Assessing qualitative long-term volcanic hazards at Lanzarote Island (Canary Islands)

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Abstract. Conducting long-term hazard assessment in active volcanic areas is of primordial importance for land-use planning and to define emergency plans able to be applied in case of a crisis. Definition of scenario hazard maps helps to mitigate the consequences of future eruptions by anticipating to the events that may occur. Lanzarote is an active volcanic island that has hosted the largest (>1.5 km^3 DRE) and longest (6 years) eruption, the Timanfaya eruption (1730-36), on the Canary Islands in historical times (last 600 years). This eruption brought severe economic losses and forced local people to migrate. In spite of all these facts, no comprehensive hazard assessment neither hazard maps have been developed for the island. In this work, we present an integrated long-term volcanic hazard evaluation using a systematic methodology that includes spatial analysis and simulations of the most probable expected eruptive scenarios.

1 Introduction

Active volcanic areas require conducting long-term hazard assessment in order to ensure a rational land planning and to elaborate precise emergency plans that can be applied in case of a crisis. Long-term hazard assessment is important to identify the main aspects related to volcanic hazards, such as the extension, the magnitude or the potential hazards impact zones hazards on an area, which should be known by local population and potential visitors, especially when these may potentially affect touristic destinations. Unfortunately, this is not the case of many active volcanic areas around the World, particularly in places with a lower eruption frequency, thus making the historical memory of local societies to rapidly forget about past events. Also, even when the impact past eruptions has not been very significant, without causing a serious damage on human life and properties, they might become nowadays a socio-economic disaster due to urban sprawl of most places and vulnerability of exposed elements.

This is, for example, the case of the Canary Islands where, despite having hosted 15 eruptions in historical times, volcanic hazard assessment is still a pending task for most of the islands. This volcanic archipelago, which includes four National Parks, is one of the most important touristic destinations in Europe. Tourism has had a considerable economic impact on the region that has suffered a tremendous demographic expansion in the last 50 years (ca 1 million inhabitants in 1970 and more than 2 million people in 2016; http://www.gobiernodecanarias.org/istac/). The latter, not always well planned and without considering potential natural hazards, may now interfere with the effective management of future volcanic crisis. The last eruption, that occurred in El Hierro (Fig. 1 Inset) in 2011-2012, is a good example of the implications of not having conducted a previous hazard assessment. Despite having an emergency plan that was correctly applied during the crisis, the occurrence of a submarine eruption was not considered as a probable scenario, having been afterwards that proved that it was one of the most probable scenarios (Becerril et al., 2013, 2014, 2015).

Here, we concentrate our attention on Lanzarote (Fig. 1), the easternmost island of the Canary archipelago. It has hosted the largest historical eruption of the Canaries (Timanfaya, 1730-1736) and one of the largest occurred on European territory. Lanzarote, declared Biosphere Reserve by UNESCO (1993, http://www.lanzarotebiosfera.org/) and Global Geopark (2015, http://www.geoparquelanzarote.org/), is an important touristic destination with 12 natural protected areas (http://www.gobiernodecanarias.org/cmayot/espaciosnaturales/) and a National Park (1974, http://www.gobiernodecanarias.org/parquesnacionalesdecanarias/es/Timanfaya/) that receives near 1.5 million visitors per year. As in the rest of the Canary Islands, local economy is tourism based and volcanism is regarded as an attraction and not as a potential problem for both local population and visitors.

During the last two decades, several attempts have been made to analyse volcanic hazard in Lanzarote. The first published works correspond to Felpeto (2002) and Felpeto et al. (2001, 2007) who presented a new methodology for the evaluation of the lava flow hazard on Lanzarote. However, these studies only focused on simulating lava flows related to a Timanfaya type eruption (see the geological setting description to obtain more information about this eruption) without performing a general susceptibility analysis or a lava flow map for the whole island. Bartolini et al. (2013) presented the first susceptibility map of Lanzarote as an example of application of the QVAST tool, using the volcano-structural information available at that time. More recently, Galindo et al. (2016) published a spatial probability map of Lanzarote and Chinijo Islands and their submarine flanks. Their analyses were based on kernel density estimation via a linear diffusion process, using chronostratigraphic, volcano-structural and geomorphological data. However, none of these previous studies tackles a thorough volcanic hazard assessment for Lanzarote, although the information they provide should contribute to accomplish such task.

