ESTIMATES OF THE TOTAL NUMBER OF VOLCANOES ON VENUS.

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Introduction: Radar imagery collected by NASA's Magellan spacecraft enabled the recognition and classification of volcanic features and structures across Venus far beyond the scope of earlier missions [e.g., 1,2]. These Magellan data revealed a planetary surface covered in volcanic edifices of a range of sizes, but the relatively low resolution (75 m/px) of the Magellan SAR (synthetic-aperture radar) FMAP (full-resolution radar map) left- and right-look global mosaics [3] prevents the accurate and consistent delineation of edifices <5 km in diameter. Here, we utilize our previously developed global catalog of volcanic edifices on Venus (**Figure 1**) [4] that contains ~85,000 features, but in which only that population of volcanoes down to 5 km in diameter is complete, to estimate the total number of volcanoes 1–5 km in diameter on Venus—and thus estimate the total number of *all* volcanoes ≥1 km in diameter across the planet. Volcanoes <5 km in diameter represent the most common volcanic feature on the surface of Venus, and the quantification of their number will shed light on the global rates of resurfacing and magma production, leading to a better understanding of volcanic processes on Venus generally.

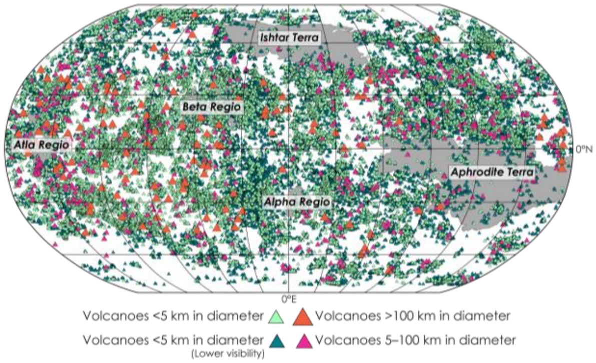

Figure 1: Our completed global survey of volcanic edifices and on Venus [4]. The outlines of major physiographic features are shown in grey for geographic context. The map is in Robinson projection, centered at 0°E.

Mixture Modeling: Previous authors found that both exponential and power-law distributions offer acceptable fits for volcano diameter–frequency distributions on Venus [5,6]. Our global catalog includes the digitized outlines of 848 volcanoes ≥5 km in diameter and the *point* locations of 84,172 volcanoes <5 km in diameter [4]. Based on the distribution of volcano diameter values for all edifices >5 km in diameter, and the poor fit of a single power law or exponential distribution to our dataset, we opted to employ a statistical approach termed "mixture modeling" to establish if there are multiple, discrete populations of volcanoes (defined on the basis of diameter) within our dataset.

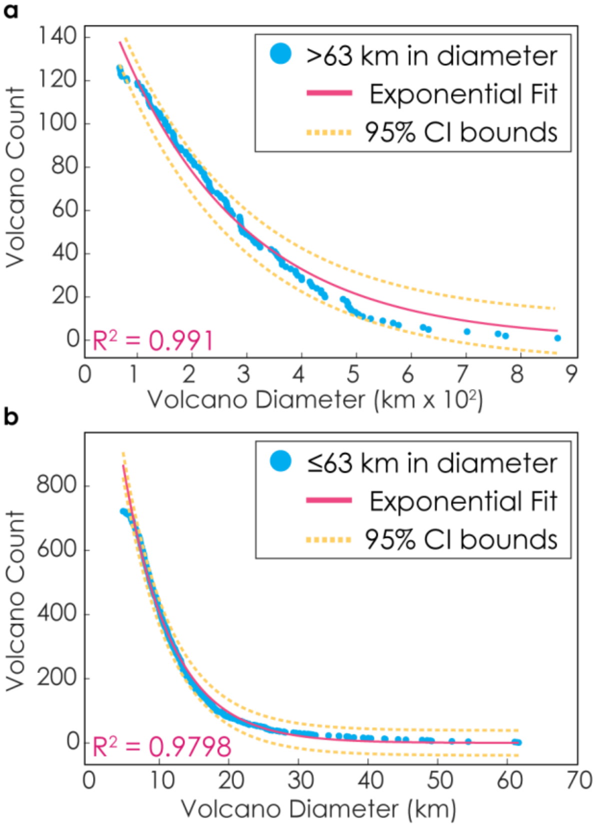

Figure 2: Venus volcano size–frequency distributions for volcanoes >5 km in diameter. Mixture-model analysis identified two sub-populations of volcano diameters that both follow and exponential distribution: (**a**) volcanoes >63 km in diameter and (**b**) volcanoes ≤63 km in diameter. Individual volcano diameters are shown as blue circles, lines of best fit are in pink with associated R^2 values, and 95% confidence interval bounds are the dashed yellow lines.

