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Numerical recognition of alignments in monogenetic volcanic areas: Examples from the Michoacán-Guanajuato Volcanic Field in Mexico and Calatrava in Spain

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ABSTRACT

Identification of geological lineaments using numerical methods is a useful tool to reveal structures that may not be evident to the naked eye. In this sense, monogenetic volcanic fields represent an especially suitable case for the application of such techniques, since eruptive vents can be considered as point-like features. Application of a two-point azimuth method to the Michoacán-Guanajuato Volcanic Field (Mexico) and the Calatrava Volcanic Province (Spain) demonstrates that the main lineaments controlling the distributions of volcanic vents (~322° in Calatrava and ~30° in Michoacán) approach the respective main compressional axes that dominate in the area (i.e. the Cocos–North America plates convergence and the main Betics compressional direction, respectively). Considering the stress fields that are present in each volcanic area and their respective geodynamic history, it seems that although volcanism may be a consequence of contemporaneous extensional regimes, the distribution of the volcanic vents in these kinds of monogenetic fields is actually controlled by reactivation of older fractures which then become more favourable for producing space for magma ascent at near-surface levels.

1. Introduction

Monogenetic volcanism is characterized by the occurrence of volcanoes that are formed during a single short-lived episode of activity and clustered within volcanic fields (see Connor and Conway, 2000; Valentine and Gregg, 2008 and Walker, 2000). Therefore, such fields can be considered as relatively self-consistent structures made up of point-like features (i.e. the volcanic vents). While location and spatial distribution of monogenetic fields are believed to be a result of the size and shape of the magma source, the distribution of the volcanic vents within a field is a consequence of the geological structure and stress conditions of the crust at the time of the activity (see Zhang and Lutz, 1989). Thus, the spatial distribution of points (in this case the volcanic vents), may be useful to reveal fracturing patterns and other geological structures. This idea is supported by current concepts on the ascent of basaltic magma through the crust (see Valentine and Gregg, 2008) which suggests that, although basaltic magmas ascend through most of the Earth's crust via self-propagating fluid driven fractures, as a rising basaltic dike nears the Earth's surface, it is increasingly influenced by pre-existing structures which may "capture" the dike path. However, identification of alignments in volcanic fields can be difficult because aligned vents are usually interspersed along a greater number of unaligned cones (Connor and Conway, 2000). This has led many authors to develop different methods to describe in a quantitative way the distribution of volcanic vents in order to relate it to the structural characteristics of the crust in volcanic areas. The main advantage of the numerical methods for the identification of geological alignments is that they can be replicated, and more importantly, they can help to reveal structures that may not be evident to the naked eye.

In this work we describe a simplified implementation of the two-point azimuth method, based on the nearest-neighbour concept, which allows easier identification of lineaments in monogenetic volcanic fields using as examples two suitable cases: Michoacán-Guanajuato in Mexico and Calatrava in Spain. Both share the characteristics of typical monogenetic fields made up of isolated volcanic vents (i.e. they can be considered as point-like features) but have different sizes and shapes, and are located in distinct geodynamic settings. The first is associated with subduction-related arc magmatism (see Gómez-Tuena et al., 2007b) and the second one with intraplate magmatism (see López-Ruiz et al., 2002).

2. Numerical identification of volcanic alignments

Some of the earliest attempts to describe in a semiquantitative or quantitative way the distribution of vents in volcanic fields relied on the average orientations of nearby cones (e.g. Kear, 1964), density mapping of cones (e.g. Porter, 1972) and also on statistical analysis based on nearest-neighbour and quadrant methods (e.g. Tinkler, 1971).

Some of the methods proposed for the quantitative description of the distribution of volcanic vents are specifically focused on the

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identification of possible alignments, particularly in areas where this kind of distribution is not evident. This relies on the observation that the extrusion of magma must be linked to fractures in the crust and therefore there exists a close relationship between volcanic vent distribution and the stress regime of the upper crust at different scales (see for example Delaney et al., 1986 or Valentine and Gregg, 2008). The methods proposed to discern those alignments that are statistically more probable can be categorized into three main types (see Hammer, 2009): (1) Spatial Transform methods, (2) Azimuth methods, and (3) Strip methods. Spatial Transform methods are usually applied in computer-aided pattern recognition or image analysis and in general involve simplifying the amount of resources required to describe a large set of data accurately. In geological applications the *Hough Transform* is one of the most widely used Spatial Transform techniques, and it is based on replotting the points onto a domain that better describes the geometric feature of interest (see Wadge and Cross, 1988 and Connor, 1990). Azimuth methods, originally implemented by Lutz (1986), quantify the angles of lines connecting all pairs of points within an area of interest, determining the most likely trends of structural anisotropies. Finally, Strip methods (see Zhang and Lutz, 1989) are based on the use of parallel strips sweeping the whole area of interest at different positions and azimuths, identifying as the most significant strips those enclosing the higher density of points.

Each of the above mentioned methods has its own advantages and shortcomings. For example, Spatial Transform methods in general simulate human visual capability, but human visual interpretation is poor at selecting sets of widely spaced points on which the *Hough Transform* method depends (Arcasoy et al., 2004). Azimuth methods are believed to be very dependent on the shape of the working area, which may introduce a bias on the directions detected (Arcasoy et al., 2004), but subsequent implementations of the original method by Lutz (1986) have overcome this problem (see for example Hammer, 2000; Lutz and Gutmann, 1995; Wadge and Cross, 1988). The Strip method was described in detail by Zhang and Lutz (1989) although a simplified variant was previously applied to the Calatrava Volcanic Province (Ancochea and Brändle, 1982), and it has also been subsequently refined in different ways (e.g. Arcasoy et al., 2004). The main disadvantage of Strip methods is that they may fail to detect small-scale features and also that the width of the strips, and therefore the spatial resolution, may vary somewhat as a function of orientation.

In the following sections we present an alternative Azimuth-based method which can be easily applied to monogenetic volcanic fields. The method is then tested in two well-known areas (the Michoacán-Guanajuato Volcanic Field in Mexico and Calatrava in Spain), with different sizes and shapes, and developed in distinct tectonic settings.

2.1. An alternative Azimuth-based method

The aim of azimuth-based techniques is to detect possible alignment directions by the determination of the orientations of lines connecting all possible pairs of points (i.e. for N points, the total number of lines is $N(N-1)/2$). If there is a preferential alignment of points, it should be evidenced by a predominant orientation of those lines. In the case of monogenetic fields, the location of each volcanic vent can be assumed to represent a discrete point. This assumption does not introduce significant errors in the results, whenever the calculations are performed at regional scale and the obtained azimuths are interpreted within adequate confidence intervals.

