Point pattern analysis of eruption points for the Mount Gambier volcanic sub-province: a quantitative geographical approach to the understanding of volcano distribution

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This paper is an examination of the method of point pattern analysis, its potential and limitations, and a discussion of the patterns of volcano geography for the Mount Gambier volcanic sub-province of southeastern Australia. Two classes of point pattern measure were employed: the centrographic measure of point dispersion and directional bias, and distance-based measures of ordered neighbours. Spatial analysis has shown the distribution and pattern of eruption points to be heterogeneous, anisotropic and not completely spatially random, and offers through the exploration of point dispersion, orientation and pattern, a viewpoint on the geography of a low-volume, basaltic monogenetic volcanic system.

Key words: *Newer Volcanic Province, Shuttle Radar Topography Mission (SRTM), volcano geography, point pattern analysis, nearest neighbours, spatial distribution ellipse*

Introduction

Landform analysis within a geographical information system (GIS) is an abstract concept. In the case of point pattern analysis (ppa), this abstraction involves the representation of 4-D features as events with zero dimensionality. Such abstract recognition may be useful in landscape interpretation where time coupled with degradation, erosion and burial takes a significant toll on the geometry, relief and identity of landforms, and where landscape is inaccessible as with extra-terrestrial surfaces. Thus, regional interpretation and the spatial statistical methods used to describe landform dispersion, orientation and pattern are often most reliant on point data.

The geography (locations) of volcanic edifices identify the termination points of the route through which magma has travelled from the mantle to surface during a short time interval relative to the recurrence rates of these events in the volcanic field. In short, ppa tells us something about an underlying tectonic process: the mechanism that produced the point pattern. Ideally, the Mount Gambier volcanic sub-province is an area of volcanic point sources (vents), each of which form a small, identifiable cone or crater and that readily suits the methods of ppa and the assumption of zero dimensionality.

Some of the earliest spatial analyses of landform distribution and their relationships to causal processes were performed on Canadian drumlin fields (Smalley and Unwin 1968; Trenhaile 1971 1975; Crozier 1976). These studies were inconclusive, owing to the pervasive problem of scaling and modifying the areal units of study, and act as a reminder to the

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considerations required of spatial data analysis. Nevertheless, pattern development for volcanic fields has been explored using a variety of data analysis techniques. Some of the earliest exploratory works on the distribution of cinder (scoria) cone fields include the density mapping of cones on the upper slopes of Mauna Kea volcano, Hawaii (Porter 1972) and the morphometric and spatial comparison of six globally distributed volcanic fields (Settle 1979). A rigorous statistical analysis, inclusive of nearest neighbour and quadrat methods, was used to examine the Bunyaruguru volcanic field in West Uganda (Tinkler 1971); while Wadge and Cross (1988) used two-point azimuth and Hough transform methods for detecting vent alignments for the cinder cones of the Michoacán-Guanajuato volcanic field, Mexico. Lutz and Gutman (1995) applied the technique of kernel density estimation to characterize the Pinacate volcanic field, Sonora, Mexico, while extensive spatio-temporal studies of the Yucca Mountain region, Nevada, were performed by Connor and Hill (1995) and Connor *et al.* (2000) to evaluate the future risk of volcanic hazards. Recently, Bruno *et al.* (2004 2006) used the nearest neighbour method to characterize and compare rootless phreatomagmatic cones in Iceland with suspected analogues on Mars. Hence, it is demonstrated that the point representation of a landform can offer accurate information about its distribution and identity in geographical space. This is well illustrated in the recent imaging of the surface of Mars and the comparative analysis of landforms (see, for example, Fagents *et al.* 2002; Bruno *et al.* 2004 2006).

Accordingly, it is the purpose of this communication to show the considerable abilities of centrographic and distance-based measures of point data for understanding and interpreting distributional trends and patterns of a select sample of monogenetic volcanoes. This paper demonstrates how such analysis offers quantitative information to the spatial process modelling of the natural landscape, which will help establish a baseline from which other attributes of higher scales of measurement and dimensionality for landform can be confidently mapped, described and modelled within a GIS. Point pattern analysis of physical geographical features to date has minimally involved the advantages of visualization and iteration offered by a GIS. Therefore the significance of this study is three-fold. Firstly, it applies spatial analysis *within a GIS* to the understanding of landforms. Secondly, it uses quantitative methods that are now available *within a GIS* to assess and test inferences concerning the alignment of volcanic cones with a regional structural trend inferred from field data. Finally, this cursory examination offers insight into a methodology that may be suitable to the spatial examination of more intricate terrains; for instance, an entire volcanic province where field data is often incomplete, as in this example, and extra-terrestrial landscapes where only analogue studies are possible at this time. It may be that similar types of landforms could be distinguished by their spatial signatures, for example, rootless cones versus cinder cones. It is suggested also that, with adaptation, the methodology presented here could be applicable not only to monogenetic volcanoes, but also for the point pattern analysis of other landforms.

