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Charles B. Connor
Florida International University, cbconnor@usf.edu

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Cinder Cone Clustering in the TransMexican Volcanic Belt: Implications for Structural and Petrologic Models

CHARLES B. CONNOR

Department of Geology, Florida International University, Miami

Cinder cone distributions have most often been characterized using univariate statistics. Here a new technique to volcano distribution studies, cluster analysis, is applied to cinder cone distribution in the central TransMexican Volcanic Belt (TMVB). A total of 1016 cinder cones are identified over an area of approximately 60,000 km². Application of cluster analysis reveals structure in cinder cone distribution. Using a search radius parameter of 16 km, 75% of the cinder cones within the central TMVB are found within eight clusters of 45-159 cones each. These clusters are each 2000 to 5000 km² in area. Only 22 cones are found within clusters of three or fewer cinder cones, indicating that clustering is a pervasive phenomenon. Some petrologic variation is evident among clusters; low-Mg alkaline cinder cones are found within a single cluster, 360-400 km from the trench. Application of alignment analysis techniques, including the two-point azimuth method, the Hough transform, and two-dimensional Fourier analysis demonstrates that cinder cone alignments have common orientations on a regional scale within three clusters, all located in the southernmost part of the Michoacán-Guanajuato volcanic field in the western portion of the study area. These alignments consist of tens of cinder cones, are 20-50 km long, and are all oriented with azimuths of 020°-040°, parallel to the direction of plate convergence. High-Mg lavas, which last fractionated at pressures in excess of 8 kbar, are only found associated with these alignments, indicating that magma transport is significantly enhanced in these areas. Although local alignments of three to six cinder cones occur within mapped fault zones that transect the area, regional cinder cone alignment patterns, and the distribution of clusters themselves, do not appear to be affected by the presence of these fault zones. The cluster analysis, the alignment analysis, and some petrologic data support the hypothesis that the TMVB is segmented near 101°W.

INTRODUCTION

Several investigators have noted that cinder cones appear to cluster within cinder cone fields, rather than being homogeneously or randomly distributed [Carr, 1976; Heming, 1980; Walker, 1981; Hasenaka and Carmichael, 1985a, b; Connor and Condit, 1989]. These studies, conducted in a variety of cinder cone fields in differing tectonic settings, suggest that cinder cone clustering is a pervasive phenomenon. The origins of such clusters remain unclear, but their occurrence and distribution may provide evidence of the processes governing magma generation and ascent beneath these fields. In this study, a technique new to volcano distribution studies, known as cluster analysis, is applied to cinder cone distribution in the central TransMexican volcanic belt (TMVB), Mexico. Hundreds of cinder cones and other volcanoes, including shields and stratovolcanoes [Connor, 1987a; Hasenaka and Carmichael, 1985a, b, 1987; Roggensack, 1988] are found within the TMVB (Figures 1 and 2). The number of cinder cones increases dramatically in the west central part of the TMVB, in an area known as the Michoacán-Guanajuato volcanic field (MGVF). The MGVF, by definition, includes all volcanoes between approximately 101° and 103°W and 19° and 21°N [Hasenaka and Carmichael, 1985a].

Volcanism in the TMVB is spatially associated with several major strike-slip fault zones [Mooser, 1968; Connor, 1987a; Johnson, 1987]. These include the Buenavista and Chapala-

Tepic fault zones (Figure 1). Both have been active in the Quaternary [Johnson, 1987]. Local alignments of cinder cones, consisting of three to seven cones spaced up to 1.5 km apart [Connor, 1987a], are found within these fault zones, usually parallel or en echelon to the strike of the fault zone.

The MGVF has previously been the subject of several quantitative studies of volcano distribution, largely in an effort to characterize the gross, regional distribution of cinder cones and other volcanoes in the field [Settle, 1979; Hasenaka and Carmichael, 1985a; Connor, 1987a] and to identify cinder cone alignments [Connor, 1987a; Wadge and Cross, 1988]. Previous authors have noted that cinder cones show a tendency to cluster in the MGVF [Hasenaka and Carmichael, 1985b; Connor, 1987a].

Using cluster analysis, it is possible to map natural clusters of cinder cones in the TMVB for the first time. Such maps formalize previous observations in a quantitative way, provide unique information about the structure of these cinder cone fields, and can serve as the basis for further hypothesis testing. For example, alignments of cinder cones are often said to be indicative of structural controls, and possibly reflect the orientations of principle horizontal stresses [Kear, 1964; Nakamura, 1977]. It has frequently been noted, however, that recognition of cinder cone alignments is subjective [cf. Williams, 1950; Nixon, 1982], and therefore their geological significance is difficult to assess. As a result, several recent efforts have focused on quantitative means of recognizing alignments [Lutz, 1986; Wadge and Cross, 1988; Connor, 1987b]. Large-scale inhomogeneities in cinder cone distributions can adversely affect the results of these methods, and cluster analysis can mitigate these effects. Furthermore, once clusters are delineated, it is possible to discuss their similarities and differences in a meaningful way. In the MGVF, spatial changes in petrologic variables, such as Mg number [Hasenaka and Carmichael, 1987], are reassessed in light of the results of cluster analysis.

