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

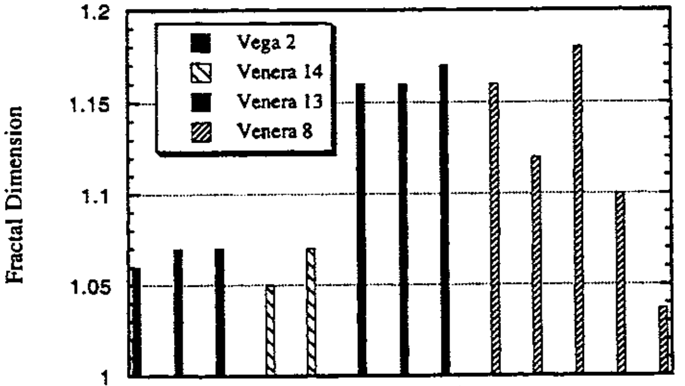

Figure 1. Fractal dimension (D) of 13 flows in Vega 2 (V2), Venera 14 (V14), Venera 13 (V13), and Venera 8 (V8) landing ellipses.

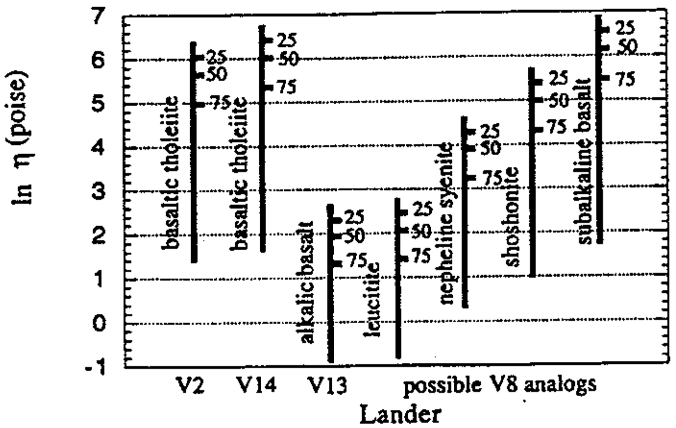

Figure 2. ln η at landing sites. The Venera 2 (V2), Venera 14 (V14), and Venera 13 (V13) viscosities were calculated based on major element chemistry data collected by the landers [*Kargel, 1993*]. V2 and V14 are both considered basaltic tholeiities based on their composition, while the V13 is considered 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.

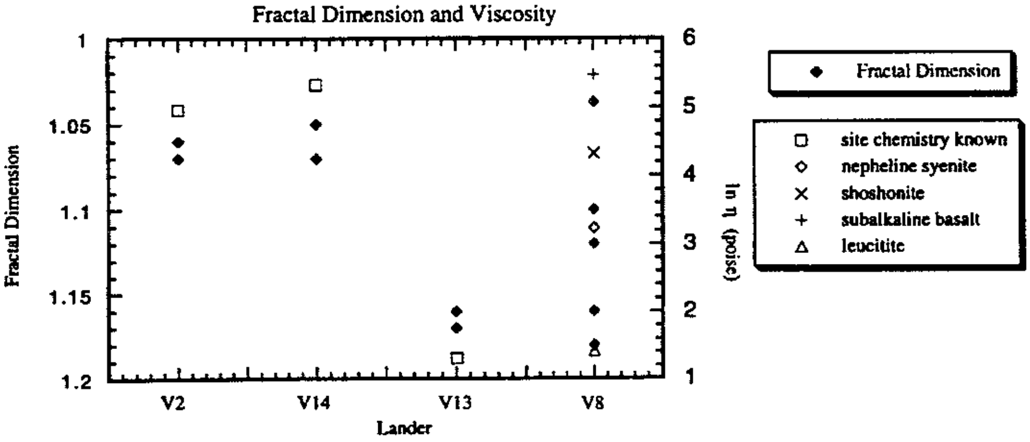

Figure 3. Plot of ln η of landing sites superimposed on a plot of the fractal dimension of the flows within the landing ellipses. Note that axis y2, η, is reversed. There is an apparent inverse relationship at the Vega 2, Venera 14, and Venera 13 sites. See text for explanation of the four possible Venera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

to the feature, and calculating the average elevation. This method was chosen to emulate the methods of *Pavri et al.* 1992 so the data could be most accurately compared.

