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Sensitivity to volcanic field boundary*

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1. Introduction

A volcanic field is an area of distributed volcanism where each eruption tends to occur in a different location. For volcanic hazard analyses, forecasts are required for both *when* and *where* future eruptions may occur. This spatio-temporal behaviour is estimated from analysis of previous eruption data. The first step is the use of exploratory statistics. These require definition of the surface extent of the volcanic field, outside of which it is assumed no eruptions occur. We assess the sensitivity of these statistics to this definition using two fields: Harrat Rahat, KSA (right) with 968 identified eruption centres, and the Auckland Volcanic Field, NZ (left) with ~50 centres. Both are located proximal to large urban centres (>1 million pop.) and show evidence of volcanic activity within the last 1000 yrs.

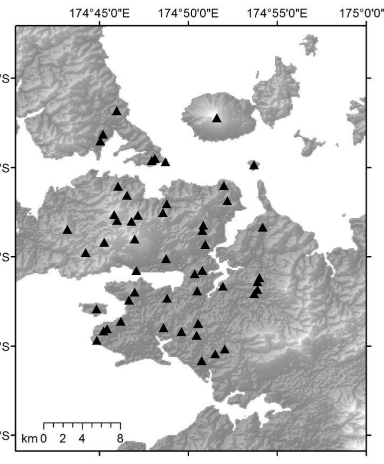


Fig: Auckland Volcanic Field (AVF), New Zealand

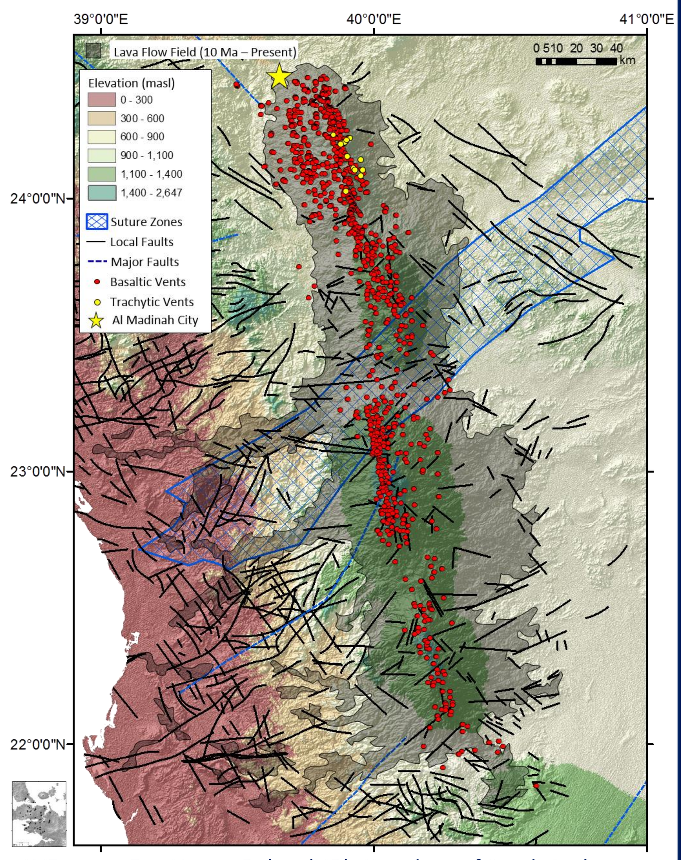


Fig: Harrat Rahat (HR), Kingdom of Saudi Arabia

2. Geological considerations

When imposing a boundary, the following five assumptions are often adopted with minimal (if any) consideration as to validity. Is this wise? We think not.

(i) Temporal invariance: Is there a fixed region within which all eruptions have, could have, and will occur? Evidence of a systematic shift in eruption location? Focussing? Spreading?

(ii) Unobserved (hidden) vents: Is the eruption record complete? Is there extensive vegetation, urbanisation, or lava flows that may be obscuring eruption centres in certain areas? (see EGU session **NH2.4/GMPV7.5**)

(iii) Anomalous vents: Vents with distinct geochemistry? Erupted volume? Age? Overlapping systems, e.g., polygenetic volcanoes? Anomalous in space and/or time? Is there such a thing as an anomalous vent?