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Fig. 1. Distribution of the 1016 cinder cones identified in this study (open circles). The study area (inset) encompasses approximately 60,000 km² in the TMVB. Major fault zones [Johnson, 1987] are shown schematically by dashed lines. These are the Buenavista fault zone (B-B') and the Chapala-Tepic fault zone (C-C'). Contour lines are of the approximate distance from the Middle America Trench, which marks the convergent boundary of the North American and Cocos plates. The area of the segment break proposed by Carr *et al.* [1974] is bounded by wavy lines. Note the offset in cinder cone distribution with respect to the trench across this segment break near 101°W. Inset: Pac, Pacific Ocean; GM, Gulf of Mexico.

Univariate descriptive statistics, such as mean distance to nearest neighbor, are often used to characterize cinder cone distributions. This approach has included the use of quartiles and quartile plots, histograms, and distribution testing [Porter, 1972; Settle, 1979; Hasenaka and Carmichael, 1985a; Connor, 1987a]. These approaches have amply demonstrated that near neighbor distributions follow lognormal or Poisson distributions, as would be expected for a uniform random distribution of cones [Larsen and Marx, 1986]. These statistics are useful for comparing overall cinder cone densities among fields in different settings [Settle, 1979].

However, univariate statistics are not useful for characterizing spatial inhomogeneities, such as the occurrence of alignments of cones or clusters, and so cannot successfully describe these important aspects of cinder cone distribution.

A second approach has been density mapping [Porter, 1972; Baker, 1974; Connor, 1987a]. In this method, contours of density distribution are drawn, based on the number of cones occurring within some arbitrary area. A density contour map for the TMVB, using cinder cones plotted in Figure 1, is shown in Figure 3. Several modes appear on this plot, suggesting that cinder cones cluster within the arc. Drawbacks

Fig. 2. Distribution of stratovolcanoes (solid circles) and shields (open circles) in the central TMVB [Roggensack, 1988]. These volcanoes, like cinder cones, show an offset in trench-arc distance at approximately 101°W. Other symbols and labels are as in Figure 1.

Fig. 3. Density map of the distribution of cinder cones in the central TMVB. The density was calculated by summing the number of cinder cones (Figure 1) within a given area about each grid point, using a grid spacing of 10 km, and a search radius of 7.5 km. The density values were then contoured using the same grid spacing by applying a minimum curvature contouring algorithm. The contour interval is 5 cones/7.5 km search radius. Darkest areas show highest cinder cone concentrations.

inherent in density mapping are that the results are strongly influenced by grid spacing and search radius about each grid point.

Generally, recognition of cinder cone alignments and clusters has been subjective. Recently, quantitative methods have emerged that help to assess the significance of alignment orientations. Three of these are the two-point azimuth method [Lutz, 1986; Wadge and Cross, 1988; Zhang and Lutz, 1989], the Hough transform [Wadge and Cross, 1988], and the two-dimensional Fourier transform [Connor, 1987b]. Although these techniques will not be discussed in detail here, it will be shown that their utility is enhanced when they are used together with cluster analysis.

CLUSTER ANALYSIS

Methods

Cluster analysis is an exploratory data analysis technique. Assumptions about the significance of a given volcano spacing [Porter, 1972; Connor, 1987a] that may mask cinder cone clusters need not be made. Many different clustering algorithms exist. In this analysis a modification of uniform kernel density fusion cluster analysis [Wong, 1982; Wong and Lane, 1983; Wong and Schaak, 1982] developed by Sarle [1985] is used to search for natural, spatial groupings of cinder cones. This method was chosen because the outcome depends on variation in the spatial density of cinder cones, rather than on the distribution of individual cones. As a result, the clustering algorithm will identify modes in cinder cone distribution. The method is robust in the sense that even if two distinct modes in cinder cone density distribution overlap slightly, they will be recognized as two clusters. Most other clustering algorithms cannot deal with this sort of overlap, or "fuzzy clustering", successfully because these algorithms identify clusters solely on the basis of individual points. For example, applying these "single-point" clustering algorithms, a single cone located between two otherwise compact clusters will frequently cause the two clusters to clump into one. Density fusion analysis will identify the two clusters because this algorithm is sensitive to the density of cones. Depending on a search radius parameter, described below, the outlying cone will be grouped with either cluster, or form a third cluster. As the number of cones between the two clusters increases, the ability to distinguish modes

becomes more important. This effect is seen in many of the results of the cluster analysis of TMVB cinder cones.