Straightforward application of this approach produces a relatively high number of non-significant data, and therefore some filtering must be applied in order to discriminate the most likely orientations. In the original implementation by Lutz (1986), Monte Carlo simulations of random point patterns were used as a reference distribution from which confidence levels were determined. Although this solution produces more solid results from a mathematical point of view, in our approach we have tried to overcome this problem in a simpler way, based on the nearest-neighbour concept. Following Kear's 1964 ideas, we propose that in monogenetic fields, any eruptive centre should be in general more closely related to the nearest vents and, very likely, this relationship should be a consequence of the presence of a fracture. According to this scheme, we propose to constrain the azimuth calculations to the lines which connect those vents that are closer to each other. A possible method to implement this idea is to start the calculations with the shortest possible inter-vent distance measured in the volcanic field of interest. Increasing the distance between vents to be connected in successive calculations a point is reached where one or more dominant directions are best exposed (i.e. those that have a higher frequency in the total population of azimuths). This is considered as the *minimum significant distance*, which should be able to reveal local-scale structures predominantly, whereas large-scale ones may be recognized more easily when considering lines connecting more distant vents. To identify the most likely orientation in each calculation, we combine the use of a graphical representation of the considered lines, histograms of frequencies of lengths of vent-connecting lines and rose diagrams, commonly used in structural geology studies. An advantage of this approach is that the representation of the *minimum significant distances* on a regional map should be able to reveal (graphically) not only

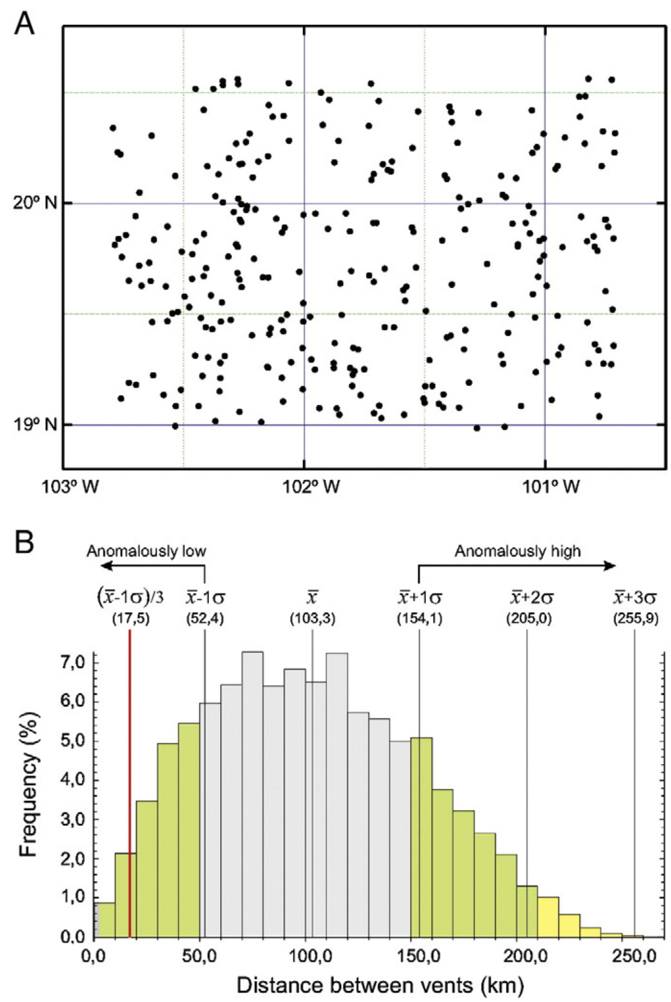

Fig. 1. A) Random dataset generated to simulate the distribution of 300 vents scattered within a rectangle-shaped area similar to the Michoacán-Guanajuato Volcanic Field. B) Frequency histogram (in %) of lengths for all possible lines interconnecting the points, which as expected approaches a normal distribution (skewness = 0.26).

distributions along straight lines, but also curved structures defined by the combination of several short straight lines.

As suggested by Arcasoy et al. (2004), one question to be considered in Azimuth methods is the possibility of obtaining a result even if no actual lineaments exist. We have produced a series of computer-generated datasets using the online *true* random number generator by Haahr (2010), consisting of ~300 points randomly distributed on rectangular-shaped areas with sizes similar to the volcanic areas considered in this work. The two volcanic regions were characterized by differences in shape and size. The number of points is also equivalent to the number of volcanic vents that were finally considered for computation purposes in each volcanic region.

The example presented in Fig. 1A can be considered as representative of these tests and corresponds to a random distribution of points in an area similar to the Michoacán-Guanajuato Volcanic Field. As expected, the distribution of points does not show any conspicuous lineaments and the histogram of frequencies of lengths (Fig. 1B) approaches a normal distribution with skewness values near zero. In our tests, skewness of these random sets is typically around −0.25, while in the considered volcanic regions skewness is usually −0.5, departing in a higher degree from pure normal scattering. Following the above described ideas, possible lineaments should be more easily revealed when considering lines connecting vents at shorter distances (i.e. more likely related by a fracture). These correspond therefore to those distances (d) for which the frequency has a maximum value of less than one standard deviation (σ) from the mean ($\overline{x}$). In the volcanic regions considered in this work, we have observed that optimum settings are obtained at the lower third portion of the anomalous end of the population (i.e. $d \leq [\overline{x} - 1\sigma] / 3$). Applying such a constraint to the random datasets does not enhance any predominant directions (Fig. 2). However, rose diagrams do always indicate some preferential directions (i.e. those that have a frequency above the mean) and therefore any mathematical implementation of this method should not be applied independently of graphical representations of the data and should also be supported by geological observations. As we will show in the following examples, this allows discriminating whether mathematically supported directions actually have a geological meaning.

