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Methodology for the computation of volcanic susceptibility An example for mafic and felsic eruptions on Tenerife (Canary Islands)

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ABSTRACT

A new method to calculate volcanic susceptibility, i.e. the spatial probability of vent opening, is presented. Determination of volcanic susceptibility should constitute the first step in the elaboration of volcanic hazard maps of active volcanic fields. Our method considers different criteria as possible indicators for the location of future vents, based on the assumption that these locations should correspond to the surface expressions of the most likely pathways for magma ascent. Thus, two groups of criteria have been considered depending on the time scale (short or long term) of our approach. The first one accounts for long-term hazard assessment and corresponds to structural criteria that provide direct information on the internal structure of the volcanic field, including its past and present stress field, location of structural lineations (fractures and dikes), and location of past eruptions. The second group of criteria concerns to the computation of susceptibility for short term analyses (from days to a few months) during unrest episodes, and includes those structural and dynamical aspects that can be inferred from volcano monitoring. Thus, a specific layer of information is obtained for each of the criteria used. The specific weight of each criterion on the overall analysis depends on its relative significance to indicate pathways for magma ascent, on the quality of data and on their degree of confidence. The combination of the different data layers allows to create a map of the spatial probability of future eruptions based on objective criteria, thus constituting the first step to obtain the corresponding volcanic hazards map. The method has been used to calculate long-term volcanic susceptibility on Tenerife (Canary Islands), and the results obtained are also presented.

1. Introduction

One of the first questions that should be answered when assessing a volcanic hazard is where future vent(s) will be located. This question may have relatively simple or quite complicated answers, depending on the characteristics of the active volcanic area under study. If the study is focused on a single volcanic edifice, it is common to limit the possible source areas to a relatively small zone or, even more precisely, to the main crater. However, in other cases, the area susceptible for hosting a future vent may be rather wide, although not all the points (pixels) of the zone will have necessarily the same probability of hosting a new vent.

The relevance of this kind of studies becomes evident when we try to determine the surface extent of the volcanic hazard we are considering. In order to compute the areas that may be affected by a volcanic event the modern techniques for volcanic hazard assessment use numerical simulation models that require the knowledge of the location of the source vent. For example, Wadge et al. (1994) evaluated a probability surface for vent opening at Mount Etna, based on a non-homogeneous Poisson process, with different intensity functions for two event types, and then they applied a numerical model for the simulation of lava flows in order to obtain a probabilistic evaluation of the associated hazard. More recently, Alberico et al. (2002) constructed a probability density function of vent opening based on the spatial distribution of different geological, geophysical and geochemical 'anomalies' that could favour or be indicative of the future opening of an eruptive fracture in Campi Flegrei. Then they applied a simulation model for pyroclastic flows for the evaluation of volcanic risk. Martin et al. (2004) analysed the likelihood of future volcanism in the Tohoku volcanic arc, Japan, by using Bayesian inference in order to combine one or more sets of geophysical information with a priori assumptions of volcano spatiotemporal distributions yielding modified a posteriori probabilities. The basic a priori assumption they made was that new volcanoes will not form far from existing ones and that such a distribution ranges from Gaussian (not so conservative) to Cauchy (conservative). Jaquet et al. (2008) have developed a Cox process, characterised by a multivariate potential, to enable assimilation of geological information and geophysical data from the Quaternary Tohoku volcanic arc in northern Honshu, Japan. This model accounts for the observed spatial patterns and since they assume that future activity is more likely to occur at past event locations, the simulation method is made conditional on these event sites. They improve the description of uncertainty of future volcanic activity using such a multivariate approach. This paper also includes evaluation of the scale at which clustering of

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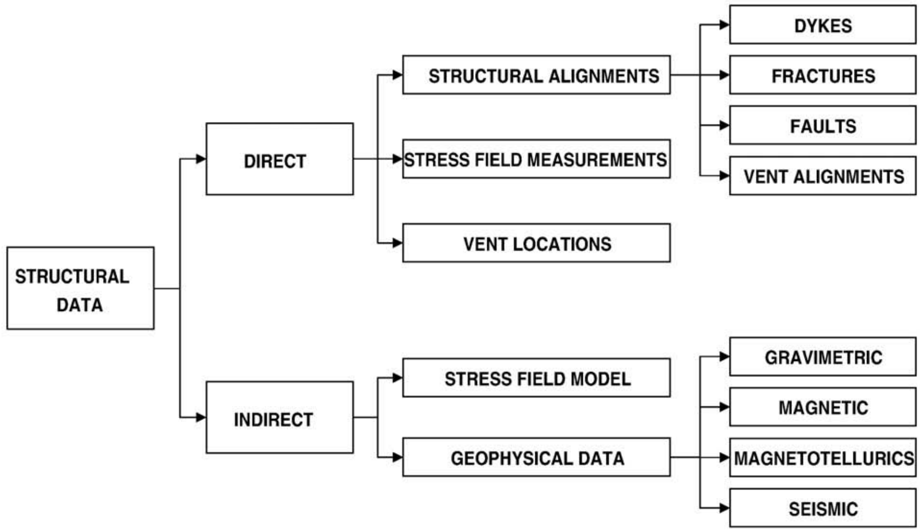

Fig. 1. Scheme of the main datasets that can be used for mid–long term assessment of volcanic susceptibility.

emission centres occurs, by means of directional variograms. This scale corresponds to the distance at which the variogram stabilises.

