KERNEL DENSITY ANALYSIS OF VOLCANOES ON VENUS AT VARYING SPATIAL SCALES. Rebecca M. Hahn[1] and Paul K. Byrne[1], [1]Department of Earth and Planetary Sciences, Washington University in St. Louis, St. Louis, MO 63130 (h.rebeccahahn@wustl.edu).

Introduction: The surface of Venus is dominated by volcanic landforms, including an abundance of edifices that range in size from less than 5 km to well over 100 km in diameter [1–3]. The style of volcanism on Venus differs from that on Earth mainly in that we see no Earth-like plate tectonics on Venus, such that volcanoes form on Venus primarily as a result of hot spot volcanism rather than being controlled by plate boundaries [3–5]. Identifying the distribution and concentration of these edifices gives valuable insight into the size and shape of the underlying magma source(s), the mechanism of magma production, and the states of stress in the crust [6,7]. Such analysis may also provide further insight into the origin of volcanism on Venus as it relates to hot-spot-style volcanism.

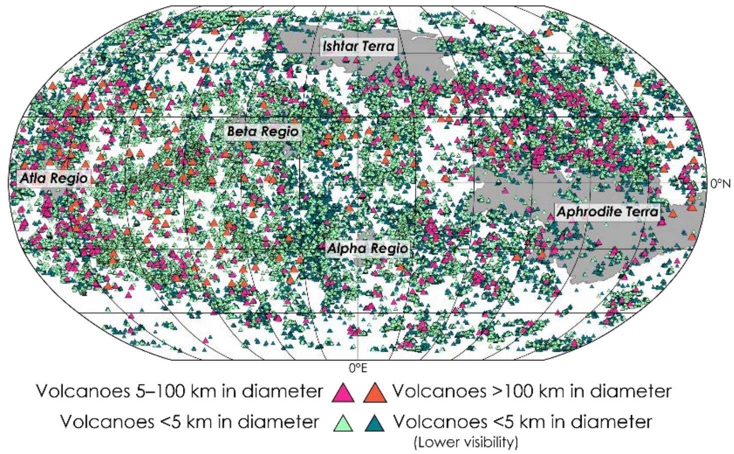

Figure 1: Our global database of volcanic edifices on Venus. This survey includes ~85,000 volcanoes distributed across virtually the entire planet. Outlines of major Venusian physiographic features are shown in grey.

One method for analyzing the distribution of edifices on a global scale is by using kernel density functions—non-parametric density estimation tools that have been used extensively in the planetary community to examine, for instance, volcano spatial density on Mars [e.g., 8,9] and on Venus [e.g., 10]. In this analysis, we utilized the Kernel Density function in ArcGIS Pro 2.7 at several spatial scales to analyze the spatial density of edifices on Venus in a global catalog we previously developed [11].

Data and Methods: We compiled a global survey of Venusian volcanoes with the Magellan SAR FMAP (full-resolution radar map) left-and right-look global mosaics, which have ~100 meter-per-pixel (m/px) resolution [12]. Our catalog includes ~85,500 volcanoes, comprising 84,069 edifices <5 km in diameter, 1,331 edifices 5–100 km in diameter, and 139 edifices >100 km in diameter (**Figure 1**). For our kernel density analysis, we used these same edifice diameter classes.

For point features, ArcGIS Pro uses a modified quartic kernel function based on work by Silverman [13] to fit a smoothly tapered surface to each point by calculating the spatial density of features around each output cell. Here we used an output cell size of 75 km × 75 km, with geodesic distance measurements to better analyze the distribution of points over a spherical surface. For this study, we varied the radius parameter from 6,000 km to 500 km for each size category of edifice, producing a set of kernel density maps to allow for the identification of any geographic concentrations of volcanoes at a range of spatial scales. This approach facilitates the systematic exploration of landforms of interest without limiting the results to specific distances [e.g., 10, 14]. We generated eight global density maps with radius values of 6,000, 5,000, 4,000, 3,000, 2,000, 1,000, 750, and 500 km, respectively, for each of the three categories of volcanoes, for a total of 24 kernel density maps. We also compared these maps with calculated crustal thickness values across Venus [15]. At a regional scale, crustal thickness may influence the spatial density of the edifices, as the average distance between concentrations of edifices is linked to the thickness of the upper medium [16]. Further analysis of this relationship may give insight into the formation mechanism of different sizes of volcano across the planet [17].

Results: Examining volcano areal density on numerous spatial scales has allowed us to identify patterns that would not have been evident in a single kernel density map. Kernel density maps for small edifices (i.e., those <5 km in diameter) revealed two high density clusters at broad spatial scales (radius = 6,000–4,000 km). One cluster is centered at ~25°W and 18°N, and partially encompasses the Beta–Atla–Themis (BAT) region, an area known for its considerable volcanism [18,19]. The other cluster is centered at ~115°E and 40°N, and surrounds Kutue Tessera (**Figure 2a**). These concentrations might plausibly outline two regions of enhanced partial melting that have contributed to increased rates of volcanism in each of these regions. As the spatial scale decreases (from radii of 3,000 to 500 km), these large clusters break into smaller concentrations, which likely reflect the discrete, shallow magma bodies feeding the small edifices that constitute these much larger clusters.