Furthermore, density fusion cluster analysis is less sensitive to cluster shape than other algorithms, which tend to search for either compact or elongate clusters [Sarle, 1985]. This is considered an advantage because it avoids a priori assumptions about cluster shape.

Despite its name, the uniform kernel density fusion clustering algorithm is relatively straightforward. A circle of radius r is drawn about each cone in the field. The number of cones within this circle is $f(X_i)$, for the i^{th} cinder cone. An $n \times n$ dissimilarity matrix is created where n is the number of cinder cones in the field and each element of the matrix is

$$d^*(X_i, X_j) = \frac{1}{2} \left[\frac{1}{f(X_i)} + \frac{1}{f(X_j)} \right] \quad \text{if } d(X_i, X_j) < r$$

$$d^*(X_i, X_j) = \infty \quad \text{otherwise}$$

and $d(X_i, X_j)$ is the map distance between the i^{th} and j^{th} cinder cone. In words, an element in the matrix will have a small value if the cinder cones i and j are separated by any distance less than r and there is a high density of cinder cones about them. The element will have a larger value if the cinder cones are separated by any distance less than r and there is a relatively low density of cinder cones about them. If cones i and j are not within distance r of each other, the value of the element is set equal to infinity.

Once this matrix is calculated, the clustering algorithm begins to join the individual elements of the dissimilarity matrix into clusters. This is done by linking cones using a single linkage clustering algorithm [Hartigan, 1975; Le Maitre, 1982] starting with the smallest values of d^* and progressing toward larger values of d^* . As each cluster is joined with another cluster or individual vent, a test is performed. If the density fusion d^* between the two clusters is less than the maximum d^* between any individual vents within either cluster, then the clusters are not joined. This process continues repetitively until a stable number of clusters are found, at which point a map is made, showing the distribution of individual cones by cinder cone cluster. These clusters are modes in cinder cone density distribution. The number of

clusters identified will depend on the search radius, the density of cinder cones, and the occurrence of gaps in cinder cone distribution.

Of course, by changing the starting search radius r , different numbers of clusters are identified. In practice, the cluster analysis is done repeatedly, using many different search radii and many maps are produced, each of which shows cinder cones by their cluster membership. If clustering is a significant aspect of cinder cone distribution, these clusters will not change membership, or change membership only slightly, with large changes in the search radius, r . If clustering is not a significant aspect of cinder cone distribution then cluster membership, and the total number of clusters, will change rapidly with changes in the search radius. Note that although cluster analysis is quantitative and the results are repeatable, the results are not tested statistically. In fact, *Wong and Lane* [1983] have shown the difficulty in developing statistics to deal with the results of cluster analysis.

Application in TMVB

Although several areas within the TMVB have been mapped at a large scale [cf. *Williams*, 1950; *Bloomfield*, 1975; *Martin-Del Pozzo*, 1982; *Connor*, 1987a; *Hasenaka and Carmichael*, 1985b], the arc has not been mapped in enough detail to show the distribution of all vents. This is due to the large area of the arc and the tremendous number of volcanoes found there. Therefore, to obtain a uniform sample, the following criteria were used to recognize cinder cones on 1:50,000 scale topographic maps. Cinder cones that are included in this analysis have basal diameters of less than 2 km, are circular or sickle-shaped, and are defined by at least four closing contour lines (20-m contour interval) (Figure 1). This places a bias on the results because smaller or highly degraded cinder cones are not included. However, smaller cinder cones are difficult to identify consistently on topographic maps and could easily be misinterpreted. Coalescing vents were counted as single cinder cones unless each vent was defined by four or more closing contours. Most authors who have mapped areas within the arc counted individual vents [*Bloomfield*, 1975; *Martin-Del Pozzo*, 1982; *Connor*, 1987a; *Hasenaka and Carmichael*, 1985b], but these

vents could not be identified consistently based on their topographic expression alone. Cinder cones identified in this manner were checked against data sets collected by previous authors that cover parts of the current study area [*Bloomfield*, 1975; *Martin-Del Pozzo*, 1982; *Connor*, 1987a; *Hasenaka and Carmichael*, 1985b]. This comparison indicates that the number of cones present has been consistently underestimated in this study by 20%, due to the presence of small cones and coalescing vents. In this case, the advantages of using rigid criteria for the identification of cinder cones outweighs the disadvantage of biasing the results. The sampled distribution provides a good estimate of cinder cone distribution unless small or coalescing vents are distributed differently than vents of greater than 80 m relief. Comparison with mapped areas indicates that this is not the case. From area to area, the percentage of missed cones remains the same with greater than 95% confidence (t test). A listing of the locations of cinder cones used in this analysis is available from *Connor* [1987b].