This paper focuses on the numerical multi-criteria evaluation of the spatial probability of hosting a new vent, named here as 'volcanic susceptibility'. The appearance of a new vent depends on the path that magma will follow from the chamber to the surface. Which is this path? is the question we should answer to identify the exact position of the new vent. Although we already know that magma will follow the easiest path to reach the surface (i.e. the path in which the energy investment will be the minimum) we do not have direct criteria to determine it a priori. It would require a detailed 3D knowledge of the stress field of the area. Although the detailed stress field could not be addressed, there are several direct and indirect sources of data that can provide information on this issue. Field structural data, including

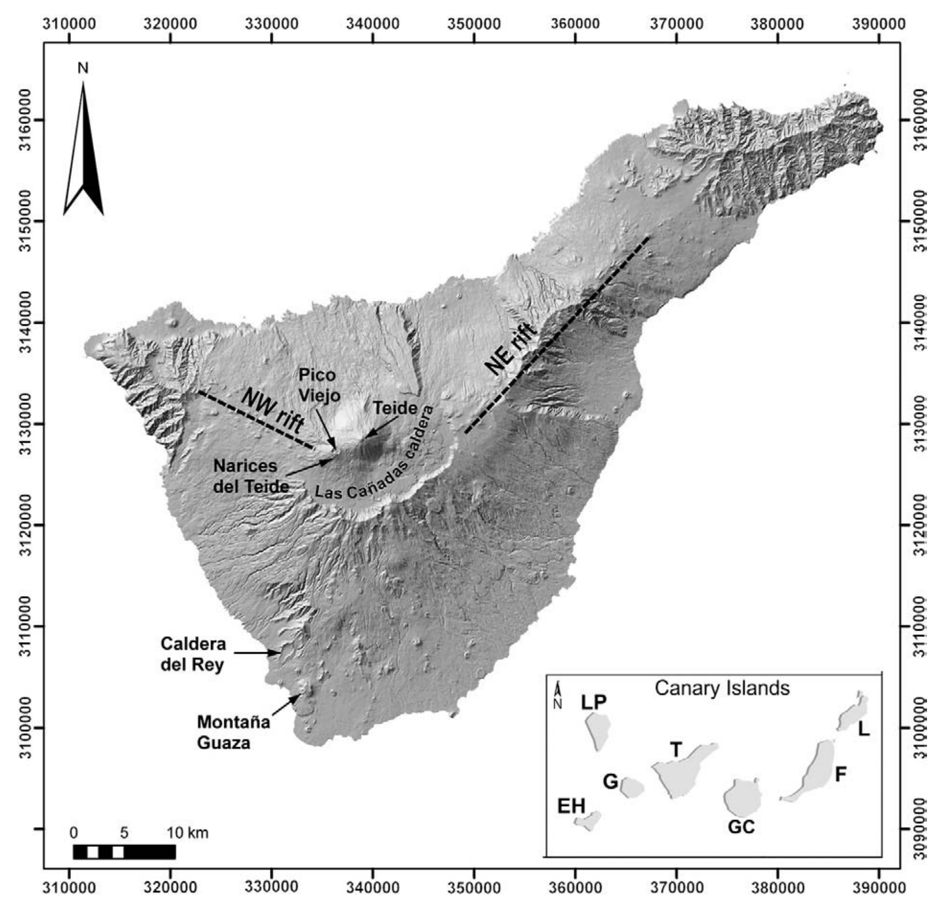

Fig. 2. Shaded relief of Tenerife. The rest of the maps comprises the same area. UTM28N coordinates. Canary Islands: T, Tenerife; GC, Gran Canaria, LP, La Palma; L, Lanzarote; F, Fuerteventura; G, Gomera; EH, El Hierro.

in situ stress field measurements (usually measured in boreholes), location of emission centres, and structural alignments (fractures, faults, cone alignments and dykes), constitute the main direct data that we can obtain. Indirect data can be obtained from theoretical 3D stress field models and structural geophysical data (gravimetric, magnetic, seismic…) (Fig. 1).

If we base our a priori hypothesis on the principle that new vents will not form far from existing ones (Martin et al., 2004; Jaquet et al., 2008), the use of direct data as structural alignments and location of past emission centres implies assuming that the general stress field has not significantly changed since the formation of these structures. In other words, we should restrict our volcanic hazard assessment to the time period during which the main stress field is believed to be constant and only structures originating during that period should be considered. This is valid for a long-term (years to decades) assessment and is indicated for appropriate land-use planning and location of settlements (Marzocchi et al., 2008). However, during unrest the time variations occur in time scales much shorter than the changes expected during a quiet phase of the volcano, so that monitoring data will play a major role in determining where a new vent may open. Therefore, a short–mid term forecast will also require to take into account monitoring data when determining the volcanic susceptibility.

In this paper we present a new method to calculate volcanic susceptibility, i.e. the spatial probability of vent opening. We consider two time scales for our approach. The first one accounts for long-term hazard assessment and considers structural criteria that provide direct information on the internal structure of the volcanic field, including its past and present stress field, location of structural lineations (fractures and dikes), and location of past eruptions. The second one corresponds to the computation of volcanic susceptibility for short term analyses (from days to a few months) during unrest episodes, and includes those structural aspects that can be inferred from volcano monitoring. The method we develop has been used to calculate long-term volcanic susceptibility in Tenerife (Canary Islands), and the results obtained are also presented. For a more general applicability of the method we have implemented it into the system for volcanic hazard assessment VORIS 2 (Felpeto et al., 2008) that can be downloaded from www.gvb-csic.es.