In this study, we applied a systematic methodology to conduct long-term volcanic hazard assessment at Lanzarote, based on a review of these previous studies, new generate information, and the application of the methodology and e-tools described by Martí et al. (2016a) (see also www.vetools.eu). It includes the sequential application of spatial analysis, temporal analysis, simulation of most probable scenarios, and vulnerability analysis. In the case of Lanzarote and due to the scarce available information (e.g.: lack of geochronological data), we only conducted the spatial analysis and the simulation of eruptive scenarios. The latter included the main volcanic hazards (fallout, lava flows, and pyroclastic density currents) documented in the Holocene volcanism in Lanzarote. Results obtained are volcanic hazard scenario maps, which should be considered for land-use planning, elaboration of emergency plans, and for managing a volcanic crisis, in order to protect people, their properties and the geological heritage of the island.

2 Geographical and Geological Setting

The island of Lanzarote (Canary Archipelago, Spain) is the north-easternmost island of the Canaries, located 125 km far from the western African coast and just 7 km towards the north of Fuerteventura (Fig. 1). It has an irregular morphology elongated NE-SW, with a maximum altitude of 671 m (Macizo de Famara) and covers an area of 846 km^2, which includes some islets located to the North. It rises approximately 2500 m from the sea bottom, being most part of the volcanic edifice submerged. Actually, its submerged part is connected with the island of Fuerteventura, both constituting the same volcanic edifice (Banda et al., 1981).

The basement of the island was constructed during the Oligocene above oceanic sediments of 65-55 Ma old, formed by submarine volcanic materials, plutonic rocks and sediments. It is located on an atypical oceanic crust, at least 11 km thick (Banda et al., 1981), or up to 15 km (Ortiz et al., 1986; Camacho et al., 2001). The subaerial volcanic history of Lanzarote started about 15.5 Ma ago (Coello et al., 1992) (Fig. 1). In addition to the volcanic materials, there are sedimentary formations, represented by aeolian sands, alluvial and colluvial deposits, mainly Pliocene and Quaternary (Fig. 1) (IGME, 2005).

Two major volcanic cycles have been established during its growth. The first cycle corresponds to the old buildings construction (between 11 and 3 Ma) and was characterised by the emission of important volumes of basaltic materials that formed a complex tabular sequence of lavas and pyroclasts gently dipping to the SE and ESE, with isolated outcrops of differentiated trachybasalts and trachytes (Fig. 1) (IGME, 2005). This first stage represents the maximum subaerial growing period (Ancochea et al., 2004), characterised by a high eruptive rate, approximately 0.01-0.02 km^3/ka (Coello et al., 1992). Los Ajaches, Famara and Tías Massifs are part of this cycle (Fig. 1) (Carracedo and Badiola 1993). The second stage (3 Ma - present) was characterised by a period of Pleistocene-Holocene eruptions and historical eruptions (last 600 years) (IGME, 2005). This second subaerial cycle includes the recent activity of Lanzarote and the growth of the small islands located to the North, the Chinijo Archipelago (Fig. 1) (Ancochea et al., 2004). It was characterised by the formation of widespread lava fields covering the materials of the first stage, and by the alignment of most vents trending NE-SW. On the other hand, the Chinijo Archipelago was also constructed by hydromagmatic eruptions (De la Nuez et al. 1997). It is marked by the emission of alkaline rocks that evolved to basaltic magmas, with a decrease of the alkalinity, and finally the emission of tholeiitic olivine basalts (Armienti et al. 1991; Carracedo and Badiola 1993). This second cycle of growth is characterised by continuous volcanic activity with eruptive rates of 0.013-0.027 km^3/ka (Coello et al. 1992).

Two historical eruptions took place on the island: Timanfaya (1730-1736) and Tao, Nuevo Fuego and Tinguatón eruption (1824). Both were multiple-fissure type eruptions but quite different in size and duration. The Timanfaya eruption lasted 6 years and formed hundreds of vents aligned along a 13-15 km long fissure, from where lava flows covered almost one-third of the island, erupting a total of > 1.5 km^3 of magma (Romero, 1991; Carracedo et al., 1992) (Fig. 2). During the 1824 eruption, three eruptive fissures were formed emitting few pyroclasts and some lava flows, with lengths in the order of hundred meters (Romero, 1991; Carracedo et al., 1992) (Fig.2).