A plot of the number of clusters by search radius (Figure 4) shows that the rate of change in the number of clusters with changing search radius is greatest at search radii less than about 15 km, changes more slowly between search radii of 15 and 27 km, and changes very slowly at search radii of more than 27 km. Based on the plot alone, it is not possible to assess the significance of clusters found at various search radii because it cannot be determined from the graph if clusters consist of small groups of outlying cones or large modes in cinder cone distribution. Consequently, maps of cinder cone distribution by cluster were produced at a large number of search radii. Altogether, 12 such maps were produced. Four of these maps are shown in Figures 5a-5d.

At long search radii, most cinder cones are members of large clusters; very few outliers (clusters consisting of few cones or isolated cones) are present. Four cinder cone clusters are found using search radii between 40 and 50 km (Figure 5a). The MGVF and cones located east of this field to about 100°W are members of a single cluster. An isolated cluster is found south of Mexico City in the Sierra Chichinautzin (cluster 2), and another in the northeast part of the study area (cluster 3; Figure 5a). Search radii of 30 km reveal two large distinctive clusters in the MGVF (clusters 1 and 2; Figure 5b). Each of these clusters encompasses an area of several thousand square kilometers and is NE trending.

Fig. 4. Number of clusters as a function of search radius. There is little change in the number of clusters at search radii greater than 27 km. Between 27 and about 15 km, the number of clusters increases steadily with decreasing search radius. At search radii less than 15 km, the number of clusters increases very rapidly with shorter search radii. Figure 5 shows maps of cinder cone distribution by cluster membership at various search radii.

Fig. 5. Distribution of cinder cones, plotted by cluster membership (integers). Cones belonging to the same cluster are plotted using the same integer; the clusters are not numbered in any specific order. These maps show cinder cone distribution by cluster membership using search radii of (a) 40 km, (b) 30 km, (c) 20 km, and (d) 16 km. Larger clusters (a,b) fragment into smaller clusters (c, d) as search radii decrease. However, even at relatively short search radii (d) cinder cone distribution is best characterized by several modes; relatively few outlying cinder cones are found.

At shorter search radii these large clusters split into smaller groups (Figures 5c-5d). Most of these clusters persist over search radii between 24 and 15 km and most variation in the total number of clusters is due to the fragmentation of clusters consisting of 10 or fewer cones. Using search radii of 16 km (Figure 5d), a total of eight clusters of 45-159 cinder cones each were identified (clusters 1-7 and 9, Figure 5d). Approximately 75% of the cinder cones in the central TMVB are found within these eight clusters. The remaining 25% are distributed among 23 clusters. Because these clusters do not change membership in a significant way over a range of search radii, they are viewed as significant features of cinder cone distribution in the TMVB. Comparing the results of the cluster analysis (Figure 5d) with a contour map of cinder cone density distribution (Figure 3) demonstrates that the large clusters correspond to modes in cinder cone density distribution. These clusters have areas of 2000-5000 km² each, and their mean centroids are separated from their nearest neighboring centroid by between 43 and 53 km. In all, only 22 cones are members of clusters of three or fewer cones. Of note on these cluster maps (Figures 5c-5d) is that the cones of the MGVF have been split into several large clusters. The few outlying cones in this field are found to the northwest.

REGIONAL ALIGNMENT ANALYSIS

Several authors have searched for and discussed the nature of alignments of cinder cones in the TMVB [Williams, 1950; Connor, 1987a; Hasenaka and Carmichael, 1985a; Wadge and Cross, 1988]. Local alignments, usually no longer than 10 km and consisting of no more than seven vents, have been found throughout the arc. Local alignments are most abundant in the northern MGVF, where they are characteristically oriented E-W, en echelon, and sometimes parallel to major fault zones. Local alignments in the southern MGVF are characteristically oriented at azimuths of 020°-040°, parallel to the direction of plate convergence [Connor, 1987a].

Methods used in these investigations have largely been subjective, although Wadge and Cross [1988] used the two-point azimuth method [Lutz, 1986] and the Hough transform, as a means of identifying alignments in a quantitative way. Lutz [1986] noted that inhomogeneities in point distributions can adversely affect the results of the two-point azimuth method. Therefore, in this study the two-point azimuth and Hough transform methods were applied on a cluster by cluster basis, using the eight largest clusters identified at search radii of 16 km (Figure 5d). The two-point azimuth method was also applied to clusters identified using longer search radii. In addition, a third method, two-dimensional Fourier analysis [Connor, 1987b], was used as a tool for the identification of alignments within large clusters.