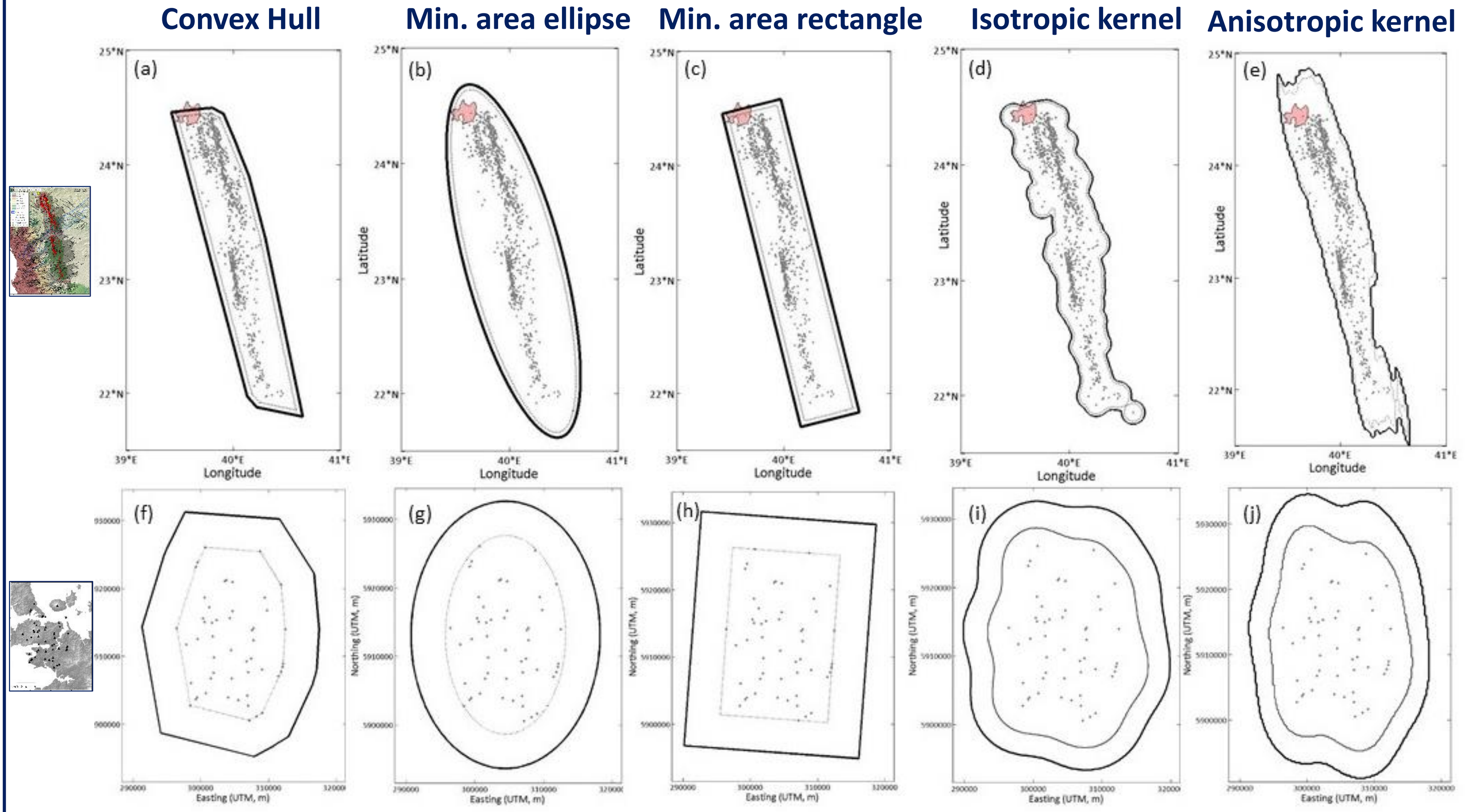
(iv) Geological constraints: Any known geological boundaries? Impenetrable lithologies? Significant crustal or fault structures? Potential regions of depleted mantle? Evidence of stalled or failed eruptions?

(v) Field maturity: Do previous eruption centres cover the extent of the subsurface source? How many eruptions are required, or after what timeframe can it be assumed that the field is mature enough to expect future eruptions to lie within a boundary fitted to the outermost previous eruptions?

3. Tested boundaries

Five boundaries were fitted to each field. A 5km buffer zone (thick line) was then also added to each fitted boundary (thin line) to accommodate the youthfulness of the AVF - ***2(v)***, and the apparent shift in locus of activity in HR – ***2(i)***. This resulted in ten separate boundaries for testing.