Background

Volcanoes formed during a single episode of volcanic activity without subsequent eruptions are collectively known as monogenetic (Connor and Conway 2000) and are landforms that are mostly of the types termed scoria cones, low lava shields, tuff rings and maars. Such volcanoes have magma supplies that are so small or episodic that the thermal pathway to the surface sufficiently cools and disables transport of ensuing magma batches along this route (Walker 1993 2000). Consequently, the activity for each volcanic centre is relatively short-lived, ranging between weeks to years only, and requires subsequent magma batches to find new thermal pathways, which in turn develop into neighbouring volcanic centres. As a result, monogenetic volcanoes appear to cluster within volcanic fields, for example, the Pinacate (Lutz and Gutman 1995) and Michoancán-Guanajuato (Hasenaka 1994; Hasenaka and Carmichael 1985) fields in Mexico and the Springerville field (Connor *et al.* 1992; Condit and Connor 1996) in Arizona, USA, whose patterns and distribution imply information about regional structural mechanisms and tectonic processes at several scales.

A volcanic province is an area of volcanic rocks consisting of more than one volcanic field of the same or different time spans (Fisher and Schmincke 1984). The basaltic Newer Volcanic Province (NVP) of southeastern Australia consists of several, if not many, volcanic fields of consanguineous volcanic rocks that include more than one volcanic centre, and which in total have a history of several million years. The province discontinuously straddles the western side of the state of Victoria (Western Plains

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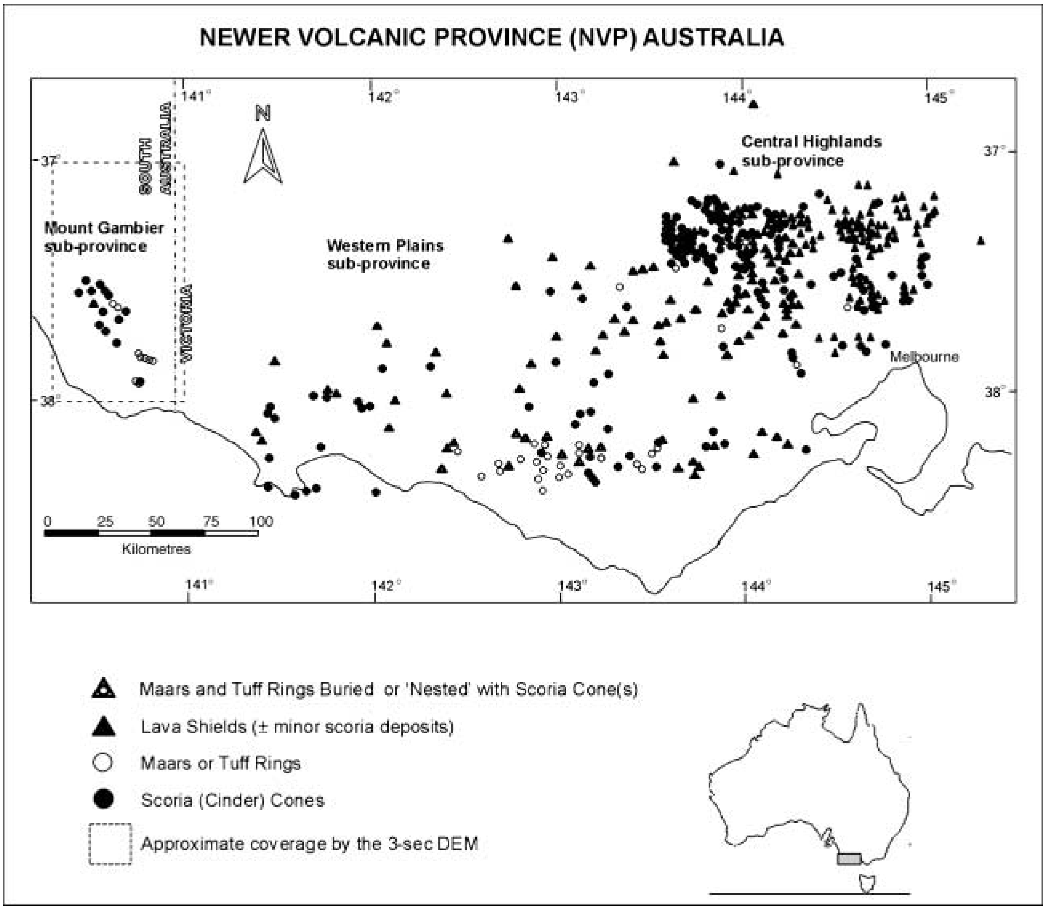

