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Morphologic identification of Venusian lavas

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Abstract. Two independent methods are applied to Venusian lavas. First, fractal properties of 30 lavas are used to identify a'a, pahoehoe and transitional morphologies. Eighteen of these flows are then categorized into these same morphologies based on their radar signal. The techniques produce similar identifications, lending confidence to the fractal identification of those flow margins that could not be studied by the radar technique. Three of these flow margins are of lavas in Mylitta Fluctus, a flood basalt. Our fractal analysis suggests all 3 margins were emplaced as a'a flows, which has implications for the emplacement of large lava plateaux in general.

Introduction

An abundance of evidence indicates that extraterrestrial lavas are generally basaltic; if more silicic flows exist, they are believed to be of limited areal extent (Basaltic Volcanism Study Project, 1981). Specific to Venus, evidence for basaltic composition comes from the Soviet Venera and Vega x-ray fluorescence analyses (Barsukov et al., 1992). The general consensus that Venusian lavas are basaltic has led to speculation on their emplacement. On Earth, high flow rates are associated with channel-fed a'a lavas, whereas lower flow rates tend to produce tube-fed pahoehoe lavas (Peterson and Tilling, 1980) and Venusian lavas would be expected to have similar flow behavior (Head and Wilson, 1986). This work is aimed at better understanding the emplacement of Venusian lavas by identifying a'a and pahoehoe morphologies. Of particular interest is the emplacement of long lavas and flood basalts.

Methodology

Fractal analysis

Our approach is to analyze selected lavas with two independent remote sensing techniques. The first technique, fractal analysis, is described in Bruno et al. (1992, 1994). Briefly, we have found that flow margins of terrestrial basalts are fractal over the range of scales studied (0.125m - 2.4km) provided that they are internally-controlled (i.e., flow margins are shaped by fluid dynamic processes, not by topography). The different styles of emplacement of a'a and pahoehoe flows lead to systematically different flow margin shapes, which can be quantified by the fractal dimension (D). A'a flows generally have lower D ($D \leq 1.09$) than pahoehoe flows ($D \geq 1.13$), and transitional flows tend to have intermediate D.

Using the terrestrial analogy, we perform a fractal analysis on selected Venusian lavas and categorize them into four flow types. Flows that are fractal are interpreted to be internally-controlled basalts. Based on D, these lavas are categorized into a'a, pahoehoe, and transitional morphologies. Non-fractal flows are interpreted to be different from internally-controlled basalts. This category could comprise topographically-controlled basalts (e.g., basalts flowing in pre-existing channels) as well as flows of more evolved compositions.

Radar analysis

Campbell and Campbell (1992) have developed a technique that identifies flows based on their S-band (12.6cm) radar-backscatter signal. A'a flows, having jagged, clinkery surfaces, are systematically rougher than pahoehoe flows at small (≤10's cm) scales, and thus tend to produce a higher backscatter signal at these short wavelengths. Thus, all other factors being equal, a'a flows would appear brighter on radar-backscatter (e.g., Magellan) images than pahoehoe flows.

This technique effectively discriminates between a'a and pahoehoe only when the short-wavelength topography dominates the radar-backscatter return; this occurs at incidence angles (θ) exceeding ~30° (Campbell and Campbell, 1992). At lower θ, the long-wavelength topography significantly contributes to the backscatter signal and this technique cannot be applied. Magellan's Cycle 1 left-looking coverage used $\theta \geq 30°$ at latitudes between 54°N and 34°S; thus lavas located within this band can be categorized as a'a, pahoehoe or transitional. The signal levels corresponding to these flow types vary with θ and therefore latitude.

Comparison between radar and fractal techniques

Our approach is first to analyze only those flows which can be studied by both techniques. We show the two methods produce similar categorizations and thus independently confirm each other. This suggests that the fractal technique is valid and can be applied to identify those flows which cannot be studied with the radar technique. Among those located south of 34°S and hence not suitable for radar analysis are three flow margins of lavas in Mylitta Fluctus, a flow field identified as a flood basalt by Roberts et al. (1992).

Data and Results

We measured the fractal properties of 30 flow margins from Magellan images (75-225m/pix). Flow margins were selected using the criteria of Bruno et al. (1994) and measured using equivalent rod lengths between 140m and 36km. The range of rod lengths used to measure a given margin depends on both the flow margin length and the image scale. We note that there is no gap in scale between the terrestrial and Venusian measurements; in fact, there is more than an order of magnitude overlap in rod lengths. Of these 30 flows, 21 fall within the appropriate latitudinal range for radar analysis. [The remaining 9 are located south of 34°S or north of 54°N.]

