Viscosity of venusian lava flows: constraints from fractal dimension and chemical composition

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INTRODUCTION

Fractal analysis can be used to quantify the morphology of lava flow margins. Work by *Bruno* et al. [1992] and *Bruno and Taylor* [1995] has demonstrated that terrestrial and venusian flows of basaltic composition are fractal and that fractal dimension can be used to categorize flows as a'a, pahoehoe, or transitional. One determinant of flow type and rheology, which are reflected in flow margin, is lava viscosity [*Bruno* et al. 1994]. Viscosity is dependent upon chemical composition, which at several sites on Venus has been measured by Venera and Vega landers. This study attempts to associate the fractal geometry of venusian lava flows with chemical data derived from lander measurements and terrestrial analogs. We hypothesize that a low-viscosity lava will produce a more sinuous flow margin, thus having a greater fractal dimension than a viscous lava. We endeavor to develop fractal analysis as a tool for use in the determination of lava viscosity and composition where lander data are unavailable.

METHODS

Radar images taken by the Magellan orbiter are used to find and analyze the lava flows. Because flows are self-similar over several orders of magnitude [*Bruno and Taylor*, 1995], we are able to use both F-MIDRS (Full-Resolution Mosaicked Image Data Records) with a resolution of 75 meters per pixel, and C1-MIDRS (Compressed-Once Mosaicked Image Data Records) with a resolution of 225 meters per pixel in our analysis. Our sample contains 72 flow margins, all of which have slopes of less than one degree and are free of cratering and tectonic or volcanic deformation. Thirteen of the flow margins are located within the 300 km landing ellipses of the Vega 2, Venera 8, Venera 13, and Venera 14 landers. We prepared three independent traces of each flow margin in the sample.

Each flow margin trace was imported into Fractal Dimension Calculator version 1.0 [*Bourke*, 1993] for analysis. This software program uses a box-counting algorithm to analyze fractal nature of flow margins. This method overlays a series of grids composed of squares with uniform side length s over the flow front trace. The relationship $L=N(s)*s$ approximates the length L of the flow margin trace, where $N(s)$ is the number of boxes of side length s needed to cover the trace. As s decreases, $N(s)$ increases according to a power law and L becomes an increasingly more accurate approximation of the length of the curve [*Pruess*, 1995]. The power that reflects the nonlinear growth in $N(s)$ is the fractal dimension D of the curve. As D increases, the sinuosity or the amount of a plane filled by the flow margin increases. Venusian lava flows have been shown to have D between 1.04 and 1.24 [*Bruno and Taylor*, 1995].

We specified ten box sizes covering three orders of magnitude. The slope of a modified Richardson plot, showing log $[N(s)]$ versus log $[1/s]$ is our approximation of D. The mean D of three traces of each flow margin is adopted as each flow's fractal dimension.

To estimate the original viscosity of the landing site rock we used the procedure outlined in detail in *Shaw* [1972]. This viscosity estimation technique employs rock chemistry, water weight percent, the temperature of the original melt, and assumes no exsolution of volatiles. Rock chemistry is given by the weight percent major element evidence we have found, we believe that this area is a result of volcanism, but the exact type is not clear. Further work to constrain the relative timing of the sediment sheet and domes will help discriminate between the two possibilities.

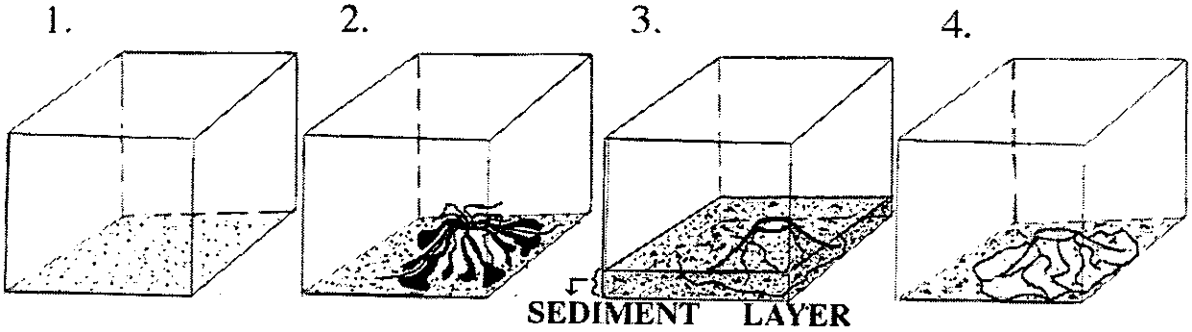

Figure 2a. Interpreted sequence of events for Cinder Cone origin:
(1) Original surface; (2) Cone formation and eruption on surface; (3) Sediment sheet burying cone; (4) Partial exhumation of cone.