We also calculated a random distribution of features for statistical comparison. Such a distribution has the number of features at a given altitude as a direct proportion of the percentage of the planet's surface at the same altitude.

Results:

The intermediate volcano population, as a whole, shows a preference for formation at intermediate altitudes (6051-6053 km), though some features form at higher elevations (Fig. 4). The mean altitude for the intermediate volcanoes is 6051.6 km. A chi-square test shows, with 85% certainty, that the intermediate volcanoes are statistically different than the predicted random population. Examining the intermediate volcanoes by morphology reveals that the steep-sided domes have a mean elevation of 6051.8 km (Fig. 5). This population is centered at, or just below, the mean planetary radius (6051.8 km). A chi-square test shows with 99% confidence that the steep-sided domes are different from a random population. The tick population has a mean altitude of 6051.7 km and a chi-square test shows with 99% confidence that the ticks are different from a randomly distributed population (Fig. 6). The mean altitude for the anemones is 6052.6 km, far above ticks or steep-sided domes (Fig 7). Again, there is a 99% confidence that the anemone population is different from a random population. This indicated that the overall population is not distributed randomly with respect to altitude.

Discussion:

Distribution of Intermediate volcanoes:

Previous studies have discussed the implications for neutral buoyancy theory for other volcanic features on Venus. *Grosfils and Head* (1995) found that radiating dike swarms form preferentially at intermediate elevations (6051 to 6053 km), with grater than 99% confidence. The distribution of large volcanoes also shows a tendency for altitude dependence (*Keddie and Head*, 1994). A chi-square test of the large volcanoes showed, with a greater than 90% confidence, a statistical preference for formation of these features in the mid-altitudes (6051 to 6053 km) over the lower altitudes (<6051 km; *Keddie and Head*, 1994). The large volcanoes form at a lower mean altitude than the dike swarms, indicating a general increase in intrusive to extrusive ratios as altitude increases, following predictions of the neutral buoyancy theory.

In the same manner, we evaluated the altitude distribution of the intermediate volcanoes as a single population. The mean altitude for the intermediate volcanoes is 6051.6 km. A chi-square test reveals that the intermediate volcanoes and the predicted random distribution are different with a greater than 85% confidence.

There are two possible interpretations for this relatively low confidence level. It could indicate that the intermediate volcanoes are a statistically random population. This conclusion does not support neutral buoyancy theory, which predicts a relative paucity of volcanic edifices at high and low altitudes. A second interpretation is the intermediate volcanoes are altitude dependent, but that the distribution curve is similar enough to the random distribution that the two data sets are indistinguishable. When examining altitude distributions of the large volcanoes and dike swarms, we find that the population curve has the same general shape as the predicted random population. However, these populations are centered at higher altitudes, resulting in a statistical difference. The intermediate volcanoes plot also has the same general shape as the random population, but the offset may be so small that a strong statistical distinction between the populations cannot be made.

A general trend seems clear when comparing the intermediate volcanoes, large volcanoes and dike swarms. The population curve for intermediate volcanoes is slightly skewed to the lower end of the intermediate altitudes (6051 to 6053 km). The large volcanoes trend towards the central intermediate altitudes, followed by the dike swarms which trend towards the upper intermediate altitudes. This overall pattern including the intermediate volcanoes suggests that neutral buoyancy plays a crucial role in the formation of volcanic edifices on Venus.

Individual morphologies:

The individual morphologies of the intermediate volcanoes also show altitude preferences. With greater than 99% certainty, all three populations are non-randomly distributed. The steep-sided dome population used in this study consisted of 141 features, and has the lowest mean elevation of 6051.5 km. The distribution follows the same basic bell shape as the random distribution, but is skewed towards the lower intermediate elevations. This suggests an altitude dependence consistent with Neutral buoyancy. The tick population (39 features) also shows a bell shape, and is centered at 6051.7 km. No ticks occur in the high elevations (>6053 km.), and few occur in the lower elevations (<6051 km.). The ticks also show altitude dependence in their distribution, which is consistent with neutral buoyancy predictions.

The anemone distribution, however, trends opposite to predictions based on neutral buoyancy. The theory predicts that the number of intermediate edifices should decrease in the higher elevations. However, of the 23 anemones in the study, over half (12 volcanoes) occur above the 6053 km demarcation. One explanation for this is the existence of an anemone "field" which accounts for nine anemones occurring in the high elevations (>6053 km.). It is possible that the size of this field in relation to the overall population represents a statistical aberration which explains the distribution of the anemones. Nevertheless, it appears that the anemone distribution does not conform to predictions based on the theory of neutral buoyancy.