Figure 1 Locality map showing the three sub-provinces and the distribution of suggested major volcano morpho-types throughout the Newer Volcanic Province, Australia. All volcano locations are approximate only (adapted from Joyce 1988)

volcanics) and southeastern corner of South Australia (Mount Gambier volcanic sub-province), the latter region being the test subject of this paper. These and a third sub-province, the Central Highlands, cover some 15 000 km^2 (Nicholls and Joyce 1989; Figure 1). The youngest eruptive centres, Mounts Gambier and Schank (*c*.4.5 ka BP; Robertson *et al.* 1996) are located in the Mount Gambier sub-province, and consist of multiple eruption points of a complex nature (Figure 2). However, the majority of volcanoes, some 15 established eruption points, lies to the north of these and indicates eruption events dating to the early Pleistocene. These volcanoes are overlain, in part, by strandlines of beach dune aeolian calcarenite (Bridgewater Formation) of mid-Pleistocene age, while the Mount Gambier-Schank group of younger age stratigraphically overlies this coastal sequence (Figure 2). The style of province is best regarded as being of volume-limited plains-type (also see for analogy, the Snake River plain, Idaho; Greeley 1982) and owing to the variety of morphologies, modification, degradation, ages, eruptive mechanisms and the absence of a clear neotectonic framework, is an ideal setting in which to trial the methods of spatial analysis for volcano patterns using a GIS and interpret these results within a geological context. The Mount Gambier sub-province is physically separate from the sub-provinces of the Central Highlands and Western Plains, and consists of near two dozen eruption points that reflect significant volcano-form. No prior

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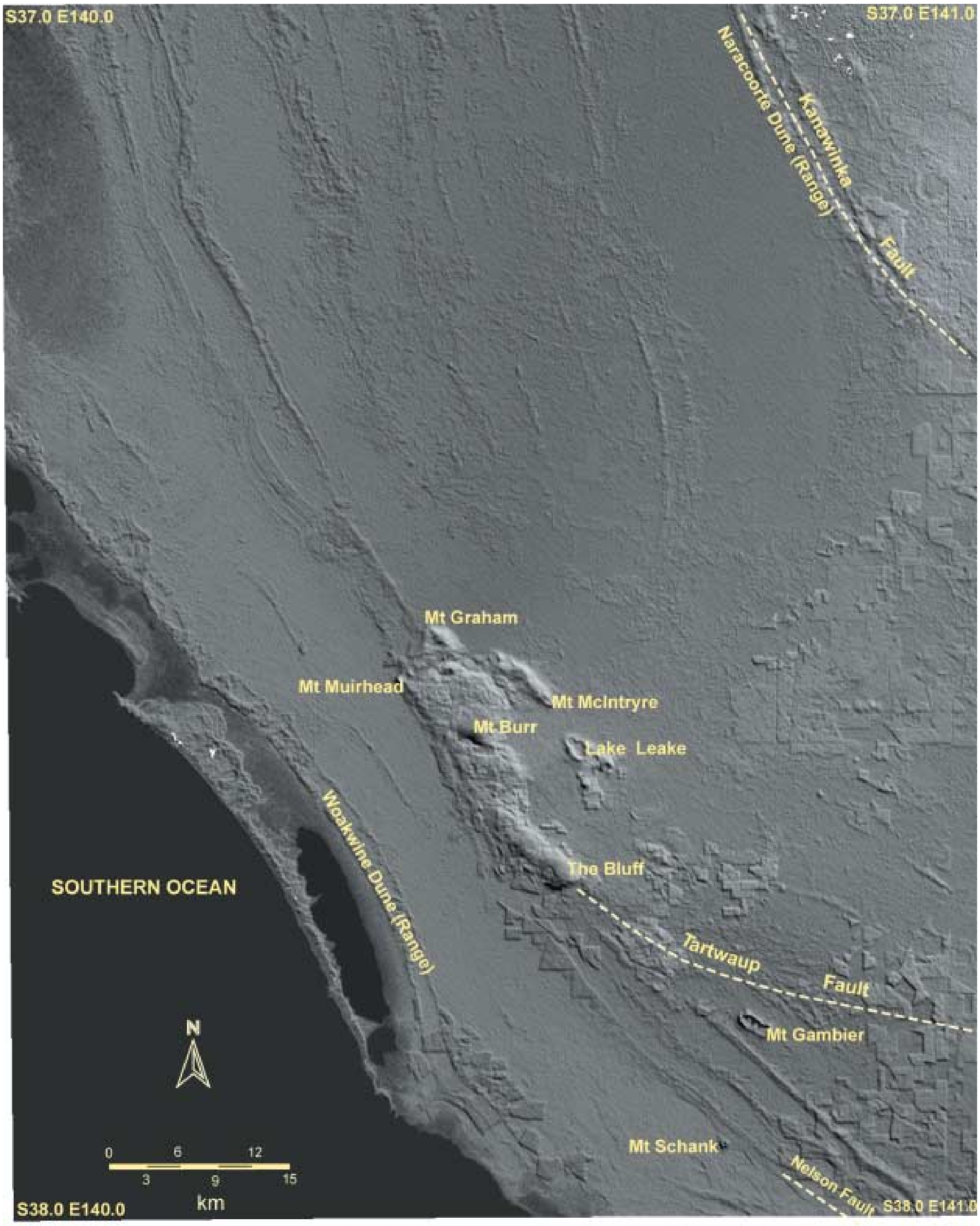