3. Volcanic alignments in monogenetic fields

To test the above proposed method and with the aim of extracting some general conclusions regarding the distribution of volcanic vents

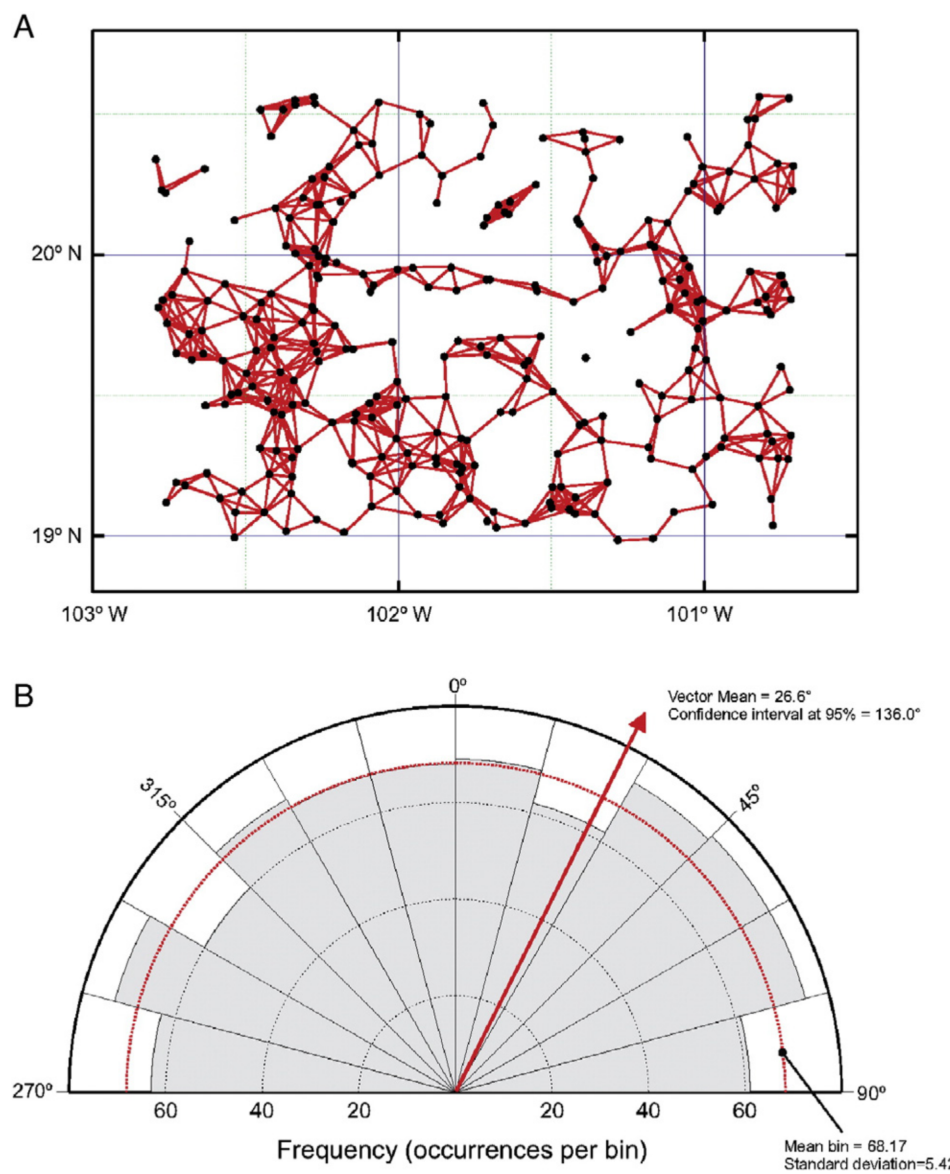

Fig. 2. A) Graphical representation of lines with lengths $d \leq (\overline{x} - 1\sigma) / 3$ (see Fig. 1A), demonstrating a general absence of apparent lineaments. B) Corresponding rose diagram at 15° bin intervals (frequencies as number of occurrences per bin).