Two-Point Azimuth Results

The two-point azimuth method is a Monte Carlo simulation model and provides a statistical test for the significance of point alignments in a particular orientation [Lutz, 1986]. Here, the two-point azimuth method was applied to individual clusters within the TMVB identified at search radii between 20 and 16 km. Alignments were identified at 10° intervals and only directions different than those expected from the Monte Carlo simulation with greater than 95% confidence are considered anomalous. Using these criteria, three clusters in the TMVB contain significant alignments. These are clusters 1, 3, and 12, all located in the southern MGVF (Figure 5d). In these clusters, cinder cone alignments are oriented between 020° and 040°. Relaxing the confidence level does not substantially alter the results, although northeast trending alignments are significant in cluster 3 (Figure 5c) at the $\alpha = 0.12$ confidence level and northwest trending alignments are

significant in cluster 9 (Figure 5d) at the $\alpha = 0.15$ confidence level. The two-point azimuth method did not reveal trends in larger clusters (Figures 5a-5b) or in the field as a whole ($\alpha = 0.05$ confidence level).

Two-Dimensional Fourier Analysis Results

The utility of two-dimensional Fourier analysis in the recognition of spatial trends has been amply demonstrated [e.g., Clement, 1973; Hildebrand, 1983; Thorarinsson *et al.*, 1988]. An important property of the Fourier transform is that a map trend will be represented on a spectral map by a few, large-amplitude spectra [Clement, 1973]. Large-amplitude spectra at short wavelengths, or anisotropy in the distribution of large-amplitude spectra are indicative of significant trends. If all large-amplitude spectra are limited to long wavelengths and are isotropically distributed on the spectral map, alignments of a particular orientation are not pervasive in the cluster. Like the two-point azimuth method, the Fourier analysis is sensitive to regional trends, that is, multiple trends in the cluster of a particular orientation. Each cluster (clusters 1-7, and 9; Figure 5d) was gridded using a 64 x 64 grid matrix, tallying the number of cones about each grid point. Small clusters, such as cluster 12 (Figure 5d), cannot be analyzed in this way because of the few cones found within the cluster. The results of the Fourier analysis for three clusters, and the results of the Hough transform described below, are given in Figures 6-8.

Spectral maps of clusters 1 and 3 have substantial anisotropy (Figures 6c and 7c). There is also significant autocorrelation within these clusters at large lag distances, indicating that significant trends exist within these clusters (Figures 6d and 7d). The distribution of these trends are revealed on phase maps, produced using only large amplitude spectra (Figures 6a and 7a). In both of these clusters, multiple alignments of cinder cones, with usually more than 10 cinder cones in each alignment, are found oriented between 020° and 040°, consistent with the results of the two-point azimuth method. Cluster 9 (Figure 5d) also contains some anisotropy, which suggests trends oriented at an azimuth of approximately 315° are present, though not as well developed as in clusters 1 and 3. Conversely, large-amplitude spectra for clusters 2 and 4-7 (Figure 5d) are limited to long wavelengths and are isotropically distributed. For example, large-amplitude spectra in cluster 4 (Figure 5d) are limited to wavelengths greater than 20 km (Figure 8c) and large autocorrelation coefficients do not occur at lags greater than 17 km (Figure 8d). A phase map of this cluster reveals the isotropic character of cinder cone distribution, although local alignments are present, they do not form a pattern, as alignments do in clusters 1 and 3.

Hough Transform Results

Wadge and Cross [1988] applied a computer enhancement technique, the Hough transform, to cinder cone distributions in the entire MGVF. Each vent in a cluster lies along an infinite number of lines, each line having a unique azimuth. These lines can be represented in polar coordinates as curves. A point on one of these curves has the coordinates ρ and θ , where ρ is the shortest (normal) distance from that arbitrary point to the line, and θ is the angle of that normal from zero [Wadge and Cross, 1988]. In this case, the mean cluster centroid is chosen as the center of the coordinate system. If, for example, four vents within a cluster align exactly, the four sinusoidal curves associated with these vents in ρ, θ parameter space will intersect at a single ρ, θ coordinate, which in turn yields the orientation and position of the line, relative to the cluster centroid.