Conclusions:

Our analysis of the altitude distribution of the intermediate volcanoes suggests that altitude is an important factor in their distribution. Our observations, in conjunction with those of previous studies (*Keddie and Head*, 1994, and *Grosfils and Head,* 1995), show a general trend for volcanic edifices on Venus that follows predictions based on the theory of neutral buoyancy. As an individual population, steep-sided domes occur in the intermediate elevations. Ticks also occur in intermediate elevations, though at higher elevations than the steep-sided domes. The anemones occur at even higher elevations, with half of the population occurring in the high elevations (>6053 km).

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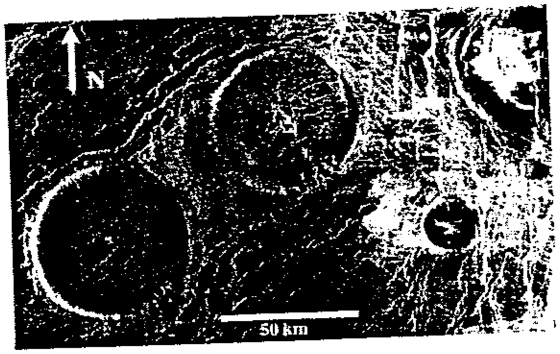

Figure 1. A steep-sided dome, located at (12°N, 8°E).

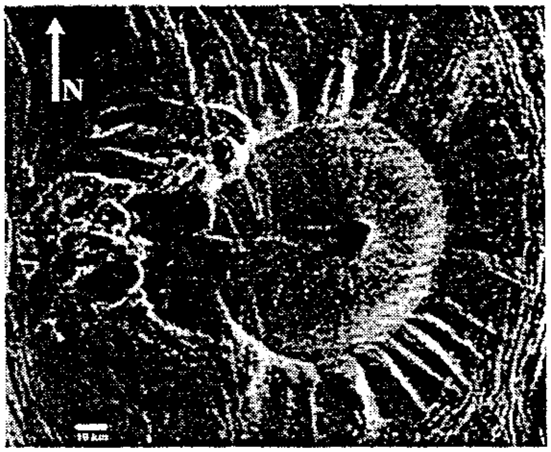

Figure 2. A tick, located at (18°N, 6°E).

Figure 3. An anemone, located at (15°S, 197°E).

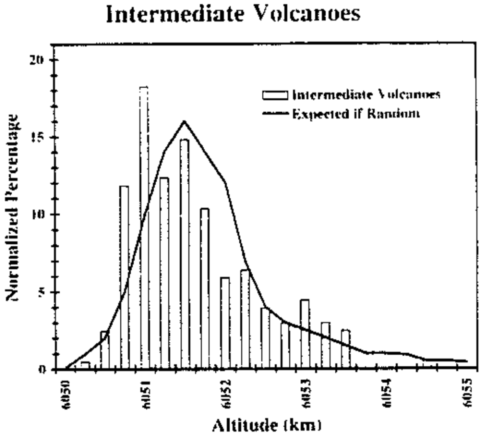

Figure 4. Graph of the distribution of the intermediate volcanoes as a function of altitude. The mean is 6051.6 km.

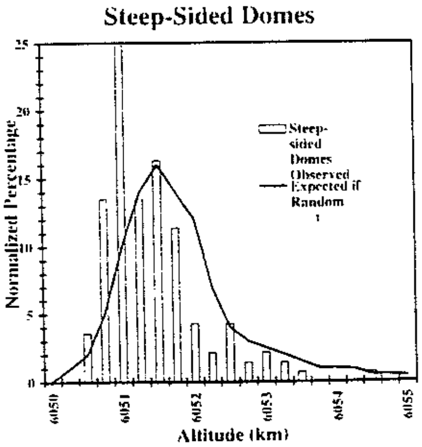

Figure 5. Graph of the distribution of steep-side domes as a function of altitude. The mean is 6051.8 km.