2. Methodology

If the spatial distribution of volcanoes in a region is completely random (i.e. it results from a process with no spatial memory), a homogeneous Poisson process can be used for estimating the probability of a point containing one or more new vents. However, in many cases, the distribution of volcanic centres is clearly not random, as vents tend to cluster. In these cases, a non-homogeneous Poisson process is the simplest alternative to model clustered random data.

Considering a non-homogeneous Poisson process, the probability of a new vent occurring in a grid area of size Δx^2 centred on the point (x,y) is given by:

$$P_{xy}(n \geq 1) = 1 - \exp\left(-\lambda_{xy}\Delta x \Delta x\right) \quad (1)$$

where n is the number of vents to occur in that area and λ_{xy} is the spatial intensity of volcanism. The computation of this λ_{xy} is the key

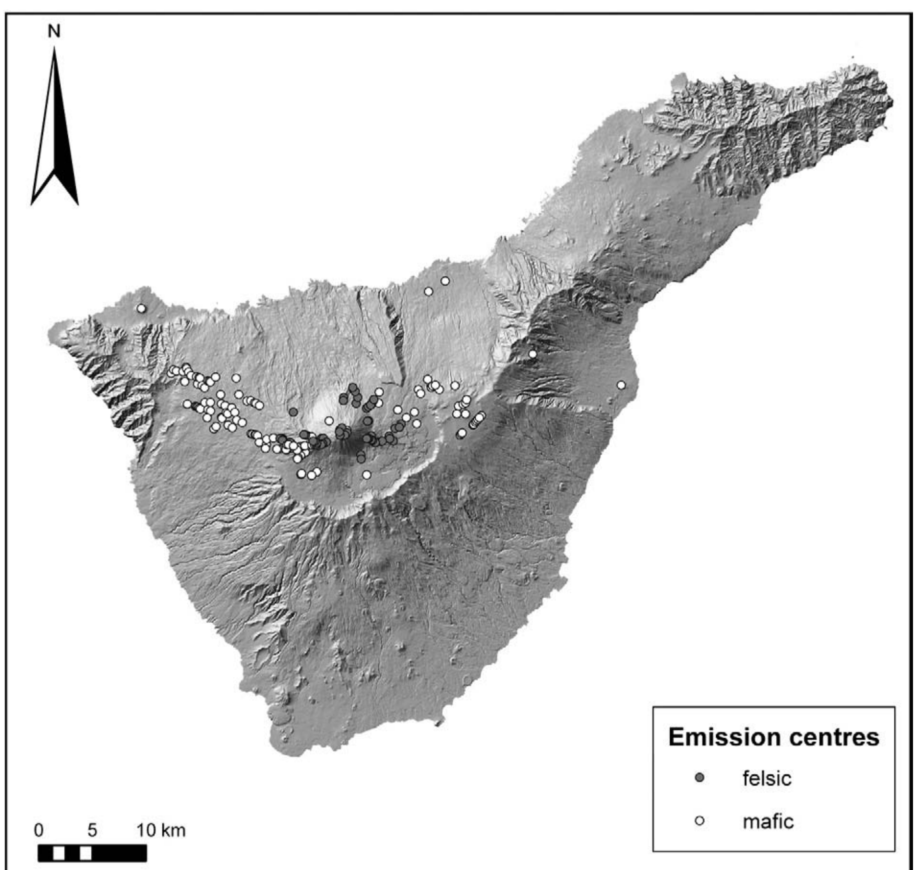

Fig. 3. Emission centres of Tenerife younger than 30 kyr considered for the computation of the susceptibility. Grey dots correspond to felsic centres and white dots to mafic centres. Back image shows a shaded relief of Tenerife Island.

point for assessing the volcanic susceptibility, and it should include all the available information regarding the propensity of each point to contain a future vent.

Assuming that the regional stress field for the area of study and the time period considered have not and will not change significantly, the first step will consist on the compilation of all the available datasets (N) (Fig. 1). For each dataset k, a probability density function should be defined (PDF^k_{xy}), which represents the spatial recurrence rate if only dataset k is considered. Furthermore, for each dataset two parameters should be assessed: the relevance and the reliability.

The relevance (Rv^k) of one item describes the relative significance of the data considered in the evaluation of the volcanic susceptibility. The value of the relevance of each item should be assessed by specialists and, probably, through an elicitation of expert judgment procedure (see Aspinall, 2006). It is necessary to note that these values are assessed for the type of data, without taking into account the quality of these data or even if they are available or not.

On the contrary, the reliability (Rb^k) of one item reflects somehow the quality of the available data, in terms of their use on the assessment of the volcanic susceptibility. Data that can be directly obtained in the field, e.g. tectonic lineations, vent locations, etc., should be fully reliable. However, the quality or the degree of confidence on data obtained by indirect methods, such as theoretical models of stress fields, structural geophysical data, and monitoring data, will depend on several aspects related to data acquisition methods and data processing. The precise weight (Rb^k) for each dataset should be established by the accuracy of the dataset, according to the criteria of the expert(s)who have collected/computed the data. This is particularly important in geophysical datasets that come from the application of inversion techniques which precision could vary depending on the numerical procedure used.

Assuming that the final intensity is a linear combination of the contribution of each dataset, weighted with the two above mentioned parameters, its value is computed by:

$$\lambda_{xy} = \frac{\sum_{k=1}^{N} Rv^k Rb^k PDF^k_{xy}}{\sum_{k=1}^{N} Rv^k Rb^k}. \quad (2)$$

2.1. Computation of PDF for each dataset

Each dataset must be re-mapped into a PDF. The method for re-mapping will depend on the relationship between the dataset and the distribution of volcanism. This relation can have a statistical or deterministic basis, depending on the knowledge of the physical process that relates the data and the spatial distribution of vents and also on the characteristics of the dataset.