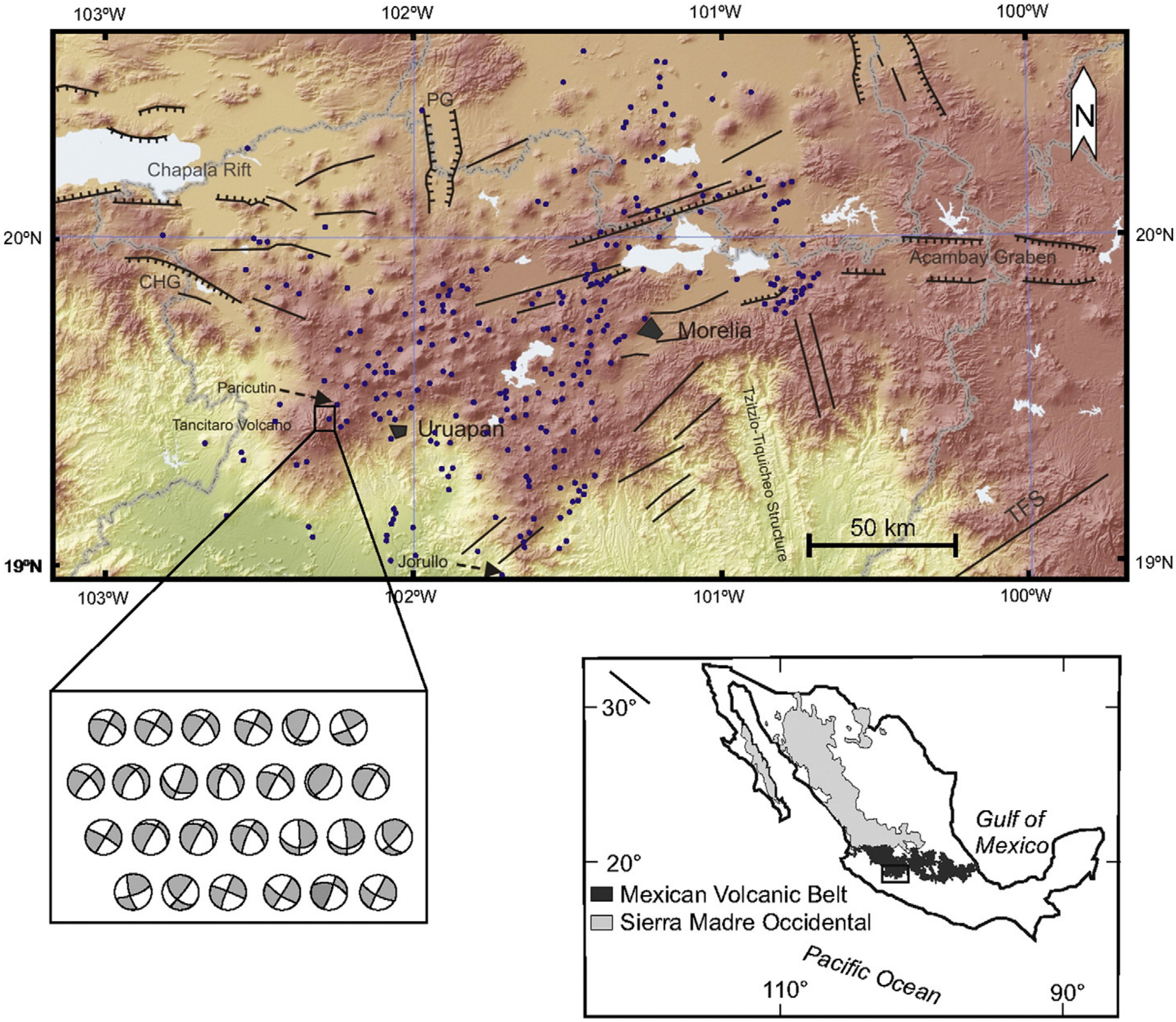

Fig. 3. Location and relief model of the Michoacán-Guanajuato Volcanic Field and surrounding areas, showing the main Cenozoic tectonic features (modified from Gómez-Tuena et al., 2007a) and the distribution of Pliocene to present day monogenetic vents in the volcanic field. CHG = Cotija half-graben, PG = Penjamillo graben, TFS = Teotihuacan fault system. Inset displays the distribution of focal mechanisms of earthquakes in the Tancitaro area (after Pacheco et al., 1999).

in monogenetic fields, we have selected two areas, developed in contrasting geodynamic settings. On one hand we have selected the Michoacán-Guanajuato Volcanic Field (MGVF), which can be considered a reference for monogenetic fields developed in a subduction-related environment. On the other hand, we have considered the so-called Calatrava Volcanic Province (CVP) as a good example of low-volume intraplate monogenetic volcanism.

3.1. The Michoacán-Guanajuato Volcanic Field

3.1.1. General characteristics and previous lineament identifications

The MGVF is situated in the west-central sector of the Trans-Mexican Volcanic Belt (TMVB), a roughly east–west trending belt of Miocene to Holocene age (Fig. 3). The MGVF, which covers some 40,000 km^2, contains more than 1000 small volcanic centres and includes scoria cones, lava domes and maars, as well as almost 400 medium-sized volcanoes, most of which are shield volcanoes (Hasenaka, 1994). Two composite volcanoes are found in the MGVF, the largest being Tancítaro

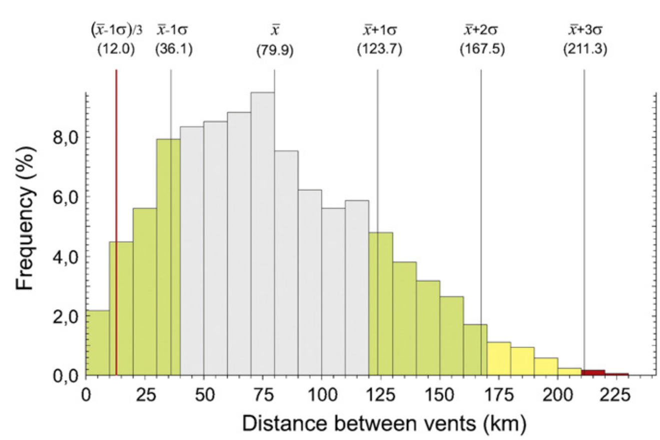

Fig. 4. Histogram of frequencies of lengths for the MGVF (skewness = 0.51). Most frequent lengths (40–120 km) can be considered as background for the region.

(Ban et al., 1992; Hasenaka, 1994; Ownby et al., 2007). Late Pliocene to Holocene volcanism of the MGVF is related to the subduction of the Cocos plate beneath the North American plate along the Middle American Trench (MAT) (Johnson et al., 2009). The front of the volcanic arc occurs at ~190 km from the MAT and MGVF volcanism extends inland another ~230 km (Hasenaka and Carmichael, 1985a).

The most conspicuous tectonic structures recognized in the central part of the TMVB are WNW–ESE to WSW–ENE striking roughly arc-parallel normal faults that have shown activity during the Quaternary and are still active (Suter et al., 2001) (Fig. 3). Suter et al. (1995) have compiled slip data indicating a left-lateral component related to normal faulting that indicates roughly N–S and NNW–SSE extension. This system of extensional faults extends from Chapala to Acambay and Tula. It clearly affects the Plio-Quaternary volcanic rocks along the eastern and western margins of the northern MGVF, but there are no evident effects of this system in the interior part of this field where there are no conspicuous E–W striking fault planes or E–W alignments of volcanic cones.

Pre-Pliocene N–S and NE–SW tectonic structures have been recognized north of the TMVB, but are considered to be part of the Basin and Range province of northern Mexico and southwestern USA (Henry and Aranda-Gómez, 1992). Other alignments recognized are the NE–SW trending Tenochitlan fault system in the central part of the TMVB, east of the MGVF (De Cserna et al., 1988). South of the MGVF, NE–SW striking lineaments are observed in pre-Miocene rocks (Fig. 3). The NE striking fractures also seem to be present beneath the Plio-Quaternary volcanic cover of the MGVF as inferred from the NE anisotropy identified by Pacheco et al. (1999) based on the study of S-wave splitting related to the 1997 earthquake swarm in the area.

On a regional scale, several attempts have been made to describe the distribution of volcanism in the Trans-Mexican Volcanic Belt from a quantitative point of view, introducing some implications on the characteristics of the monogenetic fields (e.g. Connor, 1990 and Alaniz-Alvarez et al., 1998). For the MGVF, the first discussions concerning the identification of volcanic lineaments can be found in Hasenaka and Carmichael (1985a) and Connor (1987), and especially in Wadge and Cross (1989), who applied a combination of the Hough Transform method and the two-point azimuth method. From a qualitative approach, Hasenaka and Carmichael (1985a) and previously Williams (1950), identified a main direction of 35° that dominated in the Paricutin area. However, from an analysis of densities of volcanic vents, Connor (1987) did not identify such a direction but instead recognized others at 60°, E–W and 300° that were interpreted as main fault zones. The numerical approaches by Wadge and Cross (1989) to the area produced two lineaments at 280° and N–ENE, attributed to recent normal faults related to the Chapala Graben, and a NW trend interpreted as related to the Zacoalco graben orientation. Shortly afterwards, Connor (1990) also identified NE-oriented trends in the MGVF, similar to those proposed by Williams (1950) for the Paricutin area. Kurokawa et al. (1995) also applied a variation of the two-point

