estimates obtained by the various calculation methods. In particular, the medial channel geometry suggests neither flow likely handled ~10^6 m^3/s, and particularly the Grätz number results indicate considerably smaller rates. Observations of the 1984 Mauna Loa flow show that this 27-km-long aa flow emplaced 2.2 x 10^8 m^3 over 21 days of continuous eruption [*Lipman and Banks*, 1987], indicating an average effusion rate of ~110 m^3/s, consistent with channel dimensions and laminar flow velocities observed throughout the eruption [*Moore*, 1987]. The much larger medial channels on the lunar and Martian flows, as compared to the 1984 Mauna Loa flow, allow effusion rates in the range of ~10^4 to 10^5 m^3/s to still be consistent with emplacement as a single simple flow. This result is in general agreement with the recent assessment that the CRB flows could have been emplaced at an average effusion rate of ~4000 m^3/s through inflation during emplacement [*Self et al.*, 1997], comparable to the Laki eruption that produced the largest effusion rate for an historic eruption [*Thordarson and Self*, 1993].

The environment into which the planetary flows were emplaced must have affected the surfaces of these flows. The manner is which lava loses heat can produce a range of distinctive surface features [*Griffiths and Fink*, 1992a, b; *Gregg and Fink*, 1995, 1996]. Unfortunately, the available resolution for much of the existing planetary image data may not be sufficient to detect some of these characteristic features. Radar provides valuable information on the meter- to 100-m-scale roughness on Venusian lavas [*Campbell and Campbell*, 1992], but other contributions to radar reflectivity (dielectric constant, emissivity, etc.) make unique interpretation difficult. Hopefully, the high-resolution camera on Mars Global Surveyor [*Malin et al.*, 1992] will provide crucial new meter-scale information after systematic mapping begins in March 1999.

The three planetary lava flows have relatively large length/width aspect ratios (generally, >10:1) that are difficult to reconcile with rapid effusion on a very shallow slope [*Zimbelman*, 1996]. In particular, it seems difficult for a very large extrusion rate, whether from a point source or a linear dike, to produce a flow many times longer than it is wide, especially on a regional slope of ~0.1°. Recently, *Miyamoto and Sasaki* [this issue] carried out numerical simulations of lava flow emplacement which showed that flow width appears to be sensitive to effusion rate for large simple flows; in general, wider flows required a higher effusion rate than narrow flows. From this perspective, the broad width of the proximal phase III Imbrium lavas (Figure 1) may be consistent with relatively large initial effusion similar to that modeled by *Shaw and Swanson* [1970], but no definitive evidence of turbulent flow has yet been demonstrated for terrestrial lava flows. The relatively narrow planform of the distal phase III Imbrium lava and the other planetary flows considered here are not easily accommodated by flood-like effusion. The interaction of flow segments with subtle topographic features, such as in the Strenia Fluctus flows on Venus (Figure 7), also suggest the flows were able to respond to changes in slope of the order of only 0.03°, favoring slow rather than fast effusion. While it is not possible at present to state conclusively that such considerations require modest Hawaii-like effusion rates, it is difficult to reconcile the three planetary flows examined here with the massive effusion rates and turbulent conditions attributed to flood-like emplacement.

6. Summary

Primary conclusions are as follows: (1) The long flows on the Moon and Mars are interpreted here to be simple flows from the lack of multiple flow margins and the presence of a medial channel in their proximal reaches. This observation allows their effusion rate to be estimated using several published relationships involving flow dimensions. (2) The lunar and Martian flows have a wide range of calculated effusion rates, depending on which relationship is used, but the most likely values are ~5 x 10^4 to ~10^5 m^3/s for both flows. (3) The Venus flow displays intermixed flow margins within the flow outline, suggesting it is compound. If erupted at rates typical of tube-fed eruptions on Hawaii, this flow required 494 years. (4) It is helpful to evaluate whether flows are simple or complex prior to estimating effusion rate, particularly when the flows can only be examined with remote sensing data.

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