Mixture modeling is a flexible modeling approach that treats data as coming from several classes, components, or clusters [7–9]. We employed the MATLAB package 'SNOB' [10–12], which is an implementation of finite-mixture models that uses a minimum-message-length criterion to estimate the structure of the mixture model [9]. Mean basal diameter (km) values of volcanoes >5 km in diameter (n = 848) were the input dataset, and both exponential and power-law distributions were tested. The SNOB analysis that best fit the dataset resulted in two distinct exponential distributions within our data. The number of volcanoes with mean basal diameters D can be described as $v(D) = v_o e^{-\alpha D}$, where $v(D)$ is the number of volcanoes in a mean basal diameter bin, v_o is the expected number of volcanoes of all mean basal diameters per unit area, e is the exponential constant, and α is the slope. The two distributions are defined by a break in mean basal diameter at 63 km, with the first distribution containing 126 volcanoes where $D > 63$ km (**Figure 2a**) and the second containing 722 volcanoes where $D \leq 63$ km (**Figure 2b**). For volcanoes where $D \leq 63$ km, the exponential distribution is defined as:

$$v(D_{\leq 63}) = 1836e^{-0.1454D}. \tag{1}$$

To estimate the total number of volcanoes on Venus that are 1–5 km in diameter, $v(D_{1\text{–}5})$, we used the integral of the exponential equation calculated from the mixture model for volcanoes ≤63 km in diameter, and evaluated that integral from 1 to 5 with the MATLAB integral function. The total number of volcanoes 1–5 km in diameter is thus given by the relation:

$$v(D_{1\text{–}5}) = \int_{5}^{1} v(D_{\leq 63}). \tag{2}$$

In earlier studies, estimates for the total number of volcanoes on Venus were typically made by examining the size–frequency distribution of a subset of volcanoes and extrapolating that estimate to the entire planet [cf. 5,13]. Here, we extrapolated our population of volcanoes 5–63 km in diameter (n = 722) to *all* volcanoes <5 km in diameter we identified in our global catalog (n = 84,172).

Total Volcano Number: In total, we estimate that there are ~566,000 volcanoes 1–5 km in diameter on Venus, and a total of ~567,000 volcanoes ≥1 km in diameter globally (that is, ~566,000 volcanoes 1–5 km in diameter, plus an additional 848 volcanoes ≥5 km in diameter from our global catalog, accounting for rounding to the nearest thousand). This value falls within previously published ranges by Aubele and Slyuta [5] and by Crumpler et al. [13], which span a total of 10^5–10^6 volcanoes on Venus as calculated with an exponential distribution. Based on the number of volcanoes <5 km in diameter in our dataset, we posit that there are an additional ~482,000 edifices 1–5 km in diameter that have yet to be confirmed to be present on Venus. For such confirmation, however, radar image data at resolutions far better than Magellan are required.

Similarity with Seamounts: Our estimated value of about a half-million volcanoes ≥1 km in diameter is comparable to the approximate total population of seamounts on Earth, a number that is proposed to range from 10^4 [13] to 10^6 [14]. Previous workers noted the similarities in the size and shape of small volcanoes on Venus (those <20 km in diameter) and seamounts on Earth, as well as the high-pressure ambient conditions under which such volcanoes manifest on each planet [5,15,16]. These similarities suggest the formation of small edifices on Venus and seamounts on Earth may have common controls. Small volcanoes (D <20 km) on Venus are geographically widespread and commonly clustered into volcanic fields [4,5,13]. Many small volcanoes are found within coronae and on the flanks of larger (D >100 km) shields [13]. This close association is consistent with the larger structures hosting shallow magma reservoirs that are also supplying the smaller volcanoes. However, not all small volcanoes are associated with coronae and/or large volcanoes, with many being isolated from regions suspected to host mantle upwellings (such as the Beta–Atla–Themis region). These relatively isolated volcanoes may possibly form from melt originating in locally thinned and fractured regions of the lithosphere [17].

In contrast, the origins of Terran seamounts are well understood, and are found in several tectonic settings on Earth such as mid-ocean spreading ridges, near transform faults and regions of extension, over upwelling mantle plumes, and in island-arc convergent settings [15,18,19]. Seamount size–frequency distribution has been found to vary with plate-tectonic setting [15,20]; for example, Smith [15] noted that seamounts vary in abundance and location along mid-ocean ridges that are spreading at different rates.

This trait of seamounts on Earth raises an interesting prospect: that there are systematic expressions of volcano morphology, size–frequency distribution, or other characteristic on Venus that correlate with some other property such as lithospheric thickness, geoid, or even stratigraphic age. Moreover, the spatial distributions of seamounts on Earth reflect tectonic control (principally controlled by plate tectonics, even far from plate boundaries) [19]; it remains unknown as to what extent tectonic structures control the distributions of volcanic fields and individual, small (D <20 km) volcanoes on Venus.

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