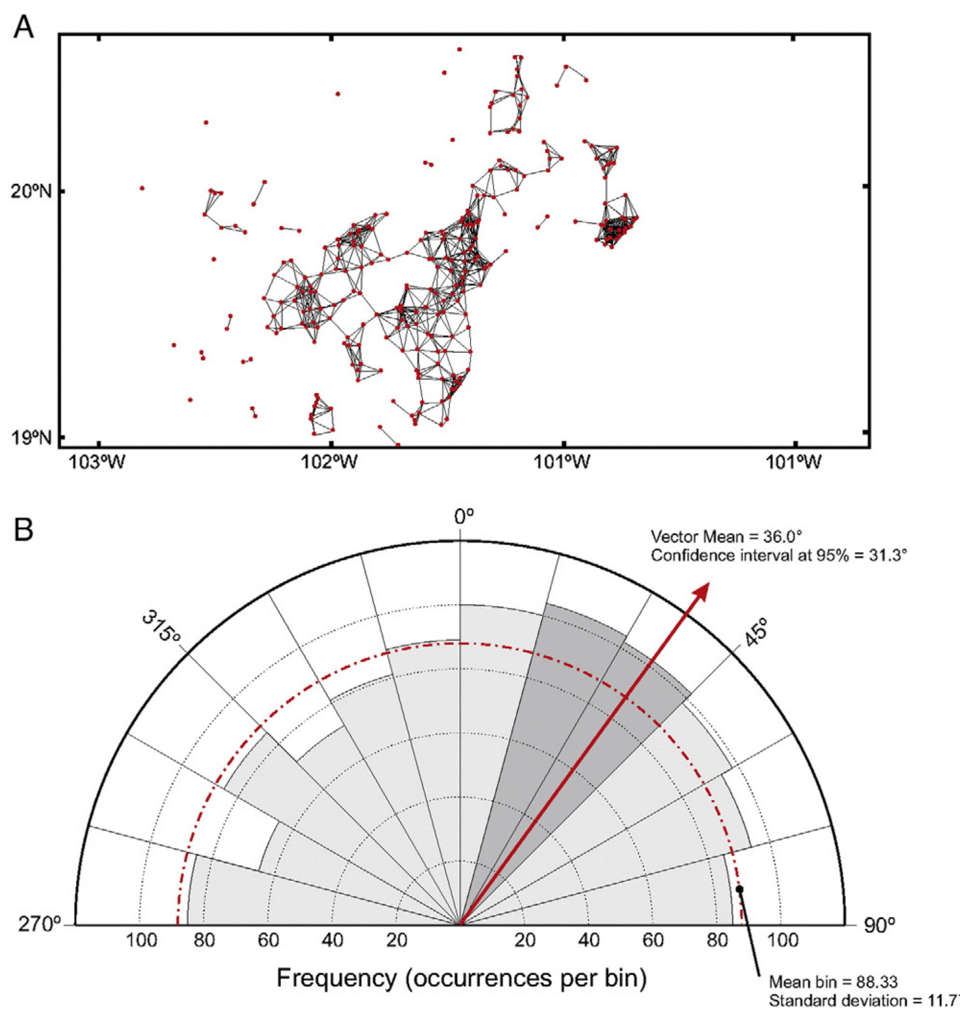

Fig. 5. Main results obtained for the MGVF. A) Map distribution of lines with lengths ≤12 km (i.e., $\leq(\bar{x}-1\sigma)/3$) where a general tendency towards NE-directed lineaments can be observed. B) Corresponding rose diagram at 15° bin intervals (frequencies as number of occurrences per bin) for azimuths obtained from ≤12 km vent-connecting lines. Dark grey bins are those with frequencies higher than one standard deviation above the mean ($1\sigma + \bar{x}$). These results support a dominance of NE-directed lineaments for the region, with a prevalent one at ~30°. If the relatively low frequencies shown by the NW-directed azimuths are considered, other secondary lineaments can be interpreted at ~280° and ~305°.

azimuth method based on Fry (1979) and identified NE trending cone clusters in the southern MGVF and concluded that this is a consequence of NW–SE tension. This interpretation is similar to that proposed later by Pacheco et al. (1999) who interpreted, based on the focal mechanism of the 1997 earthquake swarms, that the minimum stress is oriented NW–SE.