Of the 30 flow margins, most (27, or 90%) are fractal over the range of scale measured. Based on the terrestrial analogy, fractal behavior indicates basaltic composition and D can be used to distinguish basaltic flow types (Bruno et al., 1994).

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Table 1. Fractal and Radar Analyses of Venusian Flows

Flow number	Flow location (Magellan image)	Fractal Scale (km)	D	R^2	Fractal Interpretation	Radar Interpretation
V1.	W. of Aphrodite Terra (C100N043)	0.6 - 17.9	1.12	.99	trans	phh/trans
V2.	E. of Atla Regio (C100N215)	3.6 - 35.7	1.15	.90	different	
V3.	E. of Atla Regio (C100N215)	2.3 - 28.3	1.09	.90	different	
V4.	E. of Atla Regio (C100N215)	0.5 - 22.5	1.14	.98	phh	trans/phh
V5.	N. of Phoebe Regio (C100N283)	0.6 - 7.1	1.06	.95	a'a	a'a
V6.	N. of Phoebe Regio (C100N283)	0.6 - 7.1	1.07	.90	different	
V7.	N. of Phoebe Regio (C100N283)	0.6 - 9.0	1.06	.97	a'a	a'a
V8.	N. of Phoebe Regio (C100N283)	0.6 - 9.0	1.10	.97	trans	trans/phh
V9.	N. of Phoebe Regio (C100N283)	0.4 - 10.0	1.09	.95	a'a	a'a
V10.	N. of Phoebe Regio (C100N283)	0.5 - 14.0	1.09	.95	a'a	a'a
V11.	E. of Phoebe Regio (C100N317)	0.6 - 17.9	1.13	.98	phh	phh
V12.	N. of Sif Mons (F25N351)	0.3 - 11.1	1.21	.98	phh	phh
V13.	N. of Sif Mons (F25N351)	0.3 - 5.6	1.15	.95	phh	phh
V14.	N. of Sif Mons (F25N351)	1.8 - 17.9	1.20	.96	phh	phh
V15.	N. of Sif Mons (F25N351)	1.4 - 14.2	1.17	.96	phh	phh
V16.	N. of Sif Mons (F25N351)	2.3 - 28.3	1.09	.97	a'a	phh
V17.	N. of Sif Mons (F25N351)	0.3 - 11.1	1.16	.96	phh	phh
V18.	N. of Gula Mons (F25N357)	1.1 - 28.3	1.22	.96	phh	phh
V19.	N. of Gula Mons (F25N357)	0.3 - 8.9	1.16	.98	phh	phh
V20.	N. of Gula Mons (F25N357)	1.8 - 35.7	1.24	.96	phh	phh
V21.	N. of Gula Mons (F25N357)	0.1 - 7.9	1.23	.99	phh	phh
V22.	N. Sedna Planitia (F55N346)	0.3 - 8.9	1.20	.96	phh	
V23.	Mylitta Fluctus (F55S355)	0.4 - 8.9	1.09	.99	a'a	
V24.	Mylitta Fluctus (F55S355)	0.3 - 11.2	1.09	.97	a'a	
V25.	Mylitta Fluctus (F55S355)	0.4 - 5.6	1.04	.98	a'a	
V26.	SE Lavinia Planitia (F50S356)	0.3 - 22.2	1.20	.98	phh	
V27.	SE Lavinia Planitia (F50S356)	0.3 - 7.0	1.21	.97	phh	
V28.	SE Lavinia Planitia (F50S356)	0.3 - 8.9	1.13	.96	phh	
V29.	SE Lavinia Planitia (F50S356)	0.3 - 11.1	1.18	.98	phh	
V30.	SE Lavinia Planitia (F50S356)	0.3 - 11.1	1.18	.98	phh	

Flows are interpreted as a'a ("a'a"), pahoehoe ("phh"), or transitional ("trans") basalts, or different from internally-controlled basalts ("different"). Scale refers to range of rod lengths used in conducting fractal analysis. No radar analysis was performed on flows V22-30 due to their geographic locations, nor on flows V2, V3 and V6, as they are categorized as "different".