3 Methodology

The first step in any long-term volcanic hazard assessment is the reconstruction of the past eruptive history of the volcano or volcanic area. In this sense, we based our analysis on the Holocene period from where we identified the different eruptive episodes and their products, since they are better preserved and, established a relative volcano-stratigraphy for all of them. To accomplish this task, previous geological and volcanological studies of Lanzarote were taken into account (Romero, 1991; Carracedo et al., 1992; Ancochea et al 2004; IGME maps (2004), and references therein) and completing them with new field work when necessary. We also conducted a structural analysis of the island based on previous geological maps at 1:25000 scale (MAGNA, GEODE) and structural studies (Marinoni and Pasquarè, 1994; Galindo et al., 2016), and on remote sensing and morpho-tectonic analysis of orthophotos (GRAFCAN (http://www.grafcan.es/), topography (LIDAR Digital Elevation Model (1:5000), GRAFCAN ©) and bathymetry (1:100.000, IEO). In addition to these volcano-structural features, we also took into account in the computation of volcanic susceptibility the recently modelled regional stress field for the Canary Islands (Geyer et al., 2016).

All above mentioned information was used to define the input parameters necessary to run the different tools we applied to conduct the systematic hazard assessment. These form part of the methodology described by Martí et al. (2016a), (http://www.vetools.eu/), i.e. QVAST (Bartolini et al., 2013) for the spatial analysis (volcanic susceptibility), and VORIS (Felpeto et al., 2007), a GIS-based tool that allows users to simulate, fallout, lava flows and pyroclastic density current scenarios. For ashfall simulations, wind data was compiled from the University of Wyoming Department of Atmospheric Science sounding database (http://weather.uwyo.edu/upperair/sounding.html).

4 Holocene volcanism

Holocene eruptions in Lanzarote are restricted to a few sub-historical events (before the last 600 years) at the northeast (Guatiza area), and the historical eruptions located towards the western-central part of the island (Timanfaya area) (Fig. 2d).

Most sub-historical eruptions are fissure type, basic in composition (olivine basalts), with clear Strombolian character, (IGME, 2004; Guatiza map). Their main products are proximal fallout pyroclastic deposits and lava flows, mainly of ‘aa’ type, which reached the sea generating a platform, so having at least 5 km in length. Lava flows from Mt. de Guenia, Las Calderas de Guatiza, Las Calderas and Las Calderetas (Fig. 2d) come from fissures with trending N30ºE - N37ºE, being from 1-1.5 m to several meters wide. They have associated several scoria cones showing a great range of particle sizes (IGME, 2004;, Guatiza map).

Hydrovolcanic events also occurred on Lanzarote during the Holocene and previous times. They include both Surtseyan eruptions, caused by the interaction of magma with water in coastal or shallow offshore settings, and inland phreatomagmatic eruptions generated by interaction of erupting magmas with groundwater (Pedrazzi et al., 2013). Several well preserved hydrovolcanic edifices are identified on the island and islets (Fig. 2b). El Golfo (Martí and Colombo,1990); Pedrazzi et al. (2013), La Caldera del Cuchillo, Mt. Cavera and Mt. Chica are some examples of hydromagmatic coastal edifices (Fig. 2b, Table

1) (Aparicio et al., 1994). The main characteristics of these eruptions and their subsequent deposits have been gathered from geological maps (IGME (2004)) and some previous studies (Martí and Colombo (1990); Carracedo and Badiola (1991); Aparicio et al. (1994); Pedrazzi et al. (2013); IGME (2004)-Geological Maps). They are summarised in Table 1.

Historical eruptions (both 1730-36 and 1824) were also of basaltic character. Timanfaya eruption differs from the rest of the Canary Islands historical eruptions, mainly because of its long duration, magnitude, type and evolution of magmas (Carracedo et al., 1992). It is the second largest historical effusive eruption in Europe (last 600 years) after Laki (1783-85) in Iceland (Thordarson and Self, 1993). A complex fissural volcanic system of approximately 13-15 km length, with more than 30 cones, was formed during this eruption (Fig. 2c), that produced lava flows and pyroclastic fallouts that covered approximately 226 km^2 of Lanzarote's surface (Hernández Pacheco, 1960; Carracedo et al., 1992). The total volume expelled was between 3 and 5 km^3 (>1.5 km^3 DRE). Lava flows reached the coast, and maximum onshore paths reached up to 21 km (Figure 1). This eruption has been studied in detail by Romero et al. (1991), Carracedo et al. (1992) and Solana et al. (2004).

The consequences of six years of activity were that more than one-third of farmland and numerous villages of the island were buried by ash and the accompanying degassing resulted in acidic rain fall, which triggered the evacuation and economic collapse of the island (Carracedo et al., 2012; Solana et al., 2004).

The 1824 eruption was characterized by basanitic products. Three cinder cones were formed during three months of activity (Tinguatón, Tao and Nuevo del Fuego; Fig. 2), generating an intermittent fissure almost 14 km in length (Figure 1). They produced a small lava flow, with a total on land length of 7-8 km that reached the SW coast of the island.