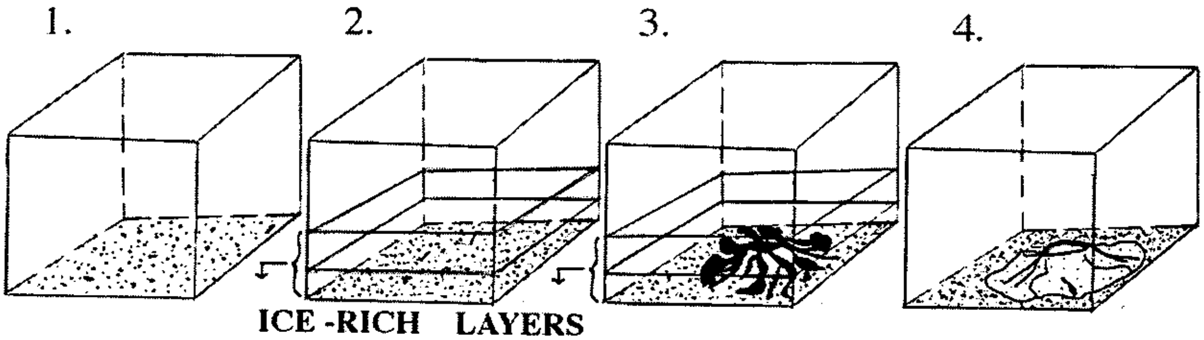

Figure 2b. Interpreted sequence of events for Table Mountain origin:
(1) Original surface; (2) Emplacement of ice-rich sediments; (3) Sub-surface eruption; (4) Partial exhumation of cone.

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data provided by Vega 2, Venera 13, and Venera 14. As no major element data exist for the Venera 8 site, we inferred a high-K basaltic chemistry from Th-U-K data [*Basilevsky*, 1997]. From this chemistry, we established four terrestrial analogs as possible Venera 8 materials: leucitite, nepheline basalt, shoshonite, and subalkaline basalt. The major element chemistry of these analogs is used in place of lander data. Water weight percent of the lava is estimated from the K_2O weight percent determined by the landers [*Johnson* et al., 1994]. *Johnson* et al. [1994] show a range of K_2O to water ratios, from 1:4 to 1:1, for K_2O values of up to 0.8 weight percent. We use the more cautious estimate of a 1:1 relationship in this study. The last component of the *Shaw* [1972] procedure is temperature; as venusian lavas are considered to be generally basaltic [*Bruno and Taylor*, 1995], we defined the possible viscosity range of the lava at each site by considering the liquidus and solidus of basalt as two end-member temperatures [*Shaw*, 1972].

RESULTS

The fractal dimension of flow margins in our sample ranges from 1.04 to 1.19. Using the categories of flow type and associated fractal dimension outlined by *Bruno and Taylor* [1995], we find that 35 of the 72 flows are a'a, having $D \leq 1.09$, while 17 have $D \geq 1.13$ and are pahoehoe. Twenty flows fall in the transitional area between these categories. We find no correlation between fractal dimension and altitude or geographic location.

Although the exact flow on which a lander performed a chemical analysis cannot be known, we assume that all lava within each landing ellipse is of a composition similar to that measured by the lander. We thus take the mean D of all flow margins within the ellipse as the characteristic D of that landing site. We find the range of landing site fractal dimensions to be dichotomous (Figure 1). The mean fractal dimension of flow margins within the Venera 14 landing ellipse is 1.06, and is 1.07 within the Vega 2 ellipse. Within the Venera 8 landing ellipse the mean is 1.12, and is 1.16 within the Venera 13 ellipse. The Venera 14 and Vega 2 fractal dimensions suggest a'a lavas, while the higher D values for Venera 8 and 13 suggest pahoehoe or transitional lavas.

We also find two distinct viscosity ranges (Figure 2). At 25% partial melt, the viscosity of the Venera 14 sample is calculated to be 616 poise, the Vega 2 sample to be 422 poise, and the Venera 13 sample to be 10 poise. The analogs of the Venera 8 sample have a range of viscosities: leucitite is 12 poise, nepheline syenite is 73 poise, shoshonite is 220 poise, and subalkaline basalt is 703 poise.