Figure 2 SRTM 3-sec DEM in shaded relief (UTM projection Zone 54 H, Datum WGS 84). Major landmarks of geomorphic significance are labelled along with the surface expression of regional faults. The Tartwaup and Nelson faults may be likely pathways for magma capture and transport to the surface. Recent sedimentary deposits and anthropogenic activity cover much of the surface expression of these neotectonic features

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published geographical analysis of these areas exists as far as the author is aware.

Methods

Data sources and software

Twenty-three clearly defined eruption points of the Mount Gambier sub-province were on-screen ('heads-up') digitized from a georeferenced 3-second (~1:250 000 scale) digital elevation model (DEM) using ArcView™ 3.3 GIS. This scale and data type was chosen for several reasons. Firstly, it coincides with the availability of up-to-date 1:250 000 geological mapsheets for the eastern sub-provinces of the NVP. These have an ideal scale, accuracy and level of attribute information concerning the location of point data with regional coverage. The establishment of volcanoes as point events at such scale shows them as definitive structures with crater or cone forms, from which estimates of the geometric centres can be discerned and labelled as the data point. Secondly, DEM data allow for 3-D visualization and 'fly-through' of ambivalent data points with coverage that now envelops the entire NVP. This data also has a corresponding scale and level of accuracy which enables it to be directly compared with available regional geological mapsheets. Moreover, an equivalent scale published geological map is not available for the Mount Gambier volcanic sub-province as a result of State boundaries. The existing Penola mapsheet (J 54–6 & 10) has not been updated since its first edition (1951) and lacks considerable detail, while a recent 1:500 000 mapsheet offers coarse information only. Therefore, DEM data are both necessary and consistent with the aims of this and a subsequent spatial analysis of the entire NVP. These data are derived from the Shuttle Radar Topography Mission (SRTM) and consist of individual tiles that are in a geographic (latitude/longitude) projection using a WGS 84 datum, and which cover an area 1° square. For planimetric accuracy the DEM tile was reprojected to UTM Zone 54H with a WGS 84 datum. A single tile covers the entire Mount Gambier volcanic sub-province (Figure 2). Although the number of eruption points within this sub-province is relatively small, the sample can be regarded as significant owing to its discrete isolation, both geographically and in part geologically, from the western-most arm of the Western District volcanic sub-province some 55 km further to the east (Figure 1). Owing to the exploratory nature of this study, it was considered worthwhile that the Mount Gambier sub-province allow testing and comparison of geographical analytical applications with field-based hypotheses prior to a more complex and intensive analysis of the Newer Volcanic Province as a whole. This approach has proven worthwhile in that local and regional point pattern analysis was found to offer different spatial information.

Spatial analytical extensions (avx) were added to the ArcView software (refer to the Acknowledgements). Such extensions offer a considerable suite of inexpensive 'off-the-shelf' spatial analytical and spatial statistical tools that are well suited to both human and physical geographical enquiry. Using these tools the investigation examined whether the location of geographic events – volcanic eruptions – produced a directional bias, and whether the distribution of eruption points identified any local or regional patterns that correlated with geological attributes and processes.

Synopsis of statistical calculations

The first of such analyses used the standard deviational ellipse (*sde*), which is a centrographic measure designed for the detection of the dispersion and orientation of a set of point locations. This tool examines whether geographic events show a directional bias. An *sde* requires that three components are calculated; an angle of rotation, the deviation along the major axis and the deviation along the minor axis (Wong and Lee 2005). If the set of points exhibits a directional bias, then the *sde* will identify the direction of maximum spread, the direction of minimum spread orthogonal to this and the angle of rotation that corresponds to the geographic orientation of the point distribution (Wong and Lee 2005). It is surmised that volcanic events that follow a structural trend will derive a standard distribution ellipse that will be approach linearity in form, which in turn may imply the orientation of underlying geological faults or structural influences. On the contrary, the absence of any such bias may indicate a distribution that is not directly overlying structural elements (faults, joints) or one that demonstrates a more complex arrangement of structural control, and that also is telling of the tectonic framework. The mean centre, or spatial mean, is the term used as the origin from which each data point is referenced. The mean centre that is defined by the mean of x coordinates and the mean of y coordinates is located at the geometric centre or centre of gravity of the spatial distribution formed by the coordinate data. The angle of rotation, θ, is calculated and referenced to the mean centre, where:

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$$\tan\theta = \frac{\left(\sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} y_i^2\right) + \sqrt{\left(\sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n} y_i^2\right)^2 + 4\left(\sum_{i=1}^{n} x_i y_i\right)^2}}{2\sum_{i=1}^{n} x_i y_i} \quad (1)$$

tan θ may be either positive or negative, thereby indicating the quadrant or orientation of the point distribution. However, the angle of rotation is always the angle between north (0°) and the y-axis rotated clockwise. The y-axis may be either the major or minor axis.