2.1.1. Emission centres

The location of emission centres has been widely used for the estimation of future vent locations (e.g. Wadge et al., 1994; Connor and Hill, 1995; Martin et al., 2004). The basic idea assumed is that a new volcano will not form far away from existing ones, or, on other words, past volcanism is the key for the future one.

One of the most common methods for the estimation of the spatial probability for the opening of future vents is the kernel technique. A

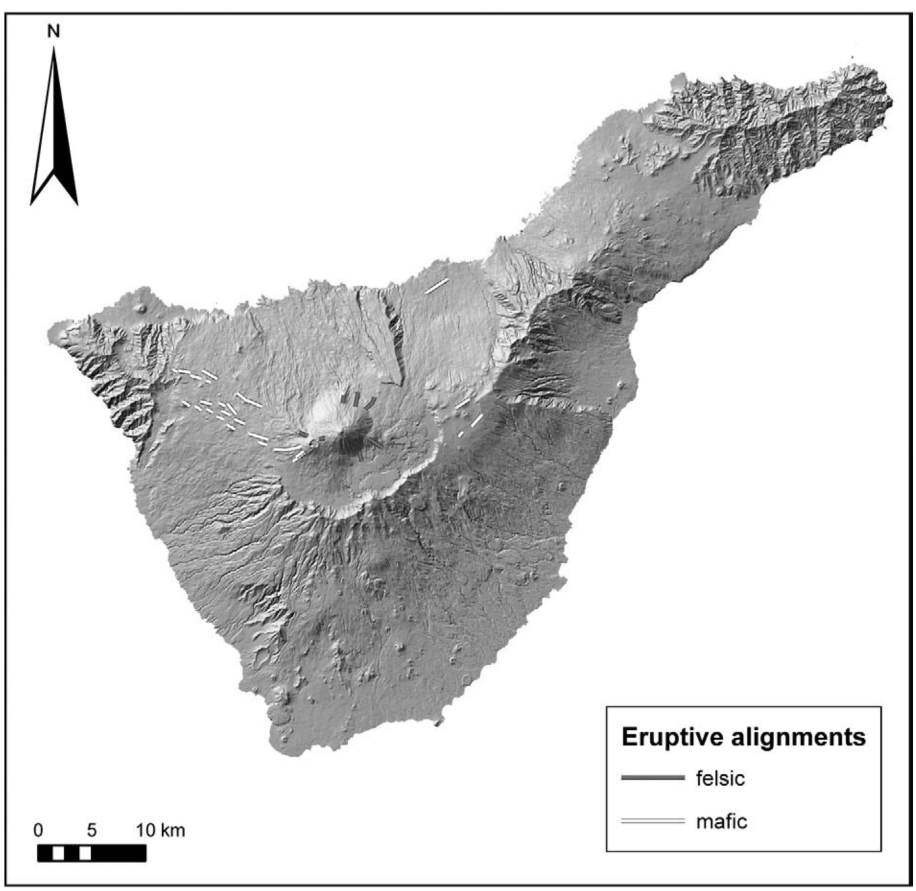

Fig. 4. Vent alignments of Tenerife younger than 30 kyr considered for the computation of the susceptibility. Grey lines correspond to felsic alignments and white lines to mafic alignments. Back image shows a shaded relief of Tenerife Island.

kernel function is used to obtain the intensity of volcanic vents at a sampling point, calculated as a function of the distance to nearby volcanoes and a smoothing factor (h). The most used kernel functions are Gaussian and Cauchy kernels.

For the two-dimensional Gaussian kernel, the spatial recurrence rate λG_{xy} at the point (x,y):

$$\lambda G_{xy} = \frac{1}{2\pi h^2 M}\sum_{i=1}^{M} \exp\left(-\frac{1}{2}\left[\left(\frac{x-x_{vi}}{h}\right)^2 + \left(\frac{y-y_{vi}}{h}\right)^2\right]\right) \quad (3)$$

where (x_{vi},y_{vi}) are the coordinates of the ith volcanic vent used in the calculation, M the total number of volcanic vents used and h the smoothing factor. The resulting PDF is normalised by dividing by the integral over the whole area of study.

For the two-dimensional Cauchy kernel, λC_{xy} at the point (x,y) is:

$$\lambda C_{xy} = \frac{1}{\pi h^2 M}\sum_{i=1}^{M} \frac{1}{1+\left[\left(\frac{x-x_{vi}}{h}\right)^2 + \left(\frac{y-y_{vi}}{h}\right)^2\right]}. \quad (4)$$

In order to evaluate which of the kernels better describes the spatial distribution of past vents, a nearest-neighbour test can be applied by plotting the distance to the nearest neighbour versus the fraction of volcanic vents considered. This test is also useful for choosing the appropriate smoothing factor for the selected kernel, by plotting the theoretical curves for different values of the smoothing factor (Martin et al., 2004).

2.1.2. Structural alignments

For the construction of the PDF corresponding to the datasets that we have referred to as structural alignments (dykes, faults, fractures, and vents alignments) we have used a similar procedure than that used for the location of emission centres. In this case, the nearest-neighbour test for the selection of the Gaussian or Cauchy kernel and the corresponding smoothing parameter is applied to the mid point of each of the lines (structural alignments) considered, as we assume that at this point the least principal stress (σ_3) is lower than at their edges, therefore it can be considered the most representative point of the alignment. For the computation of the PDF expressions (2) or (3) are used, considering that the values (x_{vi},y_{vi}) represent the point of the structure considered that is located closer to the evaluation point (i.e., the maximum probability values are located along the whole structure and the probability values decrease following a Gaussian/Cauchy tail as we move away from the alignment, in the same way that occurs when considering a single point).