5 Volcano-tectonics

To identify the different structural elements that we considered in the susceptibility analysis, we defined vents and eruptive fissures following the same criteria established by Becerril et al. (2013, 2014, and 2015) on El Hierro. Thus, we recognised: (i) craters of isolated cinder cones, (ii) craters of coalescent cinder cones belonging to the same eruptive fissure, and (iii) craters without an associated cinder cone, both, submarine and subaerial. We discarded hornitos and rootless vents as volcanic vents to avoid overvalue susceptibility analysis, since they are not lava emissions centres. Submarine eruptive vents morphologically recognisable were considered as volcanic cinder cones, including those located at the north of Fuerteventura, due to the proximity to Lanzarote and also because they belong to the same volcanic edifice.

From the volcano-structural study, we obtained different datasets that correspond to vents and eruptive fissures, both onshore and offshore the island, and onshore faults (Table 2). To identify onshore structures we considered the complete emerged history of the island (from Miocene to Holocene). Volcano-structural datasets were divided according to the age of the structures and their location (onshore or offshore) (Table 2). Thus, we obtained Miocene-Pliocene, Pleistocene and Holocene onshore vents, and eruptive fissures respectively, besides offshore vents and eruptive fissures (Fig. 3, Table 2). Only 6 faults were identified on the island. The majority of the linear structures (eruptive fissures and faults) follow the NE-SW direction and they are from less than 1 km to 15 km length (Table 2).

6 Susceptibility analyses

The spatial probability of a future vent opening, given the past eruptive activity of a volcanic system, is a crucial step for simulating possible future eruptive scenarios, as it will provide indication from where the eruption may start, and how the corresponding hazards will distribute (Martí and Felpeto, 2010). The information required to perform this susceptibility analysis is the distribution of the past volcano-structural elements, their age, and the regional stress field. The first assumption is that the regional stress field has not changed since the last eruption. Based on this premise, new vents will not form far from the previous ones, and consequently, this volcano-structural information can be used to pinpoint areas where next eruptions may most likely occur since they represent the sites where previous eruptions have taken place (Connor, 1990; Connor et al., 1992, 2000; Ho, 1992, 1995; Martin et al., 1994; Ho and Smith, 1998; Connor and Conway, 2000; Gaffney et al 2017; Martí and Felpeto, 2010; Bebbington and Cronin, 2011, Capello et al., 2012; Selva et al., 2012; le Corvec et al., 2013a; Bartolini et al., 2013; Bevilacqua et al., 2015; Martí et al., 2016b). Other kind of data such as geophysical information or the stress field configuration of a volcanic area, if available, should be also used to forecast more precisely the most probable areas to host future vents (Martí and Felpeto, 2010; Martí et al., 2016b). In particular, the stress field is a key parameter controlling magma generation, magma migration and magma accumulation inside the volcanic system, as well as the location, geometry and the distribution of the resulting volcanism at surface (Martí et al, 2016b). Therefore, knowing the stress configuration in the lithosphere at any scale (i.e. local, regional and plate-scale) is important to understand volcanism distribution and, subsequently, to predict the location of future eruptions (Martí et al., 2016b). For that reason, in this work we also considered the regional stress field configuration in Lanzarote, (Geyer et al. 2016), which updates the previous susceptibility maps developed by Bartolini et al. (2013) and Galindo et al. (2016).

We used the QVAST tool (QGIS for VolcAnic SusceptTibility; Bartolini et al., 2013), to generate a quantitative assessment of volcanic susceptibility in the island. This tool is backed on a probabilistic method that calculates a kernel function at each data location, based on the distance from nearby volcanic structures, to estimate probability density functions (PDFs).). One of the most important factors to determine this density distribution is the smoothing parameter, also known as smoothing factor, or bandwidth, which represents the degree of randomness in the distribution of past events.

In this study, we applied the Least Square Cross Validation (LSCV) method to evaluate the bandwidth of each dataset (Cappello et al. 2012, 2013; Del Negro et al., 2013), as it better represents the geometry of the vents distribution, NE-SW elongated. The dataset used is our volcano-structural information: vents, eruptive fissures onshore and offshore, and faults (Fig. 3). The bandwidth parameter (h) obtained for each of the defined datasets were (Table 3): i) 2,527 m for vents and fissures of the Miocene-Pliocene; ii) 2,808 m for vents and fissures of the Pleistocene; iii) 560 m for the vents and fissures of the Holocene; iv) 6,508 m for vents and fissures offshore; and v) 20,808 m for faults (Table 3).