Assuming the terrestrial ranges of D also apply to Venusian lavas, we make the following interpretations, as summarized in Table 1: 8 lavas are a'a (D: 1.04-1.09); 17 are pahoehoe (D: 1.13-1.24), and 2 are transitional (D: 1.10-1.12). The three lavas found to be non-fractal are interpreted to be topographically-controlled basalts.

Following Campbell and Campbell (1992), we examine the radar-backscatter signal of the 18 lavas that are both fractal and located between 54°N and 34°S. Based on the level of this signal, we categorize these lavas into a'a (high), transitional (intermediate), and pahoehoe (low) basalts (Fig. 1).

Table 1 compares the radar and fractal categorizations of these 18 flows. Four are identified by both techniques as a'a and 10 are identified by both techniques as pahoehoe. Three flows are identified by the radar technique as having both transitional and pahoehoe morphologies. The corresponding D (1.10, 1.12, and 1.14) are in the transitional or low end of the pahoehoe range. Only one flow (V16) shows an obvious disagreement between the two techniques. This is excellent evidence that Venusian basalts have the same ranges of D as terrestrial basalts, suggesting we can use D to distinguish a'a, pahoehoe and transitional flows on Venus.

Discussion

Radar and fractal techniques

Most (27 of 30) of the flow margins included in this analysis are fractal, indicating a basaltic composition. The three flows classified as different from internally-controlled basalts could represent more evolved lavas, however we favor their interpretation as topographically-controlled basalts.

The fractal dimensions of these lava flow margins indicate both a'a and pahoehoe flows, as well as morphologies transitional between these endmembers. With one exception, this morphologic categorization based on fractal analysis is similar to that based on the radar technique. The one exception is interpreted as a'a by the fractal technique and pahoehoe by the radar technique. In other words, the flow margin appears relatively unconvoluted (a'a-like) yet the surface appears relatively smooth at small scales (pahoehoe-like). This can be explained as a flow emplaced as a'a and subsequently weathered to form a smoother surface. Alternatively, there may be several flows indistinguishable in the Magellan data. A pahoehoe lava having flowed atop a pre-existing a'a lava without obscuring the original flow margins could explain the discrepancy between the two techniques. However, regardless of the exact explanation for this one exception, clearly there is an excellent agreement between the two techniques.

Pahoehoe formation favored on Venus?

We note that the majority of the Venusian flows measured in this study have pahoehoe-like D (Table 1). Similarly, the radar data of the areas studied by Campbell and Campbell (1992) indicate generally smooth (pahoehoe-like) surfaces. Among the explanations put forth by Campbell and Campbell (1992) is that flows are emplaced as a'a but subsequently weather to pahoehoe. This study disfavors that explanation, as weathering of a'a flows would not be expected to create pa-