2.1.3. Other datasets

No general method can be given for the re-mapping of the rest of the datasets proposed in Fig. 1 to a PDF. Ideally, a physical model should underlie over the re-mapping technique used, although for many of the proposed datasets, the knowledge on these physical models is not good enough for allowing a numerical re-mapping. One possible approach is that proposed by Martin et al. (2004) where geophysical data are re-mapped based on the percentage of recent volcanic vents that lie within certain ranges of geophysical value. Three different datasets are used: P velocity perturbations at 40 and 10 km depth and geothermal gradients (measured in boreholes, 300–1 km deep).

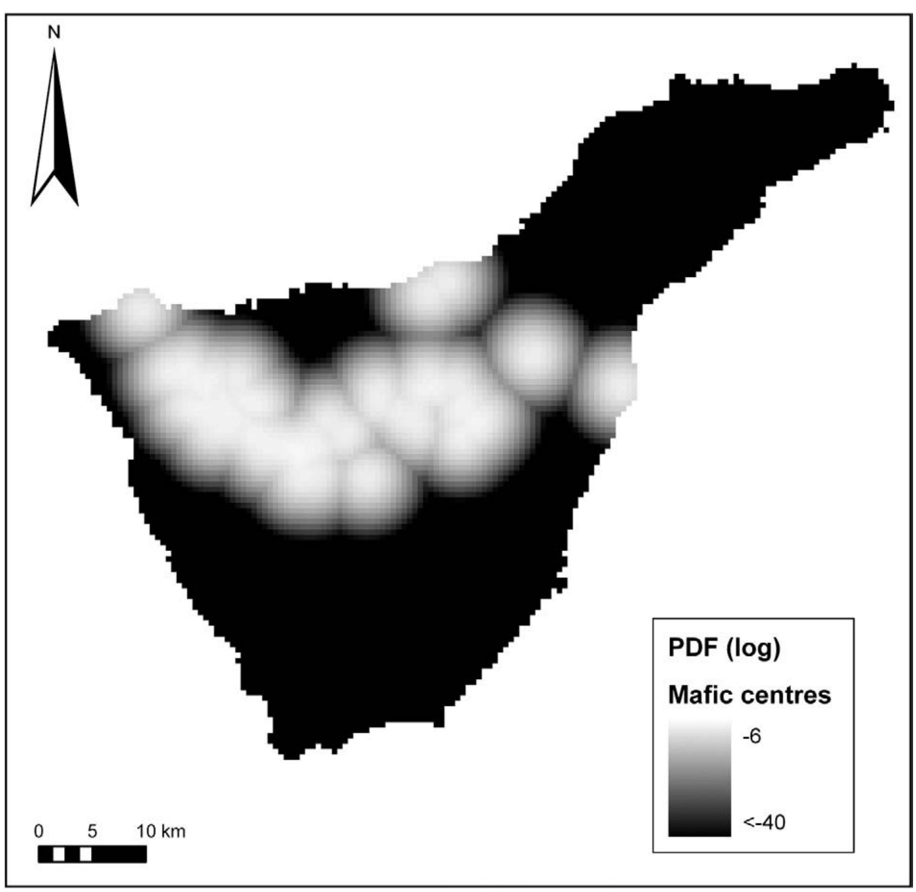

Fig. 5. PDF obtained for mafic centre dataset applying Gaussian kernel estimation with a smoothing parameter of 500 m.

A simpler approach is proposed by Alberico et al. (2008) to construct an empirical spatial density function of vent opening at Ischia Island, merging together both location of past vents, fractures and faults with hydrothermal springs and fumarole locations, Bouguer anomalies, epicentre locations and radon emissions. They divided the island into square cells and for each dataset (or group of datasets) construct a Boolean map, attributing a value of 1 or 0 to the cells in which the indicator is present or absent (defining a threshold value for continuous data). The Boolean maps obtained are then summed and normalised.

3. Application to Tenerife Island

3.1. Background

The geological evolution of Tenerife (Martí et al., 2008) (Fig. 2) involves the construction of two main volcanic complexes: a basaltic shield (>12 Ma to present) that is mostly submerged but forms about 90% of the island, continuing at present its subaerial construction through two rift zones, the NW rift (Santiago del Teide) and the NE rift (Dorsal or La Esperanza); and, the Central Complex (>3.5 Ma to present), which comprises the Cañadas edifice (>3.5 Ma–0.18 Ma), a composite volcano characterised by abundant explosive eruptions of highly evolved phonolitic magmas, and the active Teide–Pico Viejo stratovolcanoes (0.18 Ma to present) that evolved from basaltic to phonolitic and which have mostly undergone effusive activity (Ablay and Marti, 2000; Martí et al., 2008). Along the whole history of Tenerife the ascent of mantle-derived basaltic magmas has been controlled by two main tectonic lineations trending NW–SE and NE–SW, which are still active at present controlling the eruption of basaltic magmas outside the central complex and continuing the construction of the basaltic shield. The Cañadas caldera, in which the Teide–Pico Viejo stratovolcanoes stand, truncated the Cañadas edifice and formed from several vertical collapses of the volcanic edifice following explosive emptying of high-level magma chamber in addition to the occasional lateral collapse of the volcano flanks (Marti et al., 1997; Marti and Gudmundsson, 2000).