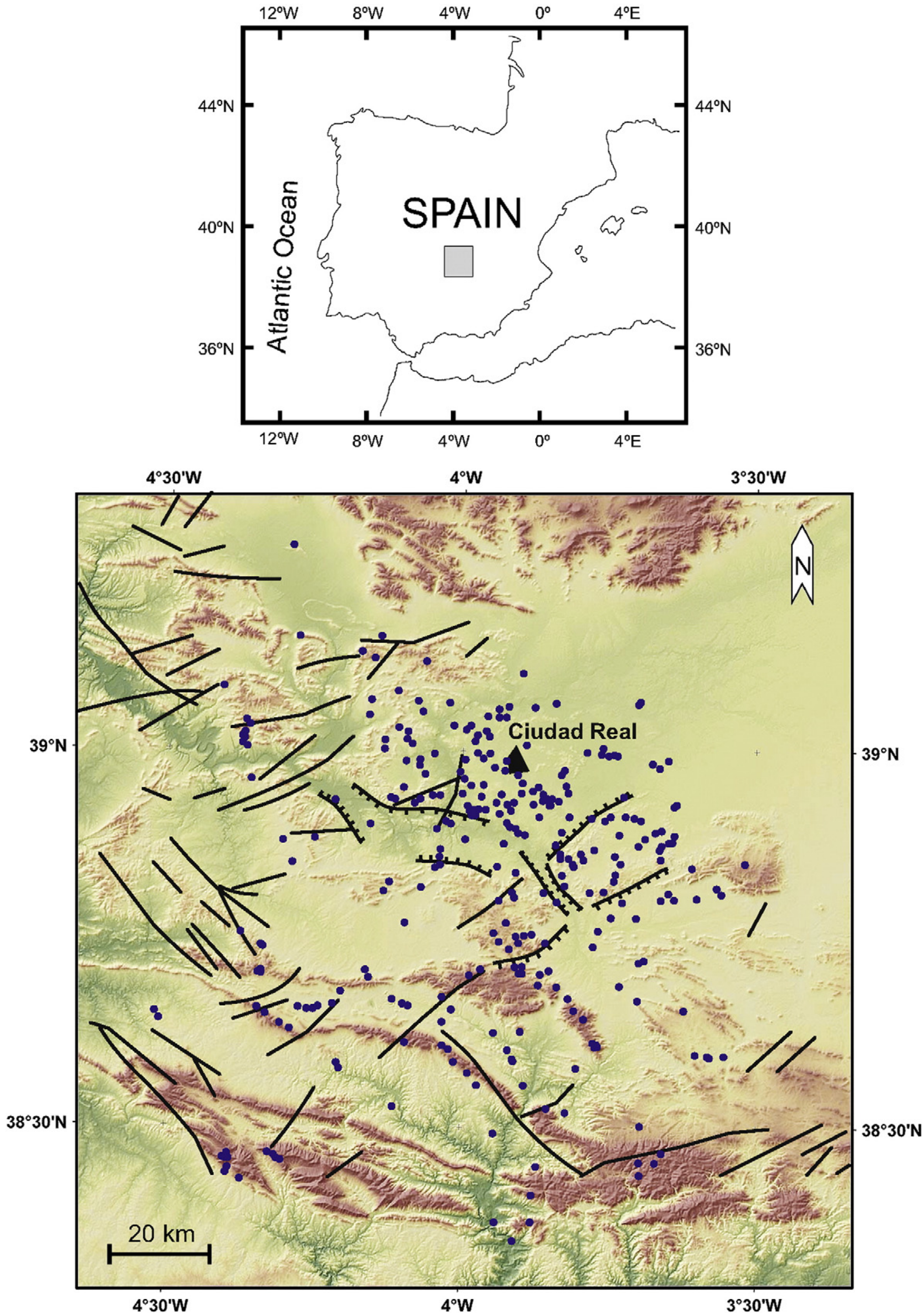

Fig. 6. Location and relief model of the Calatrava Volcanic Province (Central Spain) showing the main tectonic features (after geologic cartographic data provided by the IGME at the GEOVEO site, http://www.igme.es) and distribution of the Plio-Quaternary monogenetic vents in the volcanic field.

3.1.2. Data processing and analysis

Although the application of different numerical methods may introduce some differences in the results described above, it is very likely that some of the more significant discrepancies observed in the MGVF are a consequence of the different datasets used. In general, all the approaches above were based on different compilations of the exhaustive catalogue by Hasenaka and Carmichael (1985a) that comprises nearly one thousand volcanic edifices, or even on larger compilations of volcanoes identified from topographic maps (e.g. 1894 volcanoes, after Connor, 1987). These accounts comprise a heterogeneous set of volcanic vents of different type (from small cinder cones to large stratovolcanoes) and their age (Pliocene to present) was based on a small number of K–Ar and ^{14}C determinations available at the time (e.g. Hasenaka and Carmichael, 1985b; Murphy and Carmichael, 1984; Nixon et al., 1987), while recent age compilations (e.g. Ferrari et al., 2007, after data from Ban et al., 1992; Chesley et al., 2002; Demant, 1981; Ferrari et al., 1994, 1991; Hasenaka and Carmichael, 1985a,b, 1987; Hochstaedter et al., 1996; Luhr, 2001; Luhr et al., 1989; Luhr and Carmichael, 1985; McBirney et al., 1987; Nixon et al., 1987; Pradal and Robin, 1994; Verma and Hasenaka, 2004; Wilcox, 1954, and unpublished data partially available in Pasquarè et al., 1991) suggest that volcanism in the MGVF may be dated from Early Miocene to present. In this sense it is important to note that, as already observed by Connor (1987), there seem to exist differences in the distribution of volcanoes in the area depending on the characteristics of the edifices (polygenetic versus monogenetic). This is not surprising, since the characteristics of volcanism may be related to different geodynamic regimes and the various stress fields that may have dominated through time. Therefore we consider that, in order to identify any predominant vent alignment that may be safely related to a specific stress field at the time of the volcanic activity, it is necessary to constrain the dataset to similar volcanic vents for which activity can be ascribed to a specific period of time. In the case of the MGVF, we have therefore limited our dataset to monogenetic cinder cones generated from Pliocene to present day. According to this criteria, the dataset is constrained to 269 vents (Fig. 3) that were carefully compiled from a comprehensive catalogue of volcanic outcrops for which there is available information on their age (see Ferrari et al., 2007), and corrected from topographic maps for precise location of the eruption points and to remove redundant data (e.g. multiple samples corresponding to a single vent). Although the number of vents finally considered in this dataset may seem small relative to the actual total number of Plio-Quaternary monogenetic vents (estimated to be around 950, Hasenaka and Carmichael, 1985b), the dataset can still be considered as representative within a 95% confidence level at a standard error of 0.012 (assuming that the availability of age data follows a simple random sampling pattern). Accordingly, implementation of numerical alignment calculations to this dataset should provide specific information regarding the most recent stress field dominating the distribution of monogenetic volcanism in the MGVF.

3.1.3. Results and discussion

If, as proposed before, we only consider lines that link each vent to its neighbouring vents, it should be possible to detect smaller scale structures and other more detailed distributions. The results of this approach are summarized in Figs. 4 and 5, where the length that best exposes predominant directions in the rose diagrams corresponds to $d \leq [\bar{x} - 1\sigma] / 3$ (in this case $d \leq 12$ km). Under this constraint, the rose diagram of Fig. 5B shows a dominance of NE-directed lineaments (i.e. with a frequency anomalously high relative to the mean), with a prevalent direction of ~30° (15°–45°), very close to the mean vector (36°) calculated for the whole set of azimuths (see Fig. 5B). This direction matches the main lineament observed both qualitatively in the Paricutin area (Hasenaka and Carmichael, 1985b; Williams, 1950) and calculated by different local and regional approaches (Connor, 1990; Kurokawa et al., 1995). Other previously suggested directions are not as evident in the rose diagram, where NE-directed lineaments are the only ones with frequencies above the mean. However, when considered relative to the generally lower frequencies observed in NW-directed azimuths, it also seems that some second-order lineaments could be present at 270°–285° and at 300°–315°.

As already noted by Hasenaka and Carmichael (1985b), the ~30° direction approaches the relative motion vector of the Cocos and North America plates (40° according to DeMets et al., 1990). However, this direction does not correspond to the dominant active structures in this region of the E–W trending Chapala-Tula system.