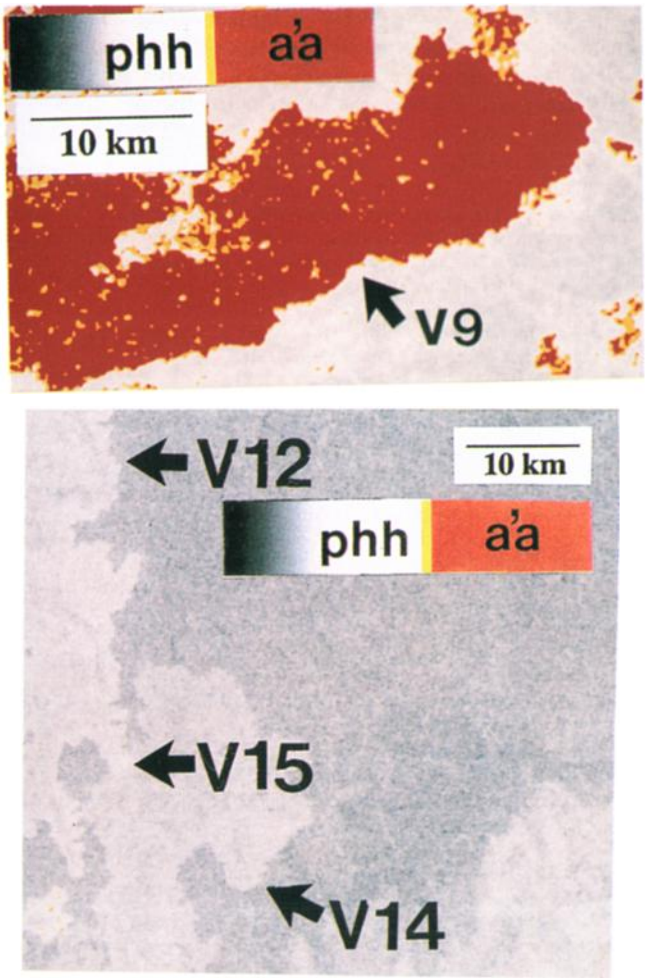

Figure 1. Based on the 12.6cm radar backscatter signal, flows are interpreted as a'a (shown in red), transitional (yellow) and pahoehoe (greyscale). Color bar shows roughness increasing toward the right. Arrows denote flow margins measured with fractal technique; numbers correspond to Table 1. (a) Magellan image C100N283 (resolution 225m/pix). V9 is interpreted as a'a. (b) Magellan image F25N351 (resolution 75m/pix). V12, V14 and V15 are all interpreted as pahoehoe.

hoehoe-like flow margins. Instead, our results suggest flows are emplaced as pahoehoe, likely reflecting modest flow rates.

A priori, it's theoretically difficult to explain why pahoehoe formation would be favored on Venus. In fact, we are not convinced that pahoehoe formation is indeed favored on Venus; this relatively small dataset may well not be representative of the global population of Venusian lavas. However, if more detailed studies using larger databases show that pahoehoe flows are common on Venus -- or on certain volcanoes on Venus -- this has important implications for the sub-volcanic plumbing systems. As summarized by Wilson and Head (1981) and Rowland (1987), an eruption will continue only if magma pressure is sufficient to maintain eruptive conduits, and magma flux is sufficient to replenish heat lost through the cooling of country rocks. Otherwise, the conduit closes and/or the dike freezes, and the eruption stops. The low magma pressures associated with eruptions of pahoehoe lava are insufficient to keep eruptive conduits open; the presence of pahoehoe lavas indicates a pre-established connection between the magma chamber and the planetary surface. Perhaps, the higher shallow crustal temperatures on Venus retard magma freezing, thereby keeping dikes fluid longer and allowing them to become mechanically-stable conduits. If the dikes remain fluid for long after the eruption stops, they can be later re-used by subsequent low-magma-flux eruptions.

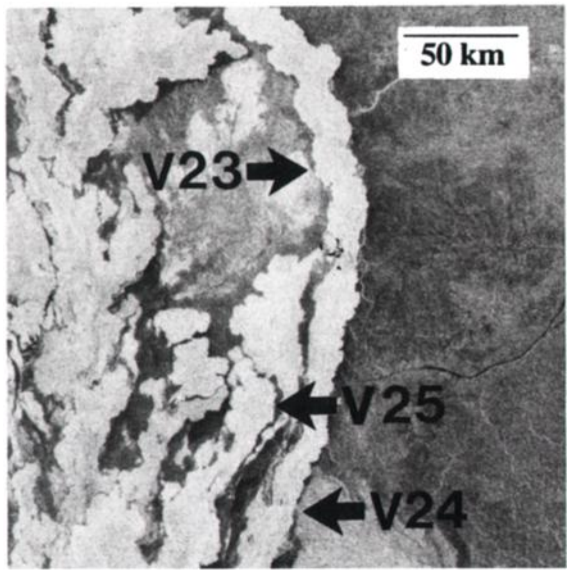

Figure 2. Magellan image F55S355 (resolution 75m/pix) showing long lavas of Mylitta Fluctus flow field.

Long lava flows

As part of this fractal analysis, we studied three flow margins of lavas in Mylitta Fluctus (Fig. 2). In terms of area, volume and thickness, Mylitta Fluctus is comparable to the Columbia River flood basalt province (Table 2). The three measured margins, all found to have a'a-like D, have lengths of ~100-200km, fairly uniform widths of ~20-30km and estimated thicknesses of ~10-30m (Roberts et al., 1992).

There has been much debate on the emplacement of long lavas. Based on terrestrial data, Walker (1973) has argued that long flows are emplaced at high effusion rates. However, Malin's (1980) study of Hawaiian lavas revealed a poor correlation between effusion rate and flow length. Pinkerton and Wilson (1988, 1992) examined the lava flows included in the two datasets and found that Walker's relationship describes cooling-limited channel-fed flows (i.e., Walker's dataset)-- not volume-limited or tube-fed flows. Pinkerton and Wilson's (1992) reanalysis of Malin's data revealed that flows shorter than predicted by Walker's relationship were immature volume-limited flows, whereas flows longer than predicted were tube-fed. As lava tubes significantly inhibit radiative heat losses from the flow surface, flows can travel much greater distances before cooling.