Explosive activity on Tenerife is mostly associated with the eruption of phonolitic magmas, but it is also represented by strombolian and violent strombolian phases during basaltic eruptions and a small number of phreatomagmatic basaltic explosions in littoral cones and at the central complex. Phonolitic volcanism has been restricted to the central complex, the Cañadas edifice and currently at the Teide–Pico Viejo stratovolcanoes, with only two existing phonolitic manifestations (Montaña Guaza and Caldera del Rey) outside the central area, on the lower south-western flank of Tenerife.

Explosive phonolitic activity, characterised by repose intervals between 5 and 30 ka, and by large volume plinian and ignimbritic eruptions, occasionally associated with caldera forming episodes, has dominated the construction of the Cañadas edifice (Martí et al., 2008). Phonolitic activity in the active Teide–Pico Viejo only began around <35 ka ago, mostly generating lava flow and domes, but some explosive events such us the subplinian eruption of Montaña Blanca (2020 BP) at the eastern flank of Teide are also present. Phonolitic activity in Teide–Pico Viejo has occurred from the central vents and also from the flanks of the two twin stratavolcanoes, with repose intervals between 250 and 1000 years, with the last eruption (Lavas Negras) dated in about 1000 years (Carracedo et al., 2007).

Recent basaltic eruptions have nearly always occurred along the NE–SW and NW–SE rift zones and the southern sector of Tenerife with

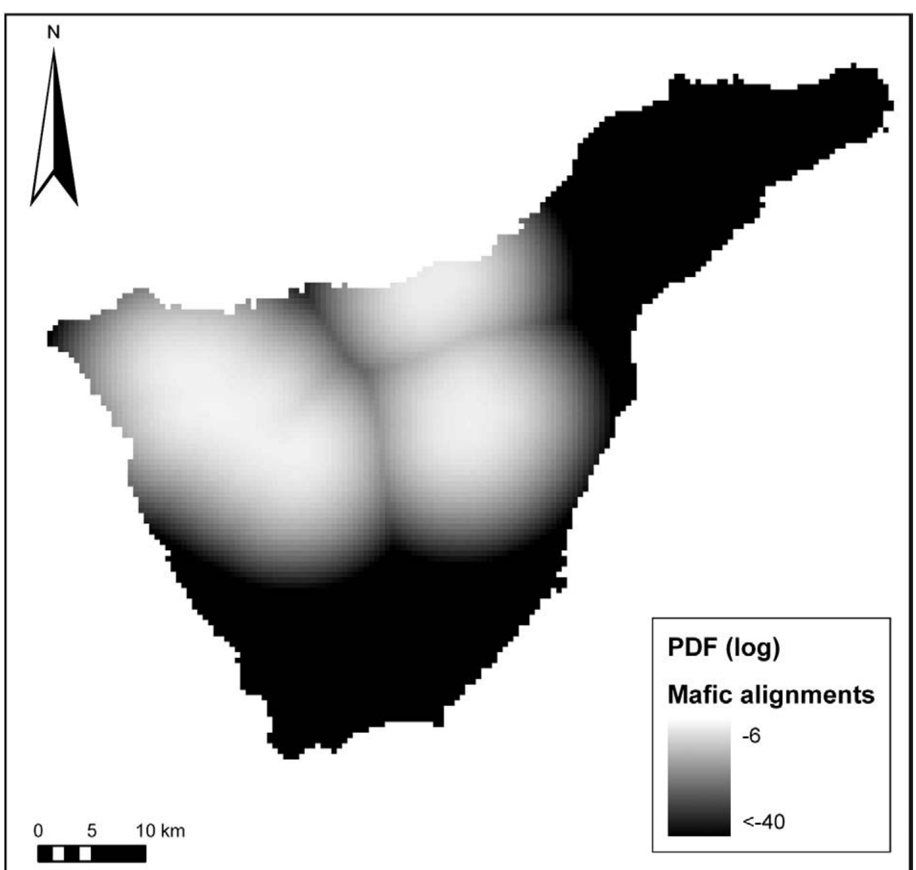

Fig. 6. PDF obtained for mafic alignments dataset applying Gaussian kernel estimation with a smoothing parameter of 1 km.

recurrence time range around 100–200 years during the last millennium, being rare in the interior of the caldera due to the shadow effect imposed by the presence of shallow phonolitic reservoirs. However, some significant basaltic eruptions also exist in the interior of the caldera, along the caldera floor or also on the flanks or earlier central vents of the Teide–Pico Viejo complex. All basaltic eruptions have developed explosive strombolian phases leading to the construction of cinder and scoria cones and occasionally producing intense lava fountains and violent explosions with the formation of short eruption columns. Violent basaltic phreatomagmatic eruptions are not rare along the coast, with the formation of maars and tuff-rings, or even associated with the Teide–Pico Viejo complex, where they have generated high energy pyroclastic surges (Pico Viejo crater, and Teide old crater) (Ablay and Marti, 2000).

3.2. Datasets

In order to conduct the susceptibility analysis for Tenerife we have first revised all the available geological and geophysical information, paying special attention to recent structural indicators such as tectonic lineations, vent alignments and vent locations. From all this information we have filtered the data that are relevant for the time period that we will consider, which is the last 35,000 years, as it represents the maximum period for Teide–Pico Viejo stratovolcanoes that can be investigated from surface geology and also represents an upper time limit for the massive appearance of phonolites on these volcanoes.