Fig. 6. Results of the alignment analysis for cluster 1 (Figure 5d). (a) A phase map constructed using only large amplitude spectra indicates that alignments are NE trending within this cluster. Only spectra having amplitudes larger than the 99th percentile (spectra larger than 99% of all spectra for the cluster) were used to produce this map; smaller-amplitude spectra were filtered completely after a Hanning filter was applied [Clement, 1973]. The same procedure was used for other clusters (Figures 7 and 8). Phase map contour interval is 0.25 cones / 2.5 km². (b) Application of the Hough transform reveals several cinder cone alignments oriented at azimuths of 020°-030° within this cluster (solid lines). These alignments are statistically significant (two-point azimuth method, $\alpha = 0.05$ confidence level). Cinder cones are plotted as solid triangles. (c) Spectral map for cinder cone density distribution. The 90th, 95th, and 99th (shaded) percentiles are contoured. Large-amplitude spectra are anisotropic and isolated large amplitude spectra occur at wavelengths of 9.5-10 km, indicative of the presence of NE trending alignments. (d) Autocorrelation surface contoured at 90th, 95th and 99th (shaded) percentiles. Large autocorrelation coefficients are elongate northeast, and isolated large autocorrelation coefficients occur at lags of up to 27 km, an additional indication of the prominence of NE trending alignments.

In practice, discrete $\Delta\theta$ and $\Delta\rho$ are used. Here $\Delta\theta = 2^\circ$ and $\Delta\rho = 400$ m, the same values used by Wadge and Cross [1988], are taken to represent reasonable fracture zone sizes. This method is sensitive to the number of cinder cones used in the analysis and the shape of the cinder cone cluster. The more cinder cones in a cluster, the more likely it is that several cinder cones will align. If a cluster is elongate, alignments will likely be found in the direction of elongation. The method also is modified by mapping only those alignments consisting of greater than a specific number of cones. In this analysis, this parameter was varied and the transform was applied to the same cluster numerous times. The results on a cluster by cluster basis were much the same as those obtained by Wadge and Cross [1988] in their analysis of the field as a whole. The results for clusters

1, 3, and 4 are presented in Figures 6b, 7b, and 8b, respectively. Again, northeast trending alignments are found in clusters 1, 3, and 12.

Summary of Alignment Analysis

Significant alignments were identified using these methods in several cinder cone clusters. Three of these clusters are located in the southernmost MGVF, at relatively short trench-arc distances (clusters 1, 3, and 12; Figure 5d). These alignments are up to 20 km long and generally consist of 10 or more cones. The alignments identified within these clusters have common orientations. The two-point azimuth method indicates that statistically significant (>95% confidence) alignments occur between azimuths of 20° and 40° within

Fig. 7. Results of the alignment analysis for cluster 3 (Figure 5d). (a) A phase map constructed using only large-amplitude spectra indicates that alignments are NE trending within this cluster. Only spectra having amplitudes larger than the 99th percentile were used to produce this map as in cluster 1 (Figure 6). Phase map contour interval is 0.1 cones / 2.5 km². (b) Application of the Hough transform reveals several cinder cone alignments oriented at azimuths of 020°-040° within this cluster (solid lines). These alignments are statistically significant (two-point azimuth method, $\alpha = 0.05$ confidence level). Cinder cones are plotted as solid triangles. (c) Spectral map for cinder cone density distribution. The 90th, 95th, and 99th (shaded) percentiles are contoured. Isolated large-amplitude spectra are found at wavelengths of 7-8 km, indicative of the presence of NE trending alignments. (d) Autocorrelation surface contoured at 90th, 95th and 99th (shaded) percentiles. Large autocorrelation coefficients are elongate northeast, and isolated large autocorrelation coefficients occur at lags of up to 25 km, again indicative of a highly structured cinder cone map pattern.

these clusters, orientations consistent with those of alignments identified using the Hough transform. NE trending alignments are so prevalent within these clusters that they create distinctive map patterns, revealed through two-dimensional Fourier analysis, unlike alignments found elsewhere the TMVB. Similar, though less developed, patterns occur in cluster 9, where alignments trend northwest, colinear to the distribution of smaller cinder cone clusters found to the southeast (Figure 5d).

In other clusters, significant alignments could not be identified using the two-point azimuth method or two-dimensional Fourier analysis. The Hough transform, which is sensitive to even short, local alignments, identifies local alignments in all of these other cinder cone clusters [Wadge and Cross, 1988].

DISCUSSION

Structural Implications

Carr *et al.* [1974] first proposed that the TMVB is a segmented arc, based on their analysis of the distribution of volcanoes. Although the mechanisms responsible for arc segmentation are still debated [Stoiber and Carr, 1979; Marsh, 1979; Nixon, 1982; Burbach *et al.*, 1984; Carr, 1984], it is clear that the trench-arc distance is offset along the axis of the TMVB. In the MGVF, cinder cones, shields, and stratovolcanoes are found as close to the trench as 200 km, and there is a high concentration of volcanoes at approximately 275 km from the trench (Figures 1 and 2) [Connor, 1987a; Wadge and Cross, 1988]. Near longitude 101°W, however, there is a shift in trench-arc distance. East of 101°W, volcanoes are found at trench-arc distances of more