Kernel density maps for edifices 5–100 km in diameter reveal a concentration of edifices that aligns with the concentration around Kutue Tessera found in the kernel density maps for edifices <5 km in diameter, further supporting our hypothesis that this portion of the mantle may be relatively enriched in heat-producing elements (**Figure 2b**). Interestingly, we do not find a concentration of large edifices (those >100 km in diameter) in this region, but do note a substantial concentration of large edifices within the BAT region at varying kernel density spatial scales (**Figure 2c**). This finding reveals a difference in edifice size between the region surrounding Kutue Tessera and the BAT region, and these differences may be related to the depth or size (and thus longevity) of the underlying magma source(s) in these two regions. For example, many large edifices on Venus preferentially occur at higher elevations at the junction of chasmata and rift zones, and are associated with geoid highs [3,18]. These large volcanoes are thought to form from a deep source mantle plume and are common in the BAT region [20]. However, Venus also hosts large volcanoes that are not associated with geoid highs or rift zones, which may manifest as a result of shallow melting of sufficient scale to produce large magma bodies [21].

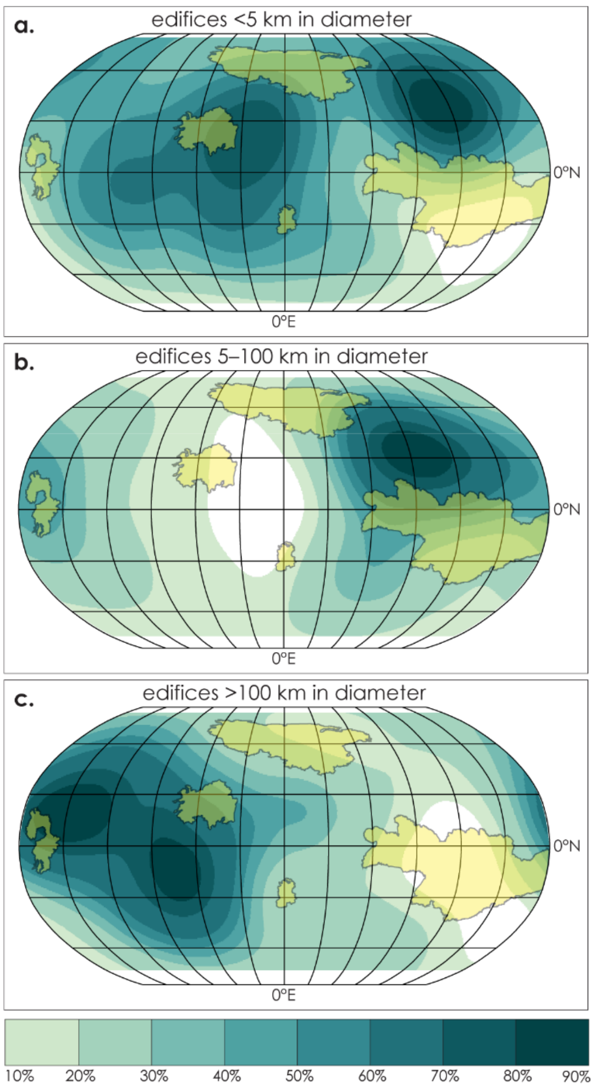

Figure 2: Kernel density maps with a radius value of 6,000 km for edifices <5 km in diameter (a), 5–100 km in diameter (b), and >100 km in diameter (c). Large radius values produce a smooth, generalized density map, whereas small radius values produce a finer more detailed map. Scale shows relative height of the probability density function (PDF) as a percentage within each cell. Higher and lower percentages correspond to higher and lower densities of edifices in each cell, respectively. White regions in maps correspond to areas with PDF values below 10% (i.e., very few edifices). Major Venusian physiographic features are shown in yellow.

In terms of smaller edifices on Venus, many are grouped into shield fields—highly spatially concentrated clusters of edifices <20 km in diameter [22] with ~4 to 10 edifices per 1,000 km² [23]. Shield fields are likely formed from distinct, small-scale eruptions fed from shallow magma reservoirs [18,22]. Our series of kernel density maps allows us to identify high spatial concentrations of edifices of differing sizes, which may correspond to regions of shallow or deep magma reservoirs.

Furthermore, we found that edifices <5 km in diameter are highly spatially correlated with regions of low crustal thickness (~14 km), whereas large edifices (>100 km in diameter) are correlated with areas of higher crustal thickness (~17 km) [15]. This result suggests that crustal thickness plays a key role in the spatial density of volcanoes on Venus, and also has some control on edifice size—perhaps as a function of how much magma can erupt for a given crustal thickness. Further analysis of tectonic structures (e.g., rift zones, ridge belts, etc.) that are proximal to high spatial concentrations of volcanic edifices will provide additional insight into how and why volcanoes of varying sizes manifest on the surface of Venus.

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