The available structural data include direct data (tectonic lineations, vents location, dykes, and vents alignments) coming from field surveys and indirect data from a series of geophysical studies carried out on Tenerife during the last two decades, including gravimetry, magnetotellurics, magnetism, and seismicity (Ortiz et al., 1986; Vieira et al., 1986; Camacho et al., 1991; Ablay and Kearey, 2000; Araña et al., 2000; Pous et al., 2002; Almendros et al., 2007; Coppo et al., 2008; Gottsmann et al., 2008). From all these data we have only considered two datasets to evaluate the volcanic susceptibility for Tenerife: vent locations and vent alignments (Figs. 3, 4). The reason is that these are the most relevant and reliable data for the period we consider. The measured dykes and tectonic lineations, mostly coming from the basaltic shield remnants and from the Cañadas caldera wall, all correspond to significantly older periods and do not offer information on the recent history of Tenerife. With regard to the available geophysical data, although they provide information on the present internal structure of the island, their scale is too large to offer the precision necessary for being acceptable in our susceptibility calculations.

From the selected datasets we make a distinction between mafic and felsic eruptions as they may behave in a very different way for what concerns vent location. Mafic eruptions are predominantly concentrated along the Santiago del Teide and La Esperanza rift zones but they have also occurred scattered in any other parts of the island event from the flanks and central vents of the Teide and Pico Viejo stratovolcanoes. The distribution of basaltic vents seems to be mainly controlled by the active rift systems as it has occurred along the whole history of Tenerife (Martí et al., 2008) and by subordinate fracture systems that allow mafic magma to intrude and erupt far from the rifts.

However, phonolitic eruptions occurred during the last 35,000 years have all been concentrated in the caldera area and more precisely on the flanks of Teide and Pico Viejo or from their central vents (Figs. 3, 4). Martí and Geyer (2009) suggest that the pathway that phonolitic magma will

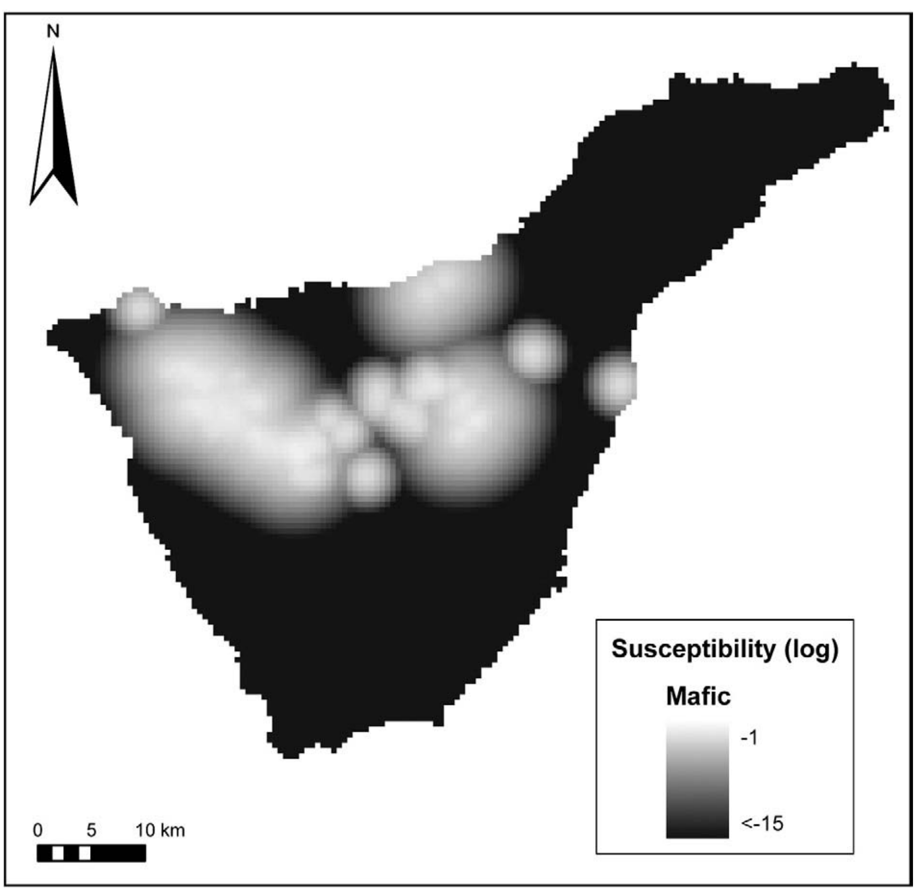

Fig. 7. Logarithm of the susceptibility for mafic eruptions in Tenerife Island (grid size 500 m).

follow to leave the chamber and reach the surface is controlled by the stress field distribution around the chamber, which is a function of the shape of the chamber. This suggests that in the case of Teide–Pico Viejo, where there is not a preferential location for new vents, each new phonolitic eruption is preceded by the modification of the existing magma chamber (or the emplacement of a new batch of magma) that does not necessarily match the structure of the previous one.

3.3. Vent locations

Vent location has been systematically determined using remote sensing analysis techniques (Lansat and Spot images of Tenerife), GRAFCAN aerial photographs at a scale 1.15,000 and ortophotomaps at a scale of 1:5000, and conducting several field surveys to check the data obtained with the previous mapping techniques. The exact location of some vents cannot be recognised in the field, but it can be easily supposed. This is the case of some central eruptions of both Teide and Pico Viejo volcanoes. In this case, the corresponding vents have been located in the present craters, assumption valid for the scale of this work, where all the computations have been made with a grid spacing of 500 m.