Convex Hull | Min. area ellipse | Min. area rectangle | Isotropic kernel | Anisotropic kernel



Isotropic kernel equation (d,i):

$$\lambda_s = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{2\pi h}\exp\left[\frac{\|x_i - x\|^2}{2h^2}\right]$$

Anisotropic kernel equation (e,j):

$$\lambda_s(x) = \frac{1}{2N\pi\sqrt{|H|}}\sum_{i=1}^{N}\exp[-0.5(x_i - x)^T H^{-1}(x_i - x)]$$

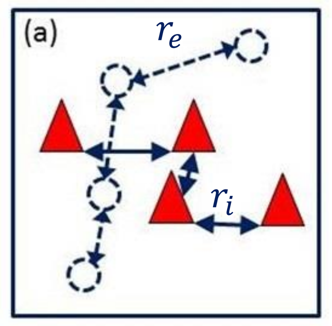
N: number of vents, h: 1D kernel bandwidth, H: 2D kernel bandwidth matrix, |H|: is the determinant of H, and $\|x_i - x\|$: distance between ith vent at x_i and location x.

4. Exploratory Statistics

These are used to look for patterns (non-random behaviour) in the eruption record of a volcanic field.

First Order Randomness

(a) Clark-Evans



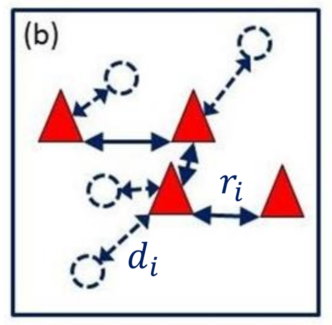
The Clark-Evans test compares the mean distance between neighbouring vents ($\bar{r}_a$) to the typical distance of an equivalent random distribution $\bar{r}_e$. The random distribution ($\bar{r}_e$) requires an average vent density and therefore relies heavily on the estimated volcanic field area (A):

$$\bar{r}_a = \frac{\sum_{i=1}^{N} r_i}{N}, \qquad \bar{r}_e = \frac{1}{2\sqrt{\rho}}, \qquad \rho = \frac{N}{A}, \qquad R = \frac{\bar{r}_a}{\bar{r}_e}$$

N: number of vents, ρ: average vent density, r_i: distance between the ith vent and nearest neighbour vent, and A: area. A ratio (R) of the two of R = 1 suggests a random distribution, while R < 1 indicates clustering, and R > 1, regular spacing or dispersion (Clark&Evans 1954).

(b) Hop-F

The Hop-F statistic compares the distance between the ith vent and its nearest neighbour vent (r_i), and the distance between a random point and the nearest vent (d_i).

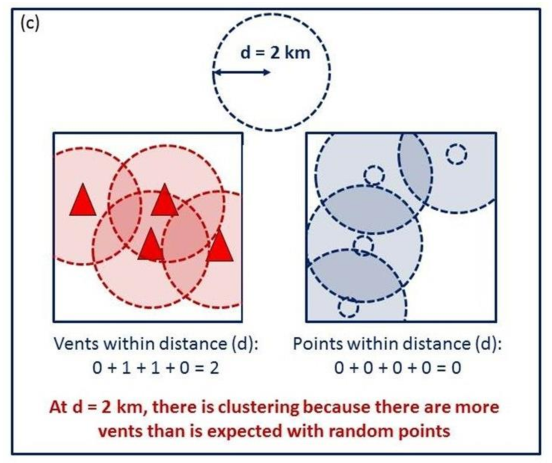


$$A_g = \frac{\sum_{i=1}^{N} d_i^2}{\sum_{i=1}^{N} r_i^2}$$

N: number of vents. The resulting coefficient of aggregation (A_g) indicates randomness if A_g = 1, clustering if A_g > 1, and regular spacing or dispersion if A_g < 1 (Hopkins&Skellam 1954).

Second Order Randomness

(c) K-function



The K-function compares the number of vents within distance *d* of another vent, with the number expected for a random distribution with the same density:

$$\hat{K}(d) = \frac{A}{N^2}\sum_{j=1}^{N}\sum_{i\neq j}^{N}\frac{H(d-d_{i,j})}{w_{i,j}}$$

