Using Spatial Density to Characterize Volcanic Fields on Mars.

J. A. Richardson[1], J. E. Bleacher[2], C. B. Connor[1] and L. J. Connor[1], [1]Geology Department, University of South Florida, Tampa, FL 33620, USA (jarichardson@mail.usf.edu), [2]Planetary Geodynamics Laboratory, Code 698, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA.

Introduction We introduce a new tool to planetary geology for quantifying the spatial arrangement of vent fields and volcanic provinces using non–parametric kernel density estimation. Unlike parametric methods where spatial density, and thus the spatial arrangement of volcanic vents, is simplified to fit a standard statistical distribution, non–parametric methods offer more objective and data–driven techniques to characterize volcanic vent fields. This method is applied to Syria Planum volcanic vent catalog data as well as catalog data for a vent field south of Pavonis Mons. The spatial densities are compared to terrestrial volcanic fields.

Kernel Density Estimation Spatial density can be estimated using a kernel function, which is simply a spatial density about a point, the center of a volcanic vent. These kernels are summed to calculate the spatial density of vents for any location in the region of interest. Kernel functions are dependent on a smoothing parameter, or bandwidth, which is analogous to standard deviation of a Gaussian distribution. For one kernel function, given by Wand and Jones [1], the bandwidth is given as a 2×2 element matrix, $\mathbf{H}$, used to estimate spatial density, $\hat{\lambda}(\mathbf{s})$, at point $\mathbf{s}$:

$$\hat{\lambda}(\mathbf{s}) = \frac{1}{2\pi N\sqrt{|\mathbf{H}|}} \sum_{i=1}^{N} \exp\left[-\frac{1}{2}\mathbf{b}^{\mathbf{T}}\mathbf{b}\right] \qquad (1)$$

where $|\mathbf{H}|$ is the determinant of the bandwidth matrix, $\mathbf{b} = \mathbf{H}^{-1/2}\mathbf{d}$ and $\mathbf{b}^{\mathbf{T}}$ is the transform of $\mathbf{b}$. $\mathbf{d}$ is a 1×2 distance matrix, and N is the total number of volcanic vents.

The bandwidth is optimized using a smoothed asymptotic mean integrated squared error (SAMSE) method, developed by Duong and Hazelton [2] and freely available in the statistical package, R.

Tharsis Low-Shield Volcanic Fields Many new small shield volcanoes (10s km in diameter) have been identified within the Tharsis Volcanic Province through post-Viking images and topography [3–6]. Using topographic data from the Mars Orbiter Laser Altimeter (MOLA) gridded dataset as well as images from the Thermal Emission Imaging System (THEMIS), the Context Imager (CTX), and the High Resolution Stereo Camera (HRSC), workers have begun cataloging volcanic vents into volcanic fields [5,6]. Two previously cataloged shield fields include Syria Planum [6] and a field of volcanic vents south of Pavonis Mons [5]. In both of these projects, volcanic vents are defined as positive topographic features (10s to 100s m in relief) that exhibit radial flow features and craters at the apex of the feature. Vents are cataloged as 2–dimensional points to represent 4–dimensional volcanic event that created the feature. The Syria Planum catalog contains $N = 263$ vents. The catalog of vents south of Pavonis Mons contains $N = 96$ vents.

Syria Planum and Pavonis Mons catalogs are each used to estimate $\mathbf{H}$ using the SAMSE bandwidth selector. The square root of the bandwidth matrix for Syria Planum vents is

$$\sqrt{\mathbf{H}} = \begin{bmatrix} 51.73 & -17.76 \\ -17.76 & 47.95 \end{bmatrix} \qquad (2)$$

This matrix gives a E-W smoothing distance of 103.46 km (twice the upper left element, 51.73) and a N-S smoothing distance of 95.9 km (twice the lower right element, 47.95). The negative values in the upper right and lower left elements rotate the kernel ellipse counter–clockwise. The square root matrix for the vent field south of Pavonis Mons is

$$\sqrt{\mathbf{H}} = \begin{bmatrix} 24.43 & 0.31 \\ 0.31 & 49.91 \end{bmatrix} \qquad (3)$$

giving a E-W smoothing distance of 48.86 km and a N-S smoothing distance of 99.82 km, with the elliptical kernel being rotated clockwise.