DISCUSSION

Viscosity is a measure of a fluid's internal resistance to flow. Factors that affect viscosity include temperature, pressure, and chemical composition. For this study, we assume a range of temperatures consistent with that of a terrestrial basalt melt. Atmospheric pressure on Venus is generally 90 to 100 bar, and our results indicate that there is no clear correlation between fractal dimension and elevation or atmospheric pressure. Major element chemical composition is known for some of the Venera and Vega sites, and we attempt to predict relative viscosities based on the weight percent of major oxides and probable water content.

Since we cannot predict viscosities for locations where there are no chemical data, we use fractal dimension as a tool to help quantify, at least in a relative sense, the viscosities of lava flows. The processes that create fractal flow margins can be hindered by high viscosity or yield strength, among other controls, creating a less sinuous flow margin. *Bruno* et al. [1994] demonstrated that highly silicic and viscous flows such as andesite, dacite, and rhyolite are not typically fractal. Basaltic lavas, which have a lower viscosity and yield strength, are not only fractal, but their fractal dimension increases with fluidity. A less viscous lava can create more lobes and fingers, reflected by a more sinuous flow margin.

There is a clear relationship between our estimated viscosity and fractal dimension values for flow margins within a landing ellipse (Figure 3). The viscosity of the Vega 2 site is slightly lower than that of Venera 14, and the average fractal dimension of the flows in the Vega 2 ellipse are slightly higher than those in the Venera 14 ellipse. The Venera 13 site's viscosity is lower than both of these, and flows within the Venera 13 ellipses have higher fractal dimensions than those in the Vega 2 or Venera 14 sites. Fractal dimension thus correlates with low viscosity and higher K_2O content.

We believe that the two low-viscosity Venera 8 analogs (leucitite and nepheline syenite) are the most probable, as prior research has indicated that the Venera 8 viscosity is similar to that for Venera 13 [*Basilevsky*, 1997]. In support of the relationship between the Venera 8 and Venera 13 lavas, we find that two flow margins within the Venera 8 ellipse have high fractal dimensions (1.16 and 1.18) similar to the Venera 13 flow margins (D=1.16). However, a viscous pancake dome with D=1.04 and two flows with transitional fractal dimensions (1.10

and 1.12) are also located within the Venera 8 ellipse, which may support the high viscosity analogs at the expense of eliminating the similarity with the Venera 13 flows suggested by *Basilevsky* [1997]. Based on our calculations, we categorize the Vega 2 and Venera 14 lavas as similarly viscous, as their viscosities are an order of magnitude larger than those in the category comprised of Venera 13 and the likely Venera 8 analogs.

Our study thus indicates that Venera 8 and 13 sites are characterized by pahoehoe lavas (high *D*) and a low calculated viscosity, while the Vega 2 and Venera 14 sites have a'a lavas (low *D*) and a high calculated viscosity. The hypothesis that high fractal dimension indicates a low viscosity is supported by these data. Furthermore, high K_2O and associated water content is reflected in high fractal dimension. Less viscous lava produces a more sinuous flow margin, resulting in a high fractal dimension.

The results obtained for the 13 flow margins within a landing ellipse allow us to theorize about the composition of the 59 flows in the sample located in areas where chemical data are unavailable. Approximately half of these flows have a fractal dimension of 1.09 or less. From our analysis, this implies a high-viscosity, low K_2O mafic rock similar to a tholeiitic basalt. As a majority of terrestrial rock is tholeiitic, it is not surprising that such a high amount of such rock would be found on Venus. Nearly one-quarter of the flow margins in the global sample have $D \geq 1.13$. These flows may be similar in composition to the non-tholeiitic Venera 13 alkaline basalt flows (D=1.16), having relatively high K_2O weight percent (~4%) and correspondingly high water content.