Considering the regional stress field model by Geyer et al. (2016) and the different ages of the volcano-structural elements, the expert judgement elicitation assigned the following weights to each data set: i) 0.107 for vents and fissures of the Miocene-Pliocene; ii) 0.207 for vents and fissures of the Pleistocene; iii) 0.357 for vents and fissures of the Holocene; iv) 0.193 for offshore vents and fissures; and v) 0.136 for faults (Table 3). In detail, the relevance and reliability values (Table 3) (Martí and Felpeto, 2010) have been assigned as follow: relevance was given through an elicitation of expert judgment procedure (Aspinall, 2006) among the members of the Group of Volcanology of Barcelona (GVB-CSIC) and external collaborators (14 experts in total); reliability was considered as maximum in all the datasets (value of 1), since all of them come from previously published volcano-structural studies and direct field observations.

The total susceptibility map was thus obtained via a weighted sum and modelled in a non-homogeneous Poisson process (Fig. 4).

7 Eruptive scenarios

7.1 Fallout Scenarios

Fallout scenarios were obtained using VORIS 2.0.1 tool (Felpeto et al., 2007). The input data regarding the eruptive column and ash particle size were inferred from historical eruptions published data (Romero 1991; Carracedo et al. 1992; Ancochea et al., 2004; IGME maps (2004) and references therein). We simulated one scenario with the same eruptive parameters as the 1824 eruption considering a maximum column height of 3 km and a total emitted volume of 0.02 km^3 (Table 4) assuming this scenario as the most probable in the near future in the island.

All simulations were conducted from one of the pixels located in the highest spatial probability area, and data inputs of wind velocities were compiled from the University of Wyoming Department of Atmospheric Science sounding database (http://weather.uwyo.edu/upperair/sounding.html) at different vertical heights (500, 1500, 2500 and 3500 m). We focused the attention of our study on the fallout scenarios for the NE direction (Fig. 5a) which represents the typical north-east trade wind that characterises the Canary Islands latitude, and for the entire wind rose directions (Fig. 5b). Results are shown in Figure 5. Particle sizes (-6 to 2 ϕ) were considered in all simulations, thereby covering the entire range of particle sizes observed in the field.

In the case of fallout scenarios we have only reproduced two scenarios (NE wind direction and entire wind rose directions) from a single vent located in the area with highest susceptibility value, instead of making the calculation from all pixels of the map. The reason is that ashfall process does not depend on the topography (DEM), but only on the position of the vent and wind direction, in addition to all eruptive parameters. Therefore, the use of the volcanic susceptibility map as base map for simulating ashfall would have required almost 150000 simulations that correspond to the number of pixels of the susceptibility model. All these simulations together would have given a superposition of many plumes that would cover the entire island, not having much sense for the purposes of this study.

7.2 Lava Flow Scenarios

The most expected processes associated with an effusive eruption in Lanzarote are lava flows. Lava flow scenarios were performed for the whole island using VORIS 2.0.1 tool (Felpeto et al., 2007), and as single vent scenarios reproducing the lava flows of the 1730-36 and 1824 eruptions (Fig. 4a, b). For the first case, we used the whole susceptibility map (Fig. 4), only taking into account the on-land pixels. For single vent scenarios, we used only those pixels with the highest spatial probability values. Lava flow input parameters were constrained by maximum flow lengths and thicknesses taken from historical eruptions and field measurements. We assumed flow lengths up to 35 km, because of the 1730-36 eruption poured out lavas that reached the sea after paths of 21 km onshore. Maximum lava flow length considered for the 1824 eruption was 7 km, while for the whole lava flow map a maximum length was 25 km, taking into account lava lengths from the 1730-1736 eruption. The thickness used as input for all the models was 10 m. The results provide two single vent scenario maps and a total map that gives the probability that any particular cell is invaded by a lava flow (Fig. 6). The total lava flow map was performed with a cell size of 75 m, thus optimizing the result and computed time.

7.3 Pyroclastic Density Current Scenarios

Hydromagmatic eruptions have also occurred on Lanzarote in recent times and have generated a wide variety of pyroclastic density currents (PDCs) deposits. It is possible to recognise pure hydromagmatic edifices and also Strombolian edifices with phreatomagmatic phases (García-Cacho and Romero, 2000). For that, we have mainly simulated hydromagmatic eruptions in areas close to the previous vents but also some phreatomagmatic phases that could occur together with Strombolian activity. PDCs were simulated with an energy cone model (Sheridan and Malin, 1983) using as input parameters topography, the collapse equivalent height (H) and the collapse equivalent angle (θ), which is obtained through the arctangent of the ratio between Hc and L, where L represents the run-out length (Felpeto et al., 2007; Toyos et al., 2007).