Fig. 8. Results of the alignment analysis of cluster 4 (Figure 5d). (a) A phase map constructed using only large-amplitude spectra indicates that regional alignment patterns are not found within this cluster. Only spectra having amplitudes larger than the 99th percentile were used to produce this map as in cluster 1 (Figure 6). Phase map contour interval is 0.1 cones / 4.5 km². (b) Application of the Hough transform reveals several cinder cone alignments within this cluster (solid lines). Alignments of these orientations are not abundant enough to be statistically significant (two-point azimuth method, $\alpha = 0.05$ confidence level). Cinder cones are plotted as solid triangles. (c) Spectral map for cinder cone density distribution. The 90th, 95th, and 99th (shaded) percentiles are contoured. Large amplitude spectra are isotropically distributed and limited to long wavelengths. (d) Autocorrelation surface contoured at 90th, 95th and 99th (shaded) percentiles. Large autocorrelation coefficients are not found at lags of greater than 17 km in this cluster, suggesting that patterns in cinder cone distribution do not persist over broad areas in this cluster.

than 325 km. Although the overall trend of the TMVB is east-west, arc segments have a trend of approximately N60°W, roughly parallel to the Middle America Trench. These trends are particularly well illustrated by the distributions of shield and stratovolcanoes in the arc (Figure 2) [Connor, 1987a]. Wadge and Cross [1988] identified a NW trending anisotropy in MGVF vents, using a data set that includes shields and stratovolcanoes [Hasenaka and Carmichael, 1985b]. Prominent fault zones, such as the Buenavista fault zone (Figure 1), parallel these northwest trending segments, as do some cinder cone alignments. These trends persist northwest of the study area. The Buenavista fault zone and nearby volcanoes are colinear to the western portion of the arc and the Zacualco graben [Connor, 1987a]. However, the analysis of cinder cone distributions reveals trends of primarily different orientations.

Multiple alignments with common orientations on a regional scale were identified within three clusters in the southernmost MGVF. These alignments, separated from one another by up to 120 km, are all oriented 020°-040°, parallel to the direction of plate convergence and the segment break. Alignments in the southern MGVF, which are generally more than 20 km in length and consist of numerous cinder cones, are unlike the local alignments identified farther to the north. The length of these alignments, and the number of cones found within them, suggests that they are produced by faults, or fault zones, up which the migration of magma is enhanced. It may be that the maximum horizontal compressive stress associated with these regional alignments is oriented 020°-040°, assuming that alignments form over a tensile fracture set. However, caution is needed in this regard because these regional alignments may owe their origins to more complex

structural features. For instance, regional cinder cone alignments can occur parallel to strike-slip shear zones, over en echelon fracture sets. Other structures along shear zones, such as overstepping faults and releasing bends, could create cinder cone alignments as well [Segall and Pollard, 1980; Christie-Blick and Biddle, 1985].

No direct relationship exists between alignment patterns in the southern MGVF and major strike-slip fault zones. Apparently, the Buenavista and Chapala-Tepic fault zones in the TMVB do serve as pathways up which some magma ascends, producing local alignments, but do not provide the permeability necessary for the development of regional cinder cone alignment patterns. Therefore, the regional pattern of alignments in the southern MGVF must be related to some pre-existing features, such as basement lineaments, or, considering their position and orientation, are formed due to stresses produced by the underthrusting of the Cocos plate.

Carr [1984] and Walker [1981] noted that cinder cone fields are characteristically emplaced at such segment breaks in the Central America arc. In the TMVB, the highest concentrations of cinder cones are found on and adjacent to the segment break, in the MGVF. This is illustrated by the cluster analysis. At large search radii, the cinder cones of the MGVF are distributed among two clusters of more than 100 cones each. These clusters are NE trending, roughly perpendicular to the orientation of the arc segments (clusters 1 and 2, Figure 5b). The large NE trending clusters identified at long search radii in the MGVF are not likely produced by crustal structures [Connor, 1987a], rather their shape and orientation may be indicative of plate segmentation.

Petrologic Implications

Penecontemporaneous high-Mg alkaline and calc-alkaline volcanism has occurred in the southern MGVF throughout the Quaternary [Hasenaka and Carmichael, 1987]. In addition, Hasenaka and Carmichael [1985a] and Luhr and Carmichael [1985] note the occurrence of Ne-normative alkaline lavas in one cinder cone, Cerro Pilita, in the southern MGVF. These alkaline lavas most likely reflect distinct, low percentage melting events of the same source which produces calc-alkaline magmas at higher percentages of melting [Luhr et al., 1989]. Elsewhere, Ne-normative alkaline basalts are found in unusual tectonic settings [DeLong et al., 1975]. These include the terminae of subduction zones, segment breaks [DeLong et al., 1975; Marsh, 1979], and grabens associated with rifting [Luhr et al., 1985; Luhr and Carmichael, 1985]. As rifting is not associated with the generation of these magmas, these observations support the segmentation model proposed by Carr et al. [1974].