CONCLUSIONS

1. We find a range of fractal dimensions for venusian lava flow margins from 1.04 to 1.19.
2. There is no apparent correlation between fractal dimension and altitude or geographic location.
3. There is a correlation between fractal dimension and viscosity. The higher the fractal dimension, the less viscous the flow. The chemical data from the Vega 2, Venera 13, and Venera 14 landing sites can be used to calculate viscosity. The Vega 2 and Venera 14 viscosities are similarly high, and the fractal dimensions of the flows in these ellipses are low. The Venera 13 viscosity is much lower, and lava flows within the ellipse have a relatively high fractal dimension.
4. Since there is no major element chemistry available from the Venera 8 site, we infer possible terrestrial analogs based on known K, Th, and U content. A wide range of fractal dimensions are found at the Venera 8 site, so we cannot assign an average relative viscosity to the area. Therefore, we cannot use the fractal dimension to infer a viscosity and likely chemical composition. Each of the four terrestrial analogs we propose fits the observed *D* range.
5. Based on our preliminary results, a low fractal dimension may correspond to a tholeiite-like basalt. Our sample suggests that about 50% of venusian lava flows are thoeiilitic, with a fractal dimension of 1.04-1.09. This is a reasonable inference, as a majority of rocks on Earth have a similar composition. Nearly 20% of the flows studied have a *D* of 1.13 or greater.
6. Future studies: Additional flows should be studied within the ellipses of the four landers to determine if our sampling was representative. Also, flows within the ellipses of the other Russian landers, Vega 1, Venera 9, and Venera 10 should be studied. These landers provide K, Th, and U content, like Venera 8, and analogs can be used to calculate viscosity. The viscosity dependence on K_2O may then be more clearly seen. The impact of bubbles on the viscosity of a flow also needs to be considered at the surface pressure of Venus.

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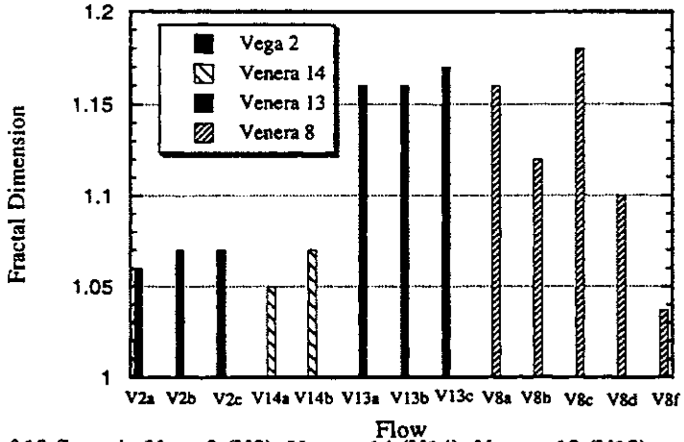

Figure 1. Fractal dimension (D) of 13 flows in Vega 2 (V2), Venera 14 (V14), Venera 13 (V13), and Venera 8 (V8) landing ellipses.

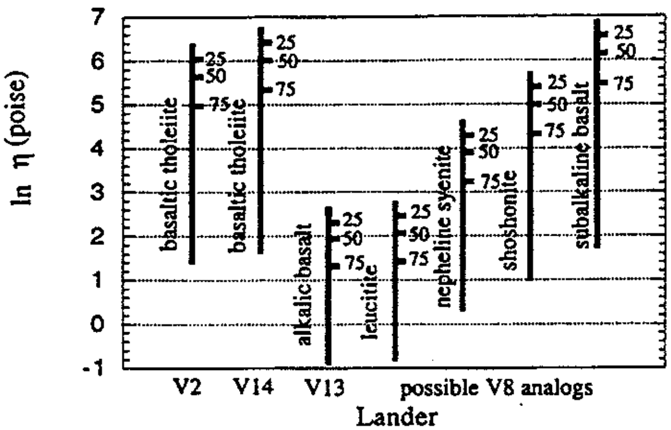

Figure 2. ln η at landing sites. The Venera 2 (V2), Venera 14 (V14), and Venera 13 (V13) viscosities were calculated based on major element chemistry data collected by the landers [*Kargel, 1993*]. V2 and V14 are both considered basaltic tholeiities based on their composition, while the V13 is considered an alkalic basalt. The leucitite, nepheline syenite, shoshonite, and subalkaline basalt are possible analogs to the Venera 8 (V8) landing site composition. The vertical bars represent a range of possible viscosities at temperatures ranging from the basaltic liquidus to solidus. The 25, 50, and 75 markers indicate the viscosity of the melt at 25% partial melt, 50% partial melt, and 75% partial melt.