L values were considered to be equivalent to the most distal exposure of PDC deposits found on the island (Tables 1 and 4), which correspond to lengths from 0.5 to 3 km. H was assumed to be 250 m for all simulations, considering similar kind of eruptive styles for these hydromagmatic eruptions (Toyos et al., 2007). We simulated PDCs with θ in the range of around 5–29º (low values for base surge type explosions and high values for PDCs derived from column collapse) (Sheridan and Malin, 1983) (Tables 1 and 4). Figure 7 shows coverage areas with different column collapse equivalent angles, reaching the deposits up to almost 15 km. Each simulation is associated with previous PDCs occurred on the island, that is, similar parameters and close areas of previous PDCs deposits have been considered. Numbers in Figure 7 are related to those from Table 1.

8 Discussion and conclusions

Lanzarote is one of the four islands of the Canary Archipelago that has hosted an important eruptive activity during the last 600 years (historical period), being the Timanfaya eruption in 1730-1736 the second largest historical eruption occurred on a European territory. This, together with the fact that it is the third preferred touristic destination of the Canary Islands, classifies Lanzarote as an active volcanic island for which a precise hazard assessment is urgently required.

Past on-land volcanism has been mainly characterised by multiple-fissure type eruptions of basaltic magmas, generating lava flows of variable length and small to medium sized cinder cones, so we should expect future eruptions being of the same type. A few hydromagmatic eruptions have also been recognised along the coast line or close to it, which generated Surtseyan activity when eruptive magma interacted directly with sea water (e.g.: El Golfo, Pedrazzi et al., 2013) or phreatomagmatic pulses when magma interacted with a saltwater intrusion near the coast (e.g.: El Cuchillo, Aparicio et al., 1994), respectively. In this case, different types of dilute PDC deposits were produced, together with ballistics and fallout, reaching distances up to 15 km from the vent. Moreover, the large number of well-preserved cones observed on the submerged slopes of the island suggests that the number of submarine eruptions in recent times may be similar or significantly higher than those from on-land. This suggests that a submarine eruption scenario should be considered as highly probable. Unfortunately, the lack of geochronological data precludes establishing the eruption recurrence in Lanzarote, so not allowing to conduct a temporal hazard assessment and to quantitatively identify the most probable eruptive scenarios. Therefore, our hazard assessment is restricted to the on-land volcanism, without this implying that a subaerial eruption is the one with the highest probability of occurrence on Lanzarote in the near future.

The spatial analysis revealed that the area with the highest probability of hosting a new subaerial eruption is mainly located in the same area than the previous 1824 and Timanfaya eruptions (Fig. 4). This is mainly due to the fact that the best preserved vents are concentrated in this zone (Fig. 3), but also that the current stress field is compatible with orientation of fractures that governed these most recent eruptions (Fig. 3). Our results slightly contrast with those recently presented by Galindo et al (2016). The differences observed for the on-land areas may be due to the different method used in both studies. Our study follows the method of Cappello et al. (2013) since it is a well tested method successfully applied to volcanic fields such as Etna, El Hierro, Deception Island or Pico (Cappello et al., 2012; Becerril et al., 2013; Bartolini et al., 2014; Cappello et al., 2015), which show similar behaviour than Lanzarote, and we considered it was more appropriate to model volcanic susceptibility in this particular case, rather than to develop a new model as it was done by Galindo et al (2016).

Simulation of the different volcanic hazards that may be produced in subaerial eruptions on Lanzarote revealed opening of new eruptive fissures in the highest probability areas. Assuming a new typical Strombolian eruption and the typical winds of the Canary Islands (NE-SE winds), would imply the dispersion of the volcanic ash mainly towards the southern part of the island. As mentioned before, this area hosts a high number of tourist resorts, therefore, in case of an eruption, a large number of people should be evacuated (Fig. 5).

Lava flows are rather constrained to the area around their vents. This implies that, according to the hazard map, if we expect a typical Strombolian eruption with lava flow emission, those areas that could be affected by this process, are mainly located surrounding the Timanfaya National Park. This area includes two protected figures (a National Park and a Natural Park), but it does not host too many towns or infrastructures. If, on the contrary, we expect larger eruptions, in terms of emitted volume, the runout distances of the lava flows would be longer, affecting numerous towns and villages around the Timanfaya area, and others located to the north (Guatiza, Mala in Fig. 6). The rest of the island would have a lower chance to be inundated by lava flows.

Finally, the occurrence of PDC is more restricted to areas close to the coast, where the majority of the identified past hydromagmatic events are concentrated, being in age older than the most recent eruptions. However, such scenarios must be also considered as they may imply larger impacts than normal Strombolian eruptions.