Subsequently, θ enables the calculation of the deviation, δ, along the x- and y-axes as follows:

$$\delta_x = \sqrt{\frac{\sum_{i=1}^{n} (x_i \cos\theta - y_i \sin\theta)^2}{n}} \quad (2)$$

$$\delta_y = \sqrt{\frac{\sum_{i=1}^{n} (x_i \sin\theta - y_i \cos\theta)^2}{n}} \quad (3)$$

These elements allow an ellipse about the mean centre to be determined (Wong and Lee 2005, 203–8).

Further to the understanding of point distributions is the characterization of the point pattern. Commonplace in the analysis of point pattern for biotic and more recently the abiotic landscape, is nearest neighbour analysis (NNA). The nearest neighbour statistic, first introduced in botanical studies (Clark and Evans 1954), has taken on a new direction through the analysis of pattern and process for suspected volcanic cones on Mars compared with cone groups in Iceland (Bruno *et al.* 2004 2006). The nearest neighbour distance for an event in a point pattern is the distance from that event to the nearest event, also in the point pattern (O'Sullivan and Unwin 2003). NNA calculates the dimensionless statistic R, which is the ratio of the observed average distance between nearest neighbours of a point distribution (r_o) and the expected average distance (r_e) between nearest neighbours as determined by a theoretical pattern. For each point, the shortest distance among all neighbours becomes the nearest distance, which is then averaged using all points. Formally, this is expressed as,

$$r_o = \frac{\sum d_i}{n} \quad (4)$$

where d_i is the nearest neighbour distance for point i and n is the number of points. For the theoretical random pattern the following expression is used to estimate the expected average distance between nearest neighbours, where n is the number of points in the distribution and A is the area of the study region,

$$r_e = 0.5\sqrt{\frac{A}{n}} \quad (5)$$

In its simplest form, the nearest neighbour statistic, R, compares the observed, r_o, with the expected, r_e, (random) nearest neighbour distances

$$R = \frac{r_o}{r_e} \quad (6)$$

and identifies whether points are random ($R \cong 1$), completely clustered ($R = 0.0$), where all points to lie on top of each other, or dispersed, where a value of $R = 2.00$ is a square lattice, or ($R = 2.149$), which is the theoretical value for the most dispersed pattern, being that of a triangular lattice.

The extent to which the observed average distance differs from the expected average distance can be measured using the comparison of their difference with the standard error of the average distances among nearest neighbours. The magnitude of the standard error is indicative of how likely any difference between the observed and the expected pattern is to occur by chance. If the difference is relatively small compared to the standard error, this difference is regarded as not statistically significant, while a large difference relative to the standard error indicates the difference is statistically significant. In other words, the difference does not occur by chance. The standard error of the difference between the observed and expected average distance for the nearest neighbour statistic is

$$SE_r = 0.26136\sqrt{\frac{A}{n^2}} \quad (7)$$

The key test statistic for evaluating the significance of the difference between an observed and random distribution is based upon the standardized Z score, where

$$Z_R = \frac{r_o - r_e}{SE_r} \quad (8)$$

If $Z_R > 1.96$ or < -1.96, it can be expressed that the difference is statistically significant at $\alpha < 0.05$. Alternatively, if $-1.96 < Z_R < 1.96$, the pattern is not statistically different from a random pattern, regardless of visual appearance.

With an ability to detect patterns, NNA has been extended to accommodate second, third and higher-order neighbour statistics to detect heterogeneous processes at different spatial scales. As with the nearest or first-order neighbour, ordered neighbour analysis (2nd, 3rd, 4th, etc.) is based on comparing the observed average distances (spacing) between neighbouring points and a known pattern, and evaluates the pattern at different spatial scales. The calculation of higher order statistics and Z-scores follow the expressions outlined above; however, the constants for the expected average distances and the standard errors need to be adjusted. Refer to Thompson (1956) and Wong and Lee (2005, 246–8) for a discussion of these.