At shorter search radii, clusters 1 and 2 (Figure 5b) within the MGVF break apart into several clusters. Much of the petrologic variation in the TMVB can be explained by an arc model, in which progressively more alkaline rocks are found with increasing distance from the trench [Hasenaka and Carmichael, 1985a; Luhr and Carmichael, 1985], as long as high-Mg lavas of the southern MGVF are excluded [Hasenaka and Carmichael, 1987]. In general, there is a shift to increasingly alkalic rocks with increasing distance from the trench. The results of the cluster analysis suggest that this is not a continuous process, even if high-Mg lavas are excluded. In the MGVF, low-Mg alkaline lavas are limited to cluster 9 (Figure 5d), at a trench distance of 350–400 km. This is spatially distinct from clusters to the south, even at long search radii (Figures 5b–5c). Low-Mg alkaline lavas occur not only at large trench distances [Hasenaka and Carmichael, 1987] but also in spatially distinct groups. This situation is similar to that observed in composite volcano petrology in several other arcs. For instance, in the Aleutians there is a gap of 50 km between calc-alkaline volcanism within the arc and

alkaline volcanism behind the arc [Marsh, 1979]. In the western TMVB, the gap between the mean center of cluster 9, containing alkaline lavas, and clusters to the south is about 50 km.

Hasenaka and Carmichael [1985a, 1987] found, through the application of ol-aug-pl geobarometry, that when all MGVF lava compositions are considered, a polybaric fractionation history is typical. Ol-aug-pl geobarometry indicates that high-Mg lavas of the southernmost MGVF last fractionated at depths of greater than 8 kbar [Hasenaka and Carmichael, 1987]. Hasenaka and Carmichael [1987] assert that these petrologic variations are related to the structural setting of the field. They suggest that high-Mg lavas ascend rapidly along fractures or faults in the southern MGVF. The results of the spatial analysis support this conclusion and provide a map of the location of these alignments (Figures 6 and 7). Although local alignments of cones are abundant in the northern part of the MGVF [Hasenaka and Carmichael, 1985a; Connor, 1987a], regional patterns of alignments do not exist in any of these clusters. High-Mg lavas are only found associated with the regional alignments, identified through spatial analysis.

Variation in the number and distribution of clusters with varying search radii may provide insight into the processes of magma generation and rise. One possibility is that clusters found at different search radii reflect spatial association of magmas at different levels in the crust or mantle. Maps of clusters produced using large search radii may reflect deep levels of spatial association; maps produced using short radii may reflect shallow spatial association. A problem with this model is that even in short alignments, cinder cones often have little in common in terms of their fractionation histories [Hasenaka and Carmichael, 1987]. Alternatively, clusters may reflect progressively more localized melting events. Broad zones of melting are reflected by large clusters, more localized (and more effective) melting reflected by clusters found at shorter search radii. Through time there is a tendency for discrete melting events to occur in close proximity to one another, rather than occurring randomly throughout the field.

CONCLUSIONS

1. Cluster analysis provides a means of identifying and mapping cinder cone clusters in a quantitative way. At search radii of 16 km, 75% of cinder cones form eight large clusters of 45–159 cones each. Few outlying cones, or clusters of three or fewer cones are identified. This distribution indicates that cinder cone clustering is a pervasive phenomenon in the TMVB. In the MGVF, low-Mg alkaline cinder cones are limited to a single cluster, located between 360 and 400 km from the trench.

2. Through the application of quantitative alignment analysis methods, multiple cinder cone alignments having common orientations on a regional scale, lengths greater than 20 km, and each consisting of 10 or more cones are found within three clusters in the southern TMVB. High-Mg lavas are associated with these alignments, a further indication that magma migration is enhanced in these areas.

3. Although the orientations of local alignments of cinder cones are influenced by the distribution of major strike-slip fault zones, regional alignment patterns, and the distribution of clusters themselves, do not appear to be affected by the presence of these fault zones.

4. Several observations support the segmentation hypothesis as originally proposed by Carr et al. [1974]. (1) There is a nearly 100 km offset in trench-arc distance in the distribution of stratovolcanoes, shield volcanoes, and cinder cones near 101°W. (2) There are a tremendous number of cinder cones in the MGVF. These form two large clusters, both elongate N35°E, roughly perpendicular to the overall trend of the arc and parallel to the direction of plate convergence. (3)

Multiple alignments of cinder cones found in the southernmost MGVF, are oriented N20°-40°E, again, parallel to the direction of plate convergence.

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C.B. Connor, Department of Geology, Florida International University, Miami, FL, 33199.

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