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Tables

Island	Map Nº	Local Name	X	Y	Start Simulation point Height (m.a.s.l.)	Collapse equivalent height (Hc) (m)	Run-out (L) (m)	Collapse Equivalent angle (Θ) (º)	Basal Diameter (km)	Type/Characteristics	Trend
LANZAROTE	1	El Golfo	614214	3205971	0	250	2500	5.71	1	Tuff Cone	N50ºE
	2	Caldera Blanca	623734	3213091	142	250	3000	7.44	1.8	Maar	N85ºE
	3	El Cuchillo	631054	3218877	42	250	3000	5.56	1.4	Tuff Ring	N65ºE
	4	Mt. Cavera	637305	3222578	40	250	1500	10.94	0.185	Coastal Eruption;	N33ºE
	5	Mt. Chica	636346	3222139	65	250	1500	11.86	0.175-0.25	Wet-surges. Last phases: Strombolian +	N50ºE
	6	Mt. Mosta	632977	3219146	87	250	1000	18.62	>0.065	Coastal Eruption	N96ºE
	7	Mt. Roja	611455	3193167	13	250	500	27.74	1.4	Tuff Cone	N75ºE
	8	Mt. Mojón	623996	3202946	318	250	1000	29.60	0.8*0.625	Tuff-ring	N60ºE
	9	Mt. Guatisea/Mt. Blanca	633449	3208190	378	250	1500	22.72	-	Strombolian cone with hydromagmatic intercalations	N006ºE

	10	Mt. Corona	646191	3211411	115	250	1500	13.68	1.2	Strombolian cone with hydro-magmatic intercalations	
	13	Mt. Ubigue	639999	3211732	231.5	250	1500	17.80	1*1	Strombolian cone with hydro-magmatic intercalations	N50E
	14	Mt. Tinaché	629288	3214639	291	250	1500	19.83	1.25	Strombolian cone with hydro-magmatic intercalations	
	15	Mt. de Halcones	615178	3209072	63	250	1000	17.38	0.65	Strombolian cone with hydro-magmatic intercalations	N50ºE
	16	Caldera Riscada	621975	3201907	322	250	5000	6.53	1*0.9	Strombolian and hydromagmatic phases	N60ºE
	17	Caldera Gritana	621228	3201274	343	250	5000	6.76	0.65*0.6	Part of a hydromagmatic edifice	N60ºE
LA GRA-CIOSA	**18**	Mt. Amarilla	642207	3233381	30	250	1000	15.64	0.9*0.65	Strombolian and phreatomag-matic phases	N45ºE
	19	Mt. Aguja Grande	645018	3236401	82	250	600	28.96		Strombolian and phreatomag-matic phases	N45ºE
MT. CLARA	**20**	Mt. Clara	642579	3242537	34	250	500	29.60	-	Wet surges	
ALEGRANZA	**21**	La Rapadura	646207	3252803	2	250	500	26.75	0.42*0.41	First phases Hydromagmatic	
	22	Mt. Lobos	645019	3251867	24	250	1250	12.36	1.2*0.87	First phases hydromagmatic	

	23	La Caldera	643151	3252587	16	250	3000	5.07	2.6 *1.75	Tuff Cone	N65ºE

Table 1. Main characteristics of hydromagmatic eruptions of Lanzarote. Run out distances correspond to minimum L due to these distances have been taken from the maximum exposure deposits on the geological maps. Different parameters have been chosen to simulate PDCs on the island (See section 7.3 for more information).

Volcano-structures	Onshore			Offshore
	Miocene-Pliocene	Pleistocene	Holocene	
Vents	23	419	171	102
Eruptive Fissures	1	69	25	9
Faults	6 (no associated age)			-

Table 2. Number of identified volcanic structures on Lanzarote Island, according to their ages and location

Nº	Structural Datasets	Age	Bandwidth	Weight
1	Miocene-Pliocene Vents and Eruptive Fissures	15 Ma- 2.5Ma	2527	0.107
2	Pleistocene Vents and Eruptive Fissures	2.5 Ma- 11.7 ka	2808	0.207
3	Holocene Vents and Eruptive Fissures	last 11.7 ka	560	0.357
4	Offshore vents and eruptive Fissures	Unknown ages	6508	0.193
5	Faults	Unknown ages	20808	0.136

Table 3. Parameters used for performing susceptibility analysis.