In fact, this kind of NE-oriented lineaments coincides with the orientation of the Tenochtitlan Fault System (e.g. De Cserna et al., 1988), which seems to have controlled the spatial distribution of many monogenetic and polygenetic volcanoes within the TMVB (see Siebe in Suter et al., 1999). Alaniz-Alvarez et al. (1998) suggested that monogenetic volcanoes in the central TMVB follow the roughly E–W direction of the Morelia-Acambay fault system. However our results suggest that the identified 270°–285° trend (which can be ascribed to an overall E–W direction) played only a secondary role in the distribution of the most recent monogenetic vents. The most prominent 30° cone alignment direction seems to be related with older fracture zones that show evidence of present reactivation. This is suggested by the distribution of epicenters of the earthquake swarms of 1997 that define ruptures along NE-oriented structures and focal mechanisms with left-lateral displacement and dip slip components. Another group of focal mechanisms related to NW trending fracture zones displays left-lateral strike slip with a large thrust component (Pacheco et al., 1999). These focal mechanisms have been interpreted as the result of a different stress field in the central and southern parts of the MGVF with respect to the extension related to the Chapala-Tula fault system farther north. Since the NE-oriented fracture zones display a dip slip component, they are more favourable for producing space for magma ascent.

3.2. The Calatrava Volcanic Province

3.2.1. General characteristics and previous lineament identifications

The CVP crops out in south central Spain, covering a subcircular area of ~5000 km^2. Except for a single Miocene vent of K-rich volcanism, the region is composed by alkaline basaltic magmas extruded in a single episode during Plio-Quaternary times (see López-Ruiz et al., 2002). This volcanism developed over a Paleozoic basement that has been variably affected by Variscan folds and thrusts and Alpine brittle deformations. This basement is unconformably covered by upper Miocene to Quaternary fluvial and lacustrine sediments deposited in a series of fault-bounded basins that formed as a result of extensional tectonics. A complex fracture pattern shaped

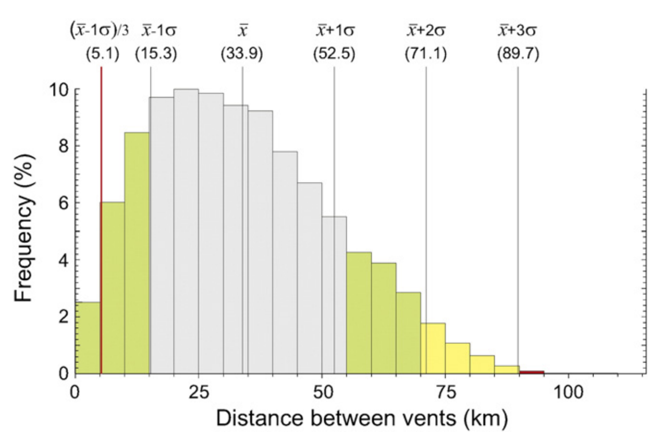

Fig. 7. Histogram of frequencies of lengths for the Calatrava Volcanic Province.

the geometry of the basins (E–W to ENE–WSW, NW–SE and NE–SW), and normal faults bound NW–SE oriented grabens (Lopez-Ruiz et al., 1993). The CVP is made up of more than 300 volcanic outcrops generated by Strombolian and hydromagmatic eruptions. The Strombolian eruptions produced relatively small monogenetic cinder cones and lava flows, whereas hydromagmatism created typical maar structures.

When considered on a regional scale, the spatial distribution of vents in the CVP does not show any clear alignments and therefore Ancochea and Brändle (1982) developed a method for the identification of the most likely orientations using an early implementation of the Strip method. Their approach was based on the identification of the predominant direction of 100 m width strips that, at different angles across the volcanic field, connected a minimum of four volcanic vents. According to their results, the CVP vents were preferentially distributed along two main lineaments 285°–300° and 340°–350°, which were interpreted as regional scale fracturing patterns resulting from a 310°–320° oriented compressive stress field.

3.2.2. Results and discussion

For our calculations we have considered a total of 293 points which correspond to volcanic vent locations compiled from the literature