These bandwidth matrices are used to map the spatial density of each vent field. These spatial density distributions are mapped in Figures 1 and 2, which display the 25^{th}, 50^{th}, 75^{th}, 95^{th}, and 99^{th} percentile of vent density as contours. Note that these maps integrate to one. Spatial intensity (vents/km^2) can be estimated by multiplying results of equation 1 by N.

Discussion/Conclusion SAMSE bandwidth estimates for Syria Planum and Pavonis Mons vent catalogs yield smoothing distances within 10% of each other, with the semi-major axes of each elliptical kernel having a smoothing distance of ~ 100 km. The most striking feature of these bandwidths is they are 1–2 orders of magnitude greater than bandwidths for monogenetic volcanic fields on Earth [7,8]. For example, vent density in the sparse Yucca Mountain, Nevada volcanic field results in a semi-major axis smoothing distance of 28.8 km [7]. Similarly, volcano density is greater among terrestrial arc polygenetic volcanoes. In the Tohoku arc, Honshu, Japan, we find a semi-major axis smoothing distance of $\sim$33 km. Thus, volcano spatial density in Syria Planum and Pavonis Mons catalogs is demonstrably lower than in terrestrial monogenetic volcanic fields and arcs.

The resulting spatial density maps for Syria Planum and Pavonis Mons catalogs reveal single modes in vent density in each field (Figures 1 and 2). The areas of these volcanic fields can be estimated from the area enclosed by the 99^{th} percentile isoline for each spatial density model. For the Syria Planum catalog this area is 445,100 km^2 and for the catalog of vents south of Pavonis it is 160,700 km^2. Again, in both cases these areas are greater than for terrestrial monogenetic volcanic fields or arcs.

The SAMSE bandwidth estimates provide a means of objectively assessing anisotropy in vent distribution that may reveal tectonic processes. The Syria Planum kernel is roughly circular. The vent field south of Pavonis Mons has an elliptical kernel. Very low deviatoric stress is expected to produce a radially symmetric kernel. While both density distributions are unimodal in nature, perhaps implying that each was created by one uniform melt region, the elongation of the resulting Syria Planum density distribution and the elongated kernel of the vent field south of Pavonis Mons pose questions. Was there preferential dike alignment in the NNE-SSW direction south of Pavonis Mons? Was the underlying melt region of Syria Planum elongated or was the shape of the shield field created by near–surface rheology? Or do these observations result from mapping biases or potential burial of sections of the Pavonis Mons field?

Kernel density estimation is a new method to provide objective estimates of spatial density of vents and area of planetary volcanic fields, simplifying comparisons. We find Syria Planum and Pavonis Mons catalogs to indicate lower vent densities and larger areas than observed for terrestial volcanic fields, but are nevertheless characterized by unimodal distributions.

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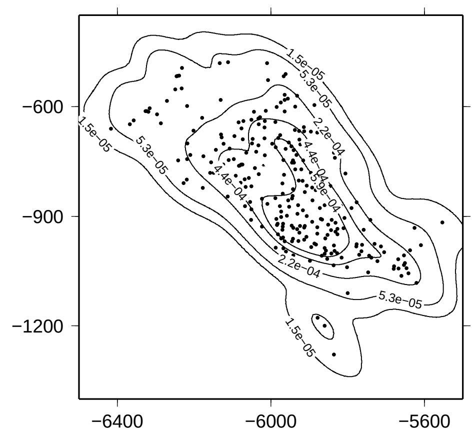

Figure 1: Spatial density distribution of vents on Syria Planum. In both figures, contours represent the 25^{th}, 50^{th}, 75^{th}, 95^{th}, and 99^{th} percentiles of vent density; black circles represent volcanic vents; north is up; eastings and northings are given in Transverse Mercator kilometers.

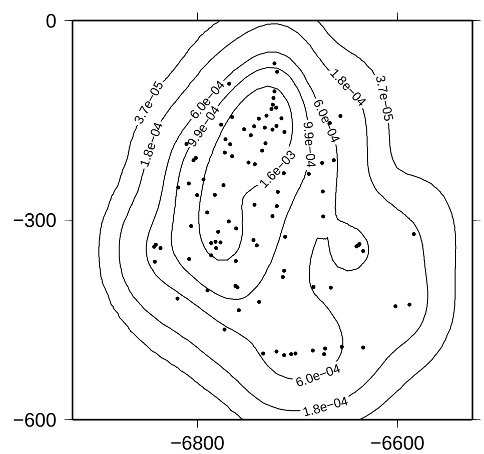

Figure 2: Spatial density distribution of vents in a vent field south of Pavonis Mons.

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