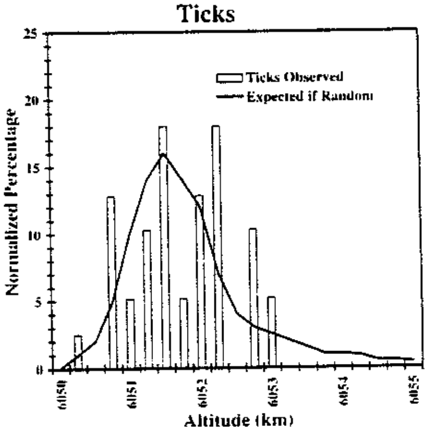

Figure 6. Graph of the distribution of tick: as a function of altitude. The mean is 6051.7 km.

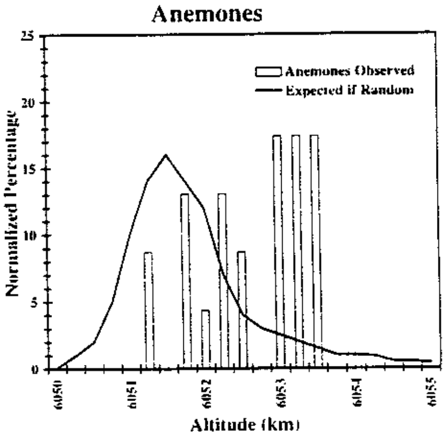

Figure 7. Graph of the distribution of anemones as a function of altitude. The mean is 6052.6 km.

The origin and modification of a trough in the Nili Fossae, Mars

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INTRODUCTION

The Nili Fossae, centered at 23° N and 282° W, is a series of curved troughs located to the northeast of the Syrtis Major shield volcano and to the northwest of the Isidis impact basin (Figure 1). The largest trough in the Nili Fossae measures 550 km in length and varies between 10 and 30 km in width. It begins to the south in Hesperian age volcanic flows from Syrtis Major, extends through Noachian aged cratered units, and ends near the North-South dichotomy, a division between the older cratered highlands in the southern hemisphere and the younger, smoother lowlands to the north. The trough has scarp-like walls, a smooth floor, and curves gently, approximately concentric to the Isidis Basin. The trough has been interpreted by various authors in large scale regional maps as a trough, a fracture, and a graben (Greenley and Guest, 1987; Spitzer, 1980; Craddock, 1994). However, its smooth, flat floor, the development of tributaries along the edge of the trough, and its large size in relation to other tectonic features in the area suggest at least a more complex history, if not a different origin. Craddock (1994) suggested that the Nili Fossae may be related to the impact event which created the Isidis Basin during the late Noachian (~4.2 Ga). The purpose of this study was to examine in detail this largest trough in the Nili Fossae region to determine its origin and subsequent modification.

METHODS

To determine the processes which had created and modified the trough, we mapped the area with Viking 1 and 2 images. We used images with a resolution of 0.087 - 0.140 km/pixel. Images were viewed using Photoshop and NIH Image software. Mapping allowed us to identify geomorphological features which may indicate which processes had been involved in the formation and modification of the trough. To further test for a tectonic origin, we measured the height of the western wall of the trough to compare it to the expected displacement pattern of a graben. The height of the wall was measured at regular intervals along the trough using a shadow method (Yingst and Head, 1997). We also compared the orientations of the trough and the tributaries to other tectonic features in the region.

RESULTS

Mapping. During mapping, we observed a number of features in the trough. The trough itself has scarp-like walls and a smooth, flat floor relative to the surrounding cratered highlands. The floor of the trough is not featureless however. Some channels and lineaments are present in the floor of the trough. The channels on the floor of the trough typically run sub-parallel to the direction of the trough. Lineaments are typically found parallel or perpendicular to the trough walls. Lineaments sometimes appear to define the boundaries of lobate flows within the floor of the trough.

Wall height. Although wall height is variable along the length of the trough, measurements of the wall height seem to suggest a pattern. The wall height generally seems to increase from the northern end of the trough to the southern end. Wall height is 0 at either end because this is where it merges with the surrounding terrain. Due to the shadow measurement method we used, the measured heights of the wall are not precise as absolute values, but are relevant in relation to each other.

Regional tectonics. The fractures near the trough provide a basis for establishing a regional tectonic pattern. We measured the orientation of 14 fractures around the trough and plotted them on a rose diagram. The fractures occur in two distinct sets. The primary set is oriented at 30°-40° and the secondary set is oriented at 320°-330°. The orientation of the trough was measured at 50 km intervals to compare it with this regional tectonic pattern. The trough has an orientation similar to the primary set of fractures, 30°-50° (Figure 2). The orientation of