GEOLOGICAL PROCESS-HAZARD	These parameters are mainly derived from 1730-36 and 1824eruptions				
	Max. Length (km)	**Mean Length (km)**	**Min. Length (km)**	**Mean Thickness (m)**	**Total emitted volume (km^3)**

Lava Flow	35/25	5-7	1.5	10	0.02-4
	Run out (km); from hydromagmatic eruptions or phreatic phases		**Collapse Equivalent angle (º)**		
Pyroclastic Density Current	0.5-3		5-29		
	Column height (km)		**Size particles (Φ)**		
Fallout	3-5		From -6 to 2		

Table 4. Main characteristics of the historical and Holocene eruptions and parameters used for scenario simulations.

Figures

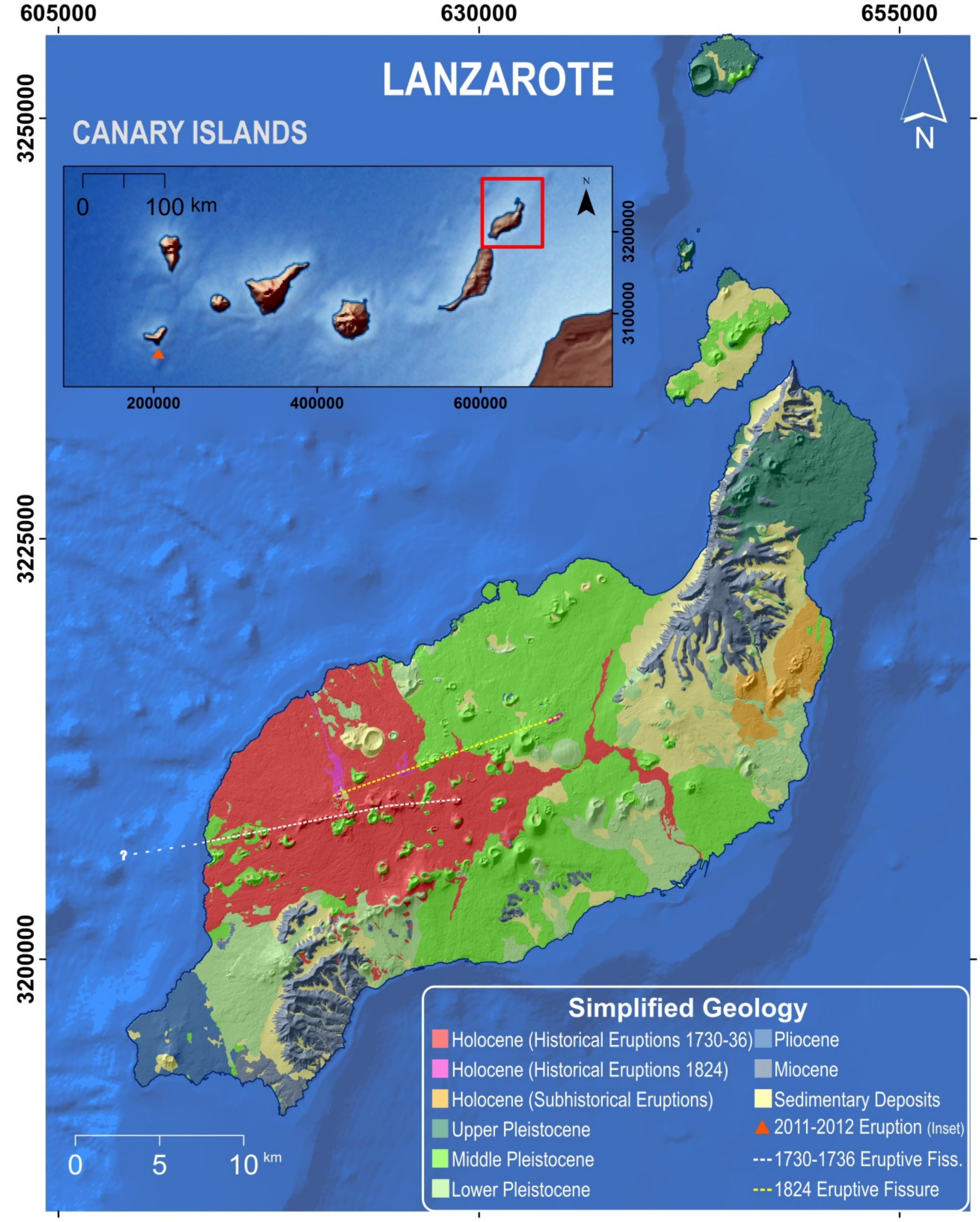

Figure 1. Simplified geological map of Lanzarote Island. The top left inset displays the location of Lanzarote within the Canary Archipelago. (Original geological map can be found in: http://info.igme.es/cartografiadigital/geologica/Geode.aspx).