N: number of vents, A: area, $d_{i,j}$: distance between ith and jth vents, H: Heaviside function, and $w_{i,j}$: edge correction (Martinez and Martinez 2001). This statistic is most easily interpreted as a graph of the L-function:

$$\hat{L}(d) = \sqrt{\frac{\hat{K}(d)}{\pi}} - d$$

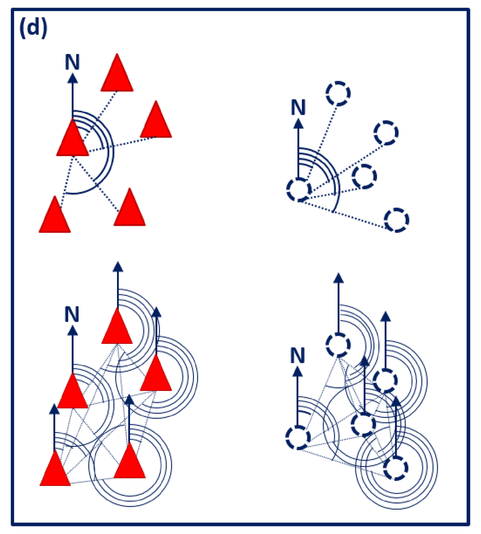
where $\hat{L}(d) = 0$ suggests randomness, $\hat{L}(d) > 0$ implies clustering, and $\hat{L}(d) < 0$, regular spacing (Ripley 1979).

Lineament Identification

(d) Two-Point Azimuth (TPA)

Lutz and Gutmann (1995)'s method (TPA) is based on the azimuth between each vent and every other vent and provides a distribution of the frequency of alignment angles, usually presented within groups of 10° intervals (Connor 1990; Wadge and Cross 1988).

To accommodate any non-circular field shape, the results are then compared to Monte Carlo simulations with the same number of vents placed within the defined area.



5. Results

First Order Randomness

HR	Area (km²)	Vent density (km⁻²)	R (Clark-Evans)	A_g (Hop-F)
Convex Hull	12,535	0.077	0.652	1.014
Ellipse	22,430	0.043	0.487	1.006
Rectangle	14,717	0.066	0.601	0.978
Isocontour	13,496	0.072	0.628	0.914
Anisocontour	15,292	0.063	0.5899	0.956

Harrat Rahat

(a) Clark-Evans: Significant clustering (R < 1). Much stronger with elliptical boundary.

(b) Hop-F: Random dispersion of vents (A_g ≈1).

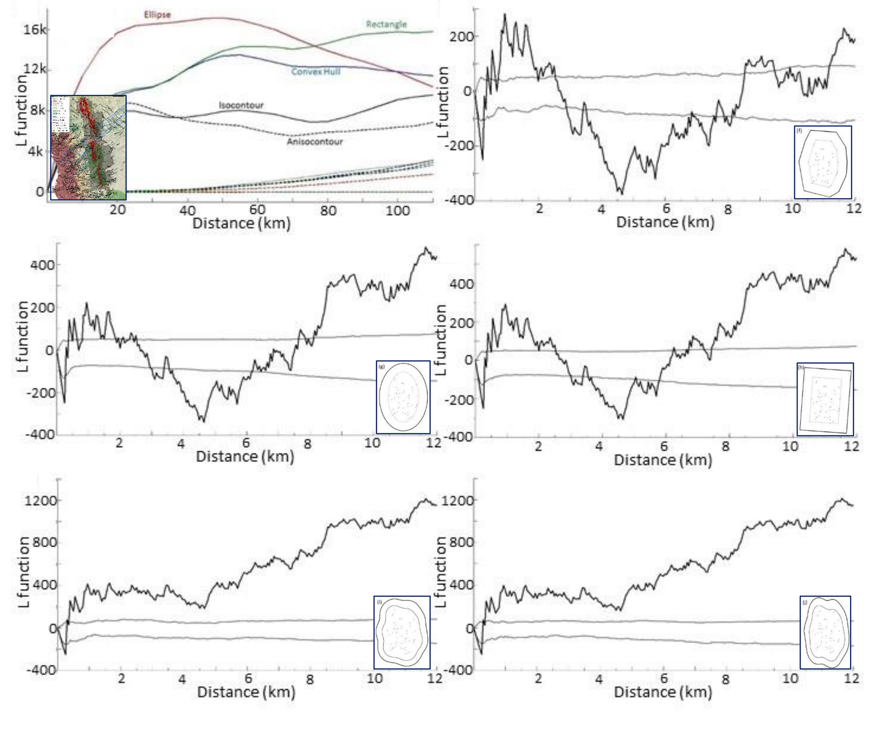
AVF	Area (km²)	Vent density (km⁻²)	R (Clark-Evans)	A_g (Hop-F)
Convex Hull	324.5	0.1527	1.134	0.887
Ellipse	385.7	0.129	1.04	1.191
Rectangle	400.2	0.127	1.021	1.0582
Isocontour	585.7	0.087	0.844	0.793
Anisocontour	579.4	0.088	0.849	0.896