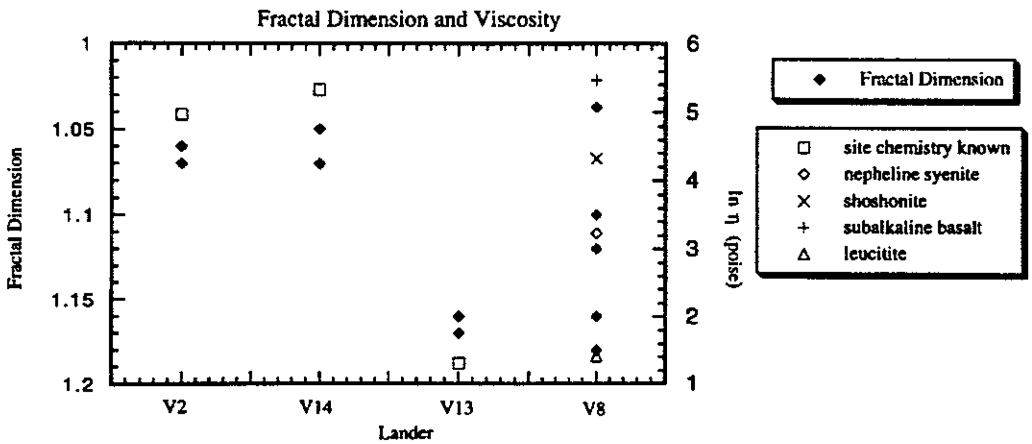

Figure 3. Plot of ln η of landing sites superimposed on a plot of the fractal dimension of the flows within the landing ellipses. Note that axis y2, η, is reversed. There is an apparent inverse relationship at the Vega 2, Venera 14, and Venera 13 sites. See text for explanation of the four possible Venera 8 analogs.

Distribution and morphology of the intermediate volcanoes on Venus as a function of altitude

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Introduction:

Volcanoes on Venus are divided into three main groups based on size. Large volcanoes have an average diameter greater than 100 km, small volcanoes are less than 20 km in diameter (*Head et al.*, 1992). Intermediate volcanoes, therefore, are all volcanoes whose average diameters are between 20 km and 100 km in diameter (*Head et al.*, 1992). This paper focuses on the intermediate volcanoes and their distribution based on altitude and morphology.

Morphologically, the intermediate volcanoes are divided into four main categories. These are steep-sided domes, ticks, anemones and a miscellaneous category including volcanoes morphologically similar to large or small volcanoes, which are in the size range of intermediate volcanoes (*Head et al.*, 1992). Steep-sided domes are broad flat-topped structures with steep sloping sides (Fig. 1). Ticks are characterizes by a raised rim encompassing a flat or bowl-shaped central area, and a series of radiating ridges (Fig. 2). Anemones are characterized by radar bright, petal-like flows radiating from a central depression (Fig. 3). This paper will only examine the three main morphologies of intermediate volcanoes and excludes the miscellaneous group due to the variability in their morphology and, presumably, their origin.

The theory of neutral buoyancy states that the thick venusian atmosphere makes nucleation of volatiles extremely difficult at lower elevations (<6051 km; *Head and Wilson*, 1992). Thus, extruded lavas will be more dense in the lower elevations, forming extensive dense volcanic plains. As the altitude increases and the atmosphere thins, the exsolution of volatiles becomes easier causing flows to be less dense (*Head and Wilson*, 1992). As lavas of certain densities build up at certain elevations (as a function of altitude), a rising magma would eventually reach a zone of neutral buoyancy, which is an altitude where its density is the same as the surrounding rock, where it would remain (*Head and Wilson*, 1992). The existence of such a zone would have a dramatic effect on the distribution of volcanic edifices.

In the lower intermediate altitudes (lower part of the 6051-6053 km range) a magma reservoir formed at a zone of neutral buoyancy will be quite shallow because of the high atmospheric pressure (*Head and Wilson*, 1992). As elevation increases, the relative depth from the surface of the magma reservoir increases (*Head and Wilson*, 1992). This increase in depth allows the magma reservoirs to increase in size, which in turn can produce larger edifices (*Wilson et al.*, 1992). At even higher elevations, the depth of the reservoir will favor an increased intrusion to extrusion ratio, thereby generating dike swarms (*Grosfils and Head*, 1995). An altitude dependence of various volcanoes would support this theory.

The purpose of this study is to determine if the altitude distribution of the intermediate volcanoes as a whole follows the prediction of the theory of neutral buoyancy. Furthermore, the distribution of the individual morphologies of intermediate volcanoes will be examined to determine of their distributions follow predictions of the neutral buoyancy theory.

Methods:

We used the Magellan Global Topography Data Record to find basal altitude for the ticks and anemones. Basal altitudes for the steep-sided domes were taken from *Pavri et al.* 1992. We determined basal altitudes for ticks and anemones by finding the altitude at four points adjacent