Results and discussion

Statistical précis

The statistical results for the *sde* of the Mount Gambier sub-province were explored using individual data groups (Burr and Gambier-Schank) and the sub-province as a whole. The data group was defined by an attribute, in this case relative age, and was found necessary so as to investigate the effects of modifying the areal units of measure, as well as to gain a perception on intra- and extra-group properties. This style of investigation is formally known as a marked point pattern analysis and was necessary so as to understand areal influences on the point distribution. Statistically, the Burr group had an angle of rotation of 54.81° with deviations of the axes being δ_x = 7109.82 and δ_y = 3892.82, respectively. The location of the spatial mean was at S37.59°, E140.53° and was the centre of an ellipse showing a distinct directional bias (Figure 3). This indicates that the points do not disperse around the mean centre equally in all directions. The maximum spread of points here has been defined by δ_x and the minimum spread of points by δ_y. However, the geographic orientation of the point distribution is the angle defined by the major axis, which in this case is $\theta° \pm 90°$, that is, 144.81° (324.81°), or approximately southeast–northwest.

Similarly, the Gambier-Schank group demonstrated a directional bias; however, the concentrated nature of the eruption points for these data, the small sample size, as well as the absence of eruption points between these and the Burr group, resulted in a narrow and elongated ellipse (δ_x = 620.65, δ_y = 5643.82), with an angle of rotation at 13.14°. With this data group, δ_y and the angle of rotation are concordant with the direction of the major axis (Figure 3). These measures clearly show a significant difference in orientation (approximately north–south) compared with the Burr group, and taken at face value could possibly indicate emplacement mechanisms or magma pathways that were oriented differently. However, when examined as a regional data group, the overall spacing and alignments between the Gambier and Schank sites appeared to be in proportion with the overall spacing seen between the northern and southern locations of the Burr group volcanoes, and more likely implies an inherent association between the two groups with regard to emplacement geography rather than invoking two spatially different proceedings.

Such an association is further realized when the two point groups are combined and the sub-province is statistically examined as a whole. The inclusion of the data points for the Gambier-Schank group with those for the Burr group established an angle of rotation equal to 56.76° alongside deviations of δ_x = 18239.76 and δ_y = 3981.73 for each the major and minor axes of the ellipse (Figure 3). This shows a preferred and concordant directionality between the southeast and northwest (146.76° to 326.76°) as also indicated by the Burr group, with the spatial centre of the sub-province having migrated southerly, now located at the geographic coordinates of S37.68° and E140.61° (Figure 3). This interpretation sees the Gambier-Schank group as a southerly extension of the Burr group. As a whole, this distribution offers stronger evidence for the points to be termed a geomorphological lineament consisting of both similar orientation and dispersion which shows temporal change, rather than invoking spatially contrary and geographically separate episodes.

Further to the occurrence of a likely geomorphological lineament, *R*-values reflect two spatial perspectives, these being regional scale inter-group distributions and local scale intra-group patterns. As aforementioned, distance-based statistical measures were severely affected by the area of the study region. Specifically, regional-scale interpretation was most distorted by modifying the areal unit of measure. Here, for instance, as area increased, the points were defined as clustered, regardless of intra-group spatial properties. This is clearly seen in Table 1, where whole-province results used areas of 1537.7 km and 489.9 km, respectively. It was shown that the larger area identified the aggregation of points to have occurred over a far greater range of ordered neighbour distances than the smaller areal extent. The identification of pattern dispersion was not identified using the unit of greatest area. Such results can erroneously draw a parallel with spatially homogenous processes

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Figure 3 The standard deviational ellipse (*sde*) for the 23 eruption points of the Mount Gambier volcanic sub-province overlying a 3-sec DEM of the region. The *sde* for the Burr group (pink) and the entire sub-province (purple) both show a concordant directional bias indicating that the location and spacing of the Gambier-Schank group (blue) corroborates this directionality. The synoptic results for the sub-province identify an angle of rotation (yellow) $\theta = 56.76°$, alongside deviations of $\delta_x = 18239.76$ and $\delta_y = 3981.73$ for each of the major (~36 km long) and minor (~8 km long) axes of the ellipse. This indicates a preferred directionality between the southeast and northwest. The mean centre of the ellipse lies at the coordinates S37.68° E140.61°. This ellipse morphology offers strong evidence for the point distribution to be termed a geomorphological lineament

occurring at different spatial scales. This example typified the modified areal unit problem (MAUP) of geographical analysis and the errors it can introduce to spatial interpretation. Because the area defined by the Theme polygon in ArcView was relatively large for the number and distribution of points, it was decided that the unit of area should be based upon a convex hull. A convex hull or minimum convex polygon represented the minimum possible area that contained all data points, thereby appreciably limiting the effect of MAUP.