Table 2. Comparison of Flood Basalt Provinces

Flow Field (References)	Area (km^3)	Volume (km^3)	Thickness (m)
Columbia River (Tolan et al., 1989; Reidel et al., 1989)			
Entire Flow Field	$1\text{-}2 \times 10^5$	$1\text{-}2 \times 10^5$	10^3
Individual Flows	$1\text{-}2 \times 10^5$	$10^2 - 10^3$	~3 - >100
Mylitta Fluctus (Roberts et al., 1992)			
Entire Flow Field	3×10^5	2×10^4	250 - 400 (?)
Individual Flows	$\leq 1 \times 10^5$	$\leq 2 \times 10^4$	10 - 30 (?)

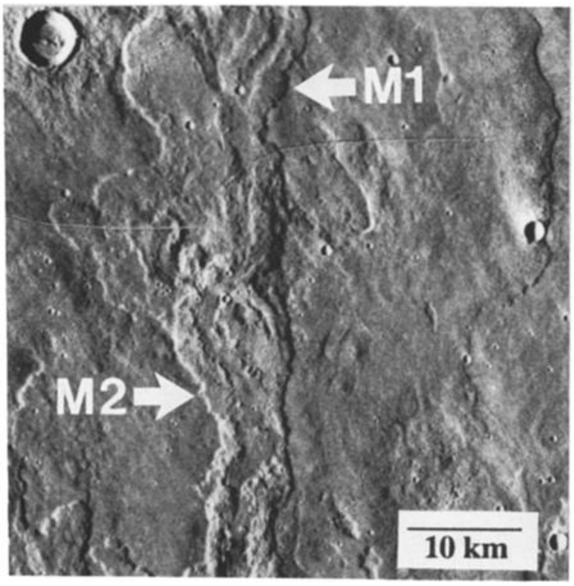

Figure 3. Photomosaic of Viking Orbiter frames 651A07-12 (resolution 52m/pix), showing long lavas in Elysium Planitia, Mars. (After Mouginis-Mark, 1985.)

Thus two theories are offered to explain the long lavas of Mylitta Fluctus (and other flood basalts): (1) channel-fed a'a lavas associated with unusually high effusion rates or (2) tube-fed pahoehoe lavas, generated by modest emplacement rates over unusually long eruption durations. Fractal analysis of the three margins studied revealed a'a-like D, favoring the former explanation and suggesting that at least this episode of Mylitta Fluctus was emplaced at high flow rates.

For comparison, we also performed a fractal analysis on morphologically-similar lavas in Elysium Planitia, Mars (Fig. 3). Like the Mylitta Fluctus lavas, these flows are long (~100-200km), narrow (~10km), and have fairly uniform widths (Mouginis-Mark, 1992). Recent photoclinometric measurements yielded average flow thicknesses of ~30-50km (M. Tatsumura, University of Hawaii, unpublished data, 1994). Fractal dimensions of these flow margins were 1.04 and 1.08, again indicating a'a morphologies (Bruno, 1994).

These a'a-like D indicate that these long lava flows are emplaced in open channels, probably at high flow rates. Even if an underground tube system is present, as suggested by Mouginis-Mark (1992), their emplacement is vastly different from pahoehoe emplacement. The low D indicate the absence of the branching tube systems that characterize terrestrial pahoehoe flow fields and result in a convoluted flow margin (Bruno et al., 1994; Taylor, 1992). Instead, most of the lava appears to be transported along one main pathway, resulting in a flow of uniform width with a linear flow margin.

Conclusions

Most (27 of 30) of the Venusian lavas included in this study are fractal, indicating a basaltic composition, with fractal dimensions similar to the terrestrial range. Combining the terrestrial and Venusian data, the fractal nature of lava flow outlines holds over five orders of magnitude in scale: from 10cm to 36km. Using fractal dimension, we have remotely identified Venusian flows as a'a, pahoehoe and transitional basalts, and this identification has been independently confirmed by a radar technique. Such flow type identification can lead to a better understanding of planetary eruption rates and eruption styles. Our fractal analysis of Mylitta Fluctus suggests that this flood basalt province has been emplaced as a'a flows.

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