Auckland Volcanic Field

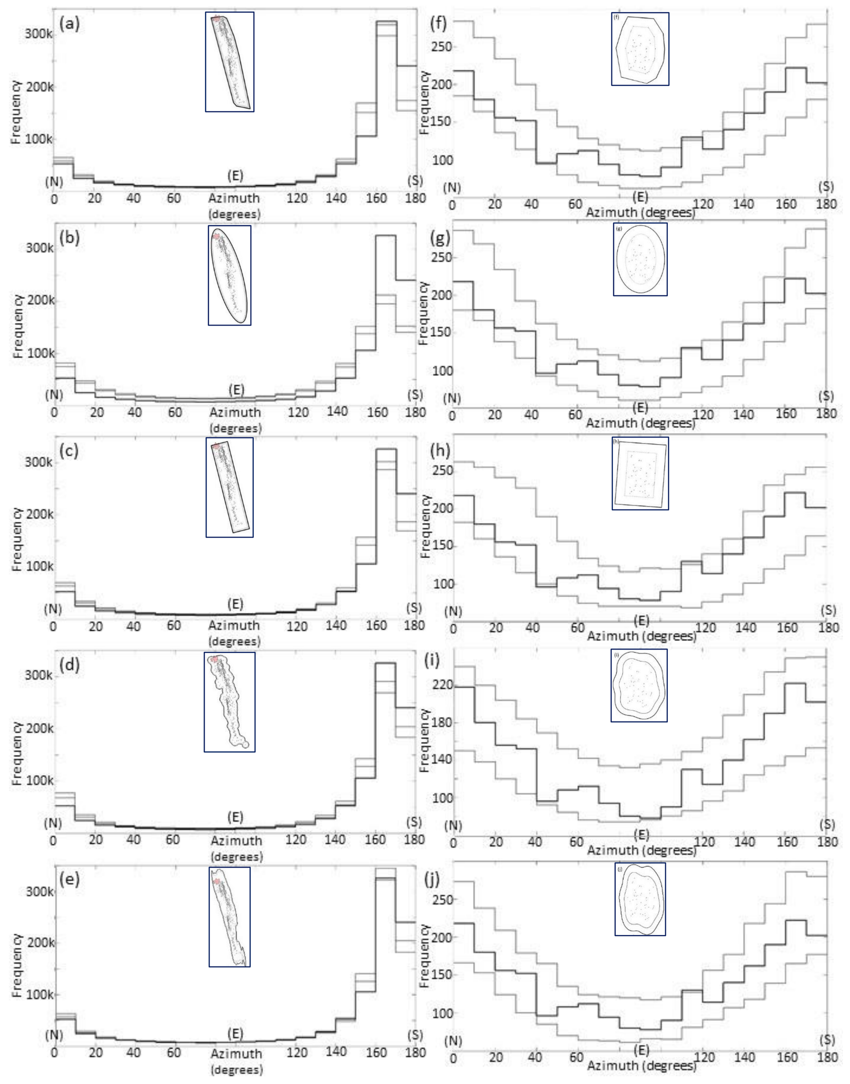
(a) Clark-Evans: Highly dependent on boundary choice. NONE were statistically significant.

(b) Hop-F: Random dispersion of vents (A_g ≈1). Except isocontour which suggests dispersed vents, and ellipse that suggests clustering.

Second Order Randomness



Lineament Identification



Harrat Rahat

(c) K-function: Clustering for all fields at all distances. Results are smoothed (obscured) by the high vent-density variations due to the spine-type structure of the field.

(d) TPA: Vents show alignment between 160° and 170° except with anisotropic kernel. Results are much stronger with elliptical boundary.

Auckland Volcanic Field

(c) K-function: All show clustering >11km. Kernel boundaries suggest clustering at all distances >0.5km. Other three boundaries show clustering 0.5–2.5km, then maximum spacing 3-6km (convex hull: to 8km).

(d) TPA: Vent alignments noted between 110° and 120°. Rectangular boundary suggests avoidance of alignments between 40° and 50°.

6. Conclusions

- Defining a volcanic field boundary is non-trivial and substantial variations may be noted for even the simplest exploratory methods for hazard forecasting.
- Harrat Rahat: results were highly sensitive to boundary definition and a buffer zone is highly recommended due to the spatio-temporal behaviour of the field.
- Auckland Volcanic Field: the range of boundaries assessed here resulted in similar shaped fields but some statistical tests still show substantial variation in results.

What you need to do NOW!

- Specify how you have defined your volcanic field boundary
- Assess the sensitivity of any subsequent results to boundary choice
- Remember to carry any boundary assumptions and related uncertainties through to estimates of future activity!

Read the full paper at: J. Applied Volcanology 4.1 (2015) 1-18

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