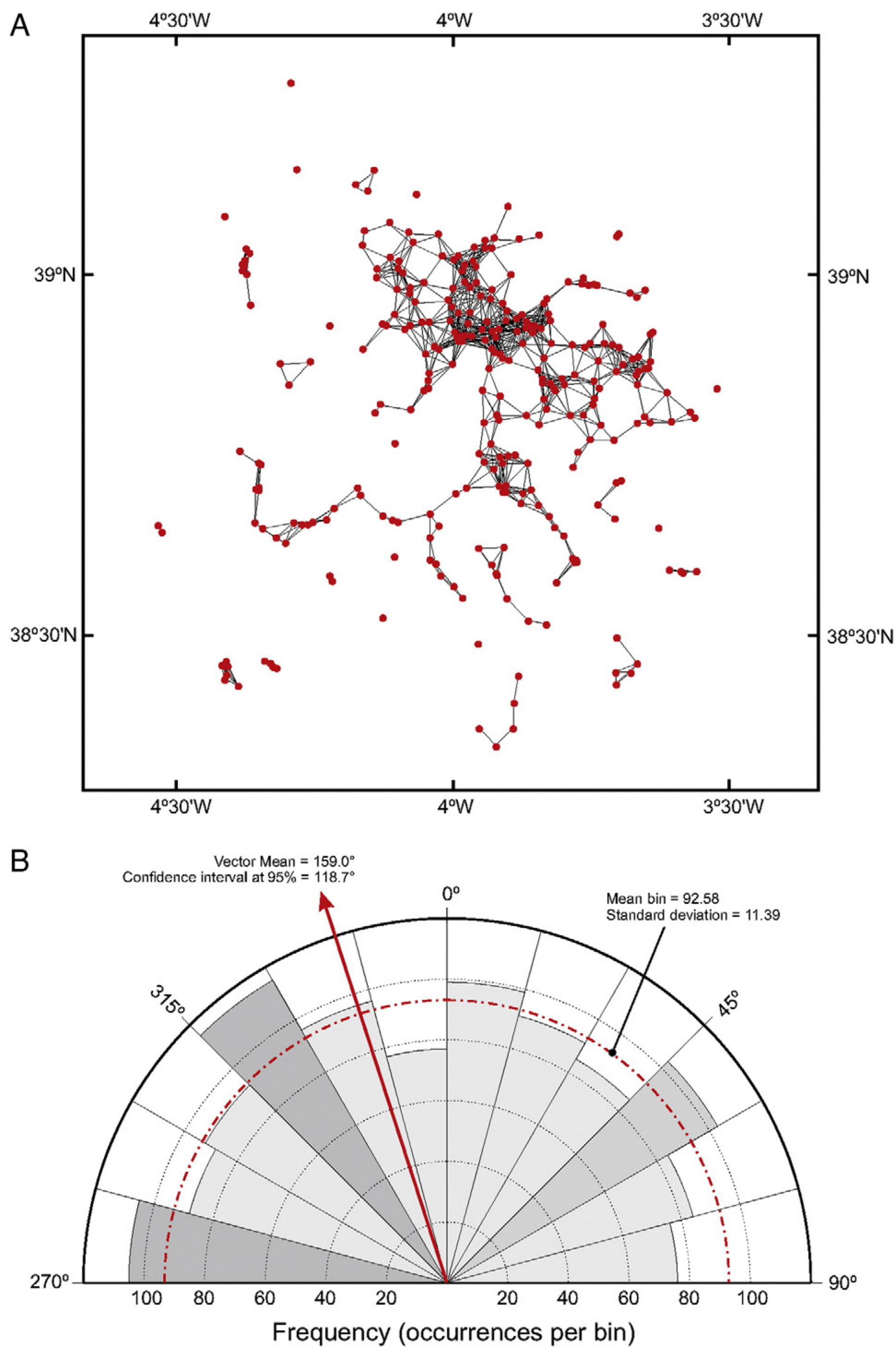

Fig. 8. Main results obtained for the CVP. A) Map distribution of lines with lengths ≤5 km (i.e., $\leq(\bar{x}-1\sigma)/3$) where a general tendency towards NW-directed lineaments can be observed. B) Corresponding rose diagram at 15° bin intervals (frequencies as number of occurrences per bin) for azimuths obtained from ≤5 km vent-connecting lines. Dark grey bins are those with frequencies higher than one standard deviation above the mean ($1\sigma+\bar{x}$). These results support the existence of two main lineaments at ~278° and ~323°, and a secondary one at ~53° (the frequency of the 45°–60° bin is just slightly under $1\sigma+\bar{x}$).

(Ancochea, 1982; Cebriá, 1992; Crespo, 1992; González-Cárdenas and Sánchez-González, 1990; Hernández-Pacheco, 1932; Rodríguez-Pascua and Barrera, 2002) updated according to the available topographic and geological maps covering the area (Fig. 6).

The main results obtained for the CVP are summarized in Figs. 7 and 8. The length of all the lines that connect each point to the remaining ones ranges from 0.2 km to 110 km, with a slightly skewed frequency distribution (Fig. 7) that, similarly to the MGVF, departs from a pure normal distribution and in this case shows a predominance of distances between 15 km and 55 km.

The distance that best exposes predominant directions in the rose diagrams also follows the condition $d \leq [\bar{x} - 1\sigma]/3$ (in this case $\leq$5.1 km). According to these results (see Fig. 8B), most volcanic alignments in Calatrava follow a 323° direction, which prevails in the northern and eastern sectors of the volcanic field, whereas secondary directions at about 53° and 278° are also detected in the region.

The main 323° direction is equivalent to one of those identified by Ancochea and Brändle (1982), which is interpreted as corresponding to the main compressional axis (320°–340°) imposed by the Betic Cordillera onto its foreland (Vegas and Rincón-Calero, 1996). The secondary 53° direction is also roughly coincident with the other main compressional axis (60°–70°) identified by Vegas and Rincón-Calero (1996) on the basis of a detailed analysis of brittle fault structures. However, the approximately E–W lineament (~278°) suggested by our approach has not been identified previously as a predominant volcanic axis, and roughly corresponds to a secondary 260°–290° Betic orientation identified by Vegas and Rincón-Calero (1996) as previous transcurrent structures in the area.

To account for the presence of extension in the CVP, thus allowing the ascent of basaltic magma, Lopez-Ruiz et al. (1993) proposed an indentation tectonics model based on Doblas et al. (1991), in which NW-directed compression in the southeastern tip of Iberia produced the generation of two symmetrically-disposed rift arms, one of them WNW-orientated in the west, hosting the Calatrava Volcanic Province. However, this model does not explain the apparent contradictory relationship between the distributions of volcanic vents along the main NW compressional axis. This could be explained by invoking the reactivation of the previous NW-directed fractures during the extensional processes induced by the indentation of the Betics onto its foreland, creating favourable paths for magma ascent at crustal levels.

In addition to the main lineaments recognized in the rose diagrams, the distribution of $\leq$5 km lines in Fig. 8A also help to reveal some apparently curved or even nearly circular distributions at different scales, especially in the southern sector of the region. These seem to coincide in general terms with the shape of the sedimentary basins in the region, which as described above are a consequence of the complex fracturing pattern of the area.

4. Conclusions

Straight application of quantitative methods to identify possible alignments in the geological record may produce mathematically acceptable results but also meaningless from a geological point of view. To avoid this, any attempt at numerical recognition of alignments resulting from a geological process should be supported by field observations and in general, by an approach that considers the geodynamic setting of the area. In the case of areas of monogenetic volcanism, two main data should constrain any possible calculation: (1) Time-related development of volcanism, and (2) Structural control depending on the geodynamic evolution of volcanism.

From a variation of the two-point azimuth method, we have examined the distribution of vents in two examples of monogenetic volcanism areas with different shapes and sizes and developed in contrasting geodynamic settings (intraplate and subduction-related). Although in both cases the distribution of volcanic vents follows lineaments that are roughly parallel to the main compressional direction that dominates on a regional scale, they actually correspond to older structures that have been reactivated. In the MGVF the prevalent 30° direction closely approaches the relative motion vector of the Cocos and North America plates, and in Calatrava the calculated 323° lineament coincides with the main compressional axis imposed by the Betic Cordillera onto its foreland. In Calatrava, indentation tectonics was invoked to account for extensional processes in the volcanic field area, but volcanic vents are still distributed along the main Betics compressional axis. This suggests that magma ascent was favoured by possible reactivation of the older NW-directed fractures during extension. Similarly, in the MGVF it also seems likely that magma ascent was favoured by present reactivation of older NE-oriented fracture zones.

Such behaviour corresponds to the so-called low magma flux fields, where magma ascent is more susceptible to fault capture and eruptive fissures are preferably oriented according to structural grain rather than the principal stress orientation at the time of volcanism (Valentine and Gregg, 2008).

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