Therefore, using the convex hull of area, the exploration of the sub-province as a whole identified that the pattern of volcanoes had a tendency for clustering, relative to the expected pattern of randomness for both the nearest and 2nd-order neighbours. However, the *R*-values were not statistically significant. In other words, the average distance between nearest neighbours was not less than that of a random pattern, thereby showing a tendency towards a random distribution of volcanic events. Standardized scores of $-1.59 > -1.96$ for the nearest neighbour and $-0.64 > -1.96$ for the 2nd-order neighbour, ascertain that the null hypothesis, the observed pattern was not statistically different from a random pattern, must be accepted. Such results demonstrate the importance of defining the extent to which the observed average distance differed from the expected average distance, that is, the standard error of the average distances among nearest neighbours (Table 1). Furthermore, at

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Table 1 Comparisons of the ordered neighbour statistics (*R*) and significance (Z_R) of each of the eruption points of the Mount Gambier volcanic sub-province. Polygon areas are defined by the theme polygon of some 1537 square kilometres and convex hulls of some 489, 195 and 15 square kilometres, respectively. All *r*-values are measured in kilometres, however the *R*-statistic is dimensionless. If $-1.96 < Z_R < 1.96$, it can be concluded that the observed point pattern, whether it be visually clustered or dispersed, is not statistically different from a random pattern. Therefore, the null hypothesis must be accepted. The nearest neighbour statistic shows a Donnelly correction (in parentheses) for any distortions imposed by the boundary limits of the study area (Donnelly 1978)

Ordered neighbour	r_o	r_e	*R*-statistic	Z_R	Hypothesis	Pattern
Area of the Theme Polygon for All Points (1537.704 square km)						
1st	2.10	4.09	0.52 (0.47)	–4.45 (–4.46)	Reject H_0	Clustered
2nd	3.29	6.13	0.54	–6.12	Reject H_0	Clustered
3rd	5.57	7.67	0.73	–4.46	Reject H_0	Clustered
4th	6.67	8.94	0.75	–4.81	Reject H_0	Clustered
5th	9.38	10.06	0.93	–1.43	Accept H_0	Random
Area of a Convex Hull for All Points (489.004 square km)						
1st	2.10	2.31	0.91 (0.81)	–0.80 (–1.59)	Accept H_0	Random
2nd	3.29	3.46	0.95	–0.64	Accept H_0	Random
3rd	5.57	4.32	1.29	4.71	Reject H_0	Dispersed
4th	6.67	5.04	1.32	6.09	Reject H_0	Dispersed
5th	9.38	5.67	1.65	13.86	Reject H_0	Dispersed
Area of a Convex Hull for the Burr Group (195.028 square km)						
1st	2.93	1.80	1.63 (1.43)	4.63 (2.86)	Reject H_0	Dispersed
2nd	4.64	2.70	1.72	7.63	Reject H_0	Dispersed
3rd	5.83	3.38	1.72	9.53	Reject H_0	Dispersed
4th	7.27	3.94	1.84	12.88	Reject H_0	Dispersed
5th	8.26	4.44	1.86	14.75	Reject H_0	Dispersed
Area of a Convex Hull for the Gambier-Schank Group (14.647 square km)						
1st	0.56	0.68	0.82 (0.62)	–1.78	Accept H_0	Random
2nd	0.76	1.02	0.75	–1.94	Accept H_0	Random
3rd	5.09	1.27	4.01*	28.99	Reject H_0	Dispersed

*Value is meaningless as the most dispersed pattern is one of a triangular lattice where $R = 2.149$. In such cases no further statistical estimates are warranted

an observed average distance of 5.6 km (the 3rd nearest neighbour distance), the distribution became dispersed. The degree of dispersion also increased with subsequent higher order neighbours (Table 1). In all cases the statistical significance at $\alpha = 0.05$ was demonstrated. The regional spatial pattern for the Mount Gambier sub-province is one that is heterogeneous across a variety of spatial scales, not homogenous as indicated by unit areas of exaggerated extent.

Additionally, the exploration of individual groups identified local patterns within each. The Mount Burr group identified the nearest neighbour pattern as being a dispersed distribution. Commencing at an observed average distance of some 4.6 km (the 2nd-order neighbour), the pattern approaches that of a square lattice, with the degree of dispersion increasing for all subsequent ordered neighbour distances. Similarly, the pattern for the Gambier-Schank volcanoes was tested to be significantly random for the 1st and 2nd neighbour distances, regardless of the *R*-statistics and visual appearance, and exceeded the maximum value of dispersion at an observed average distance of some 5 km (3rd-order neighbour) (Table 1). It is noteworthy that for the 3rd and higher order neighbours of this group, the value of the *R*-statistic becomes meaningless when it exceeds $R = 2.149$, this being the value of maximum dispersion defined by a triangular lattice.

Overall the sub-province showed that the spacing between eruption points based upon the observed nearest neighbour distance was 2.1 km, and represented a pattern of randomness at this local scale. As the scale became more regional, the pattern changed to one that was increasingly dispersed. Intra-group spatial characterization reflected patterns that ranged from random to dispersed over several orders of

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magnitude. The inclusion of the Gambier-Schank group increased area and spacing, which in turn increases the likelihood of clustering due to the effect of MAUP, but at the same time offers a perspective on any intrinsic segregation between data groups. Overall, these patterns are longitudinally confined and show an orientation that has not significantly changed for the two groups of age-based events. Spatial heterogeneity and anisotropy are processes that characterize the Mount Gambier volcanic sub-province.