We have performed the nearest-neighbour test both for mafic and felsic vents, obtaining that the best fit is given in both cases by the Gaussian kernel with corresponding smoothing parameters of 500 and 300 m. PDFs have been computed applying expression (3), with a grid spacing of 500 m. Fig. 5 shows the result for mafic vents.

3.4. Vent alignments

We have used the same cartographic techniques described above to map the apparent vent alignments. As they can be not all representing true multivent eruptions, we have checked in the field the stratigraphy of the resulting deposits and their petrology and mineralogy in those cases with doubt, in order to be sure that the vents located on the same alignment belong to the same eruption.

The selection of the kernel that better describes the spatial distribution of vent alignments was made by means of the nearest-neighbour analysis between the mid points of each of the structures considered. Gaussian kernel was again the best fit for the distribution, with a smooth parameter of 1 km for mafic aligments and 2 km for felsic alignments. Fig. 6 show the PDF obtained for mafic alignments.

3.5. Susceptibility results

Once the PDFs for the different datasets have been calculated, for obtaining the final PDF (eq. (2)), relevance and reliability values should be assigned to each dataset. Regarding the reliability, values of 1 have been considered, as all the datasets represent information that can be checked in the field, and the accuracy of the determination of their location is under the work scale (cell size 500 m).

The values of the relevance considered are 0.7 for the vents dataset and, 0.3 for alignments. Those values are the result of an expert judgement elicitation procedure (Aspinall, 2006) conducted between ten researchers of the Volcanology group of the Institute of Earth Sciences 'Jaume Almera'. Although the number of experts is rather small, it can be considered viable, as pointed by Aspinall (2010).

After applying Eq. (2) for both the felsic and mafic eruptions and obtaining the two final PDFs, the final susceptibility maps have been calculated using Eq. (1). Results are shown in Figs. 7 and 8 where the probability of hosting a new mafic and phonolitic vent, respectively, is represented.

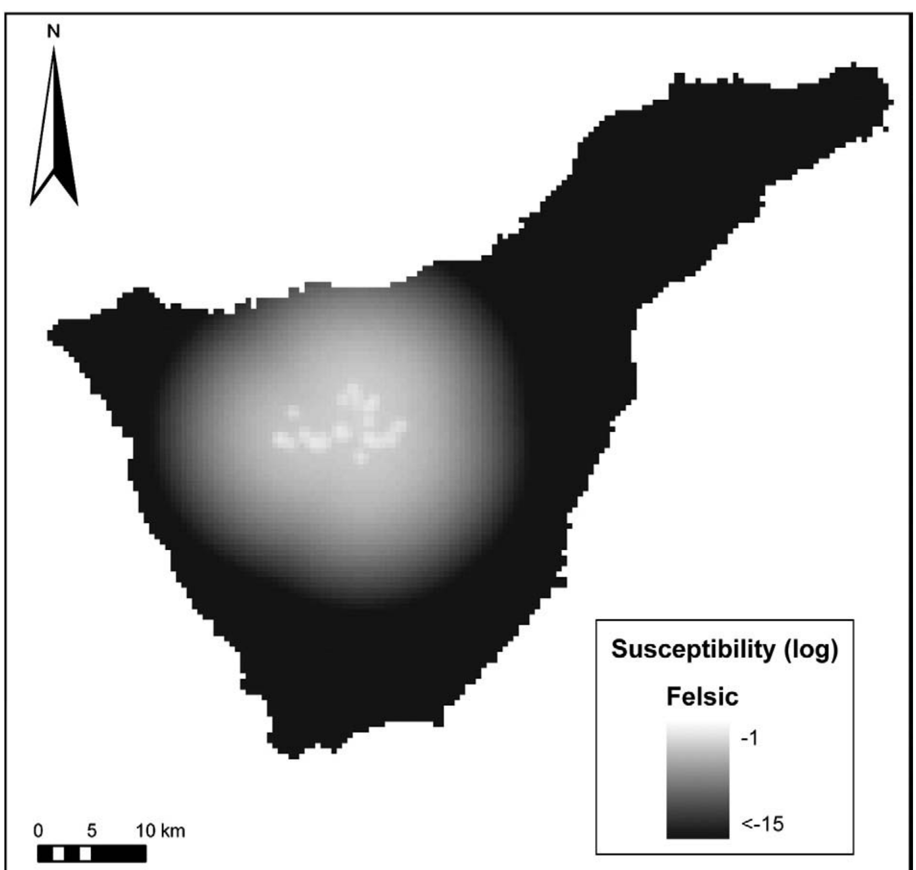

Fig. 8. Logarithm of the susceptibility for felsic eruptions in Tenerife Island (grid size 500 m).

4. Conclusions

A new method to calculate the volcanic susceptibility (spatial probability of vent opening), has been developed and successfully applied to Tenerife. The elaboration of a susceptibility map based on the quantification of objective geological and geophysical data should correspond to the first step in the computation of hazard and risk maps. The limitations of the present method are imposed by the data available, which are classified and quantitatively combined according to their relevance, reliability and utility for each particular area. In the case of Tenerife the availability of data is rather restricted, in particular concerning data related to the stress field distribution, but the preliminary results obtained are significant enough to be considered in the local territorial planning and risk mitigation programmes. This encourages us to propose the use of this method as a common way to determine the susceptibility of future volcanic eruptions in active regions and as a necessary contribution to the reduction of volcanic risk.

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