Geological précis

The Mount Gambier sub-province exhibits volcano groups that have a well-defined directional bias at both local and regional scales. The directional bias of the eruption points indicates that the spatial process departs from stationarity and shows that intensity variation is due to an underlying tectonic process varying with spatial direction, or anisotropy. Subsequently, ordered neighbour distances have discriminated that both intra- and inter-group patterns exist. Although evidence exists elsewhere for geological faults being pathways for magma transport, such associations may not always be necessary or clearly defined; see for example Connor *et al.* (2000). Within the Mount Gambier sub-province, the alignment of the southeast–northwest oriented groups with the orientation of regional geological faults is fair only. The directional mean (~118°) for known local faults, Kanawinka, Tartwaup and Nelson within the 1° × 1° area of the DEM tile (Figure 2) only approximately corresponds with the directional bias (~145°) shown by the standard deviational ellipse (Figure 3). Therefore, geographic analysis of the volcano pattern and plan-view orientation of regional fault lines does not offer sufficient information with regard to the interplay between structure and vent distribution. For instance, vent distributions on local scales can be highly variable due to fault geometries, as well as variations in the magnitude and orientation of a regional stress field with depth (Connor *et al.* 2000).

The regionally extensive and more exposed Tartwaup fault is closest of the three faults to the greatest number of points, being only some 6 km north of the younger Mount Gambier field, while intersecting with vents in the southern portion of the older Mount Burr group (Figure 2). Likewise, the Nelson fault may be associated with the Mount Schank eruption points owing to its proximity and apparent orientation; however, in each case an association between pattern and structure can be implied but not established. At most, the alignments for groups of volcanic vents such as the five eruption points of Mount Gambier and the concordant alignments of the Burr group's volcanic fields imply that ascending magmas have repeatedly exploited similarly oriented crustal structure during separate low volume and low energy single episodes of tectonic activity throughout the mid-to-late Pleistocene. The nature of low volume magma transport did not allow a single thermal pathway to remain open indefinitely, owing to the annealing effect of the conduit with low volume dyke development, thereby requiring successive batches of magma to ascend along neighbouring 'open' pathways. However, the precise nature, density, location and control of such pathways over pattern development cannot be ascertained with the information available in this instance.

Overall, spatial analysis has shown that the distribution and pattern of eruption points for the Mount Gambier volcanic sub-province is not completely spatially random, and offers through the exploration of point dispersion, orientation and pattern a viewpoint on the geography of a basaltic monogenetic system.

Conclusions

It has been shown that spatial statistical analysis using a GIS offers quantitative methods from which an understanding of both geographic and environmental processes can be surmised for volcano geography. Several major findings have been determined for the spatial characterization of the Mount Gambier volcanic sub-province and serve as benchmarks for understanding the techniques, results and interpretations of ppa. These findings include that:

1. The eruption points show a well-defined orientation towards the northwest–southeast.
2. Such orientation implies an alignment that can be termed a geomorphological lineament.
3. Such orientation may imply an alignment which reflects the influence of geological faults and/or an interaction of a magma supply with a regional stress field.
4. The spatial pattern of eruption points is random over local spatial scales up until about 3 km, thereafter becoming increasingly dispersed.
5. A pattern of dispersion is the foremost distribution type across the sub-province.
6. Migration of volcanic activity has occurred towards the southeast.

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In this study, two distinct classes of point pattern measure were employed, the centrographic measure of point dispersion and directional bias, and distance-based measures of ordered neighbour spatial effects. This assessment helped establish a baseline from which other attributes of higher scales of measurement and dimensionality for landform can now be confidently mapped, described and modelled within a GIS. The geography of points portrays the necessity of conducting both inter- and intra-group analyses. Intra-group analysis using an area deduced from a convex hull is the most representative geographical synopsis of the eruption points. Such methodology allows the perspective to range from local to regional scales, to minimize the effect of the modified areal unit problem (MAUP) and to identify the inherent spatial character of a set of data points derived from magma emplacement. Only through the interpretation of various areal groups can objective discussion and conclusions be reached. A 'one-step' regional approach to the analysis of point pattern is not an all-encompassing or necessarily accurate spatial interpretation of the data. Groups of points need to be investigated at local scales and subsequently compared with multi-group analyses at scales of increasing magnitude. Owing to this, groups need to be confirmed not only by location, but also by attributes (for example, age, morphology or morphometry), as long as the criterion of these is globally established. In this manner, a marked point pattern analysis is more likely to result in information that better represents natural processes. Geographic point signatures, therefore, are in themselves a tool that can further interpret and understand regional landscapes across a variety of scales, and which may offer a parameter that is useful in the identification of like-structures within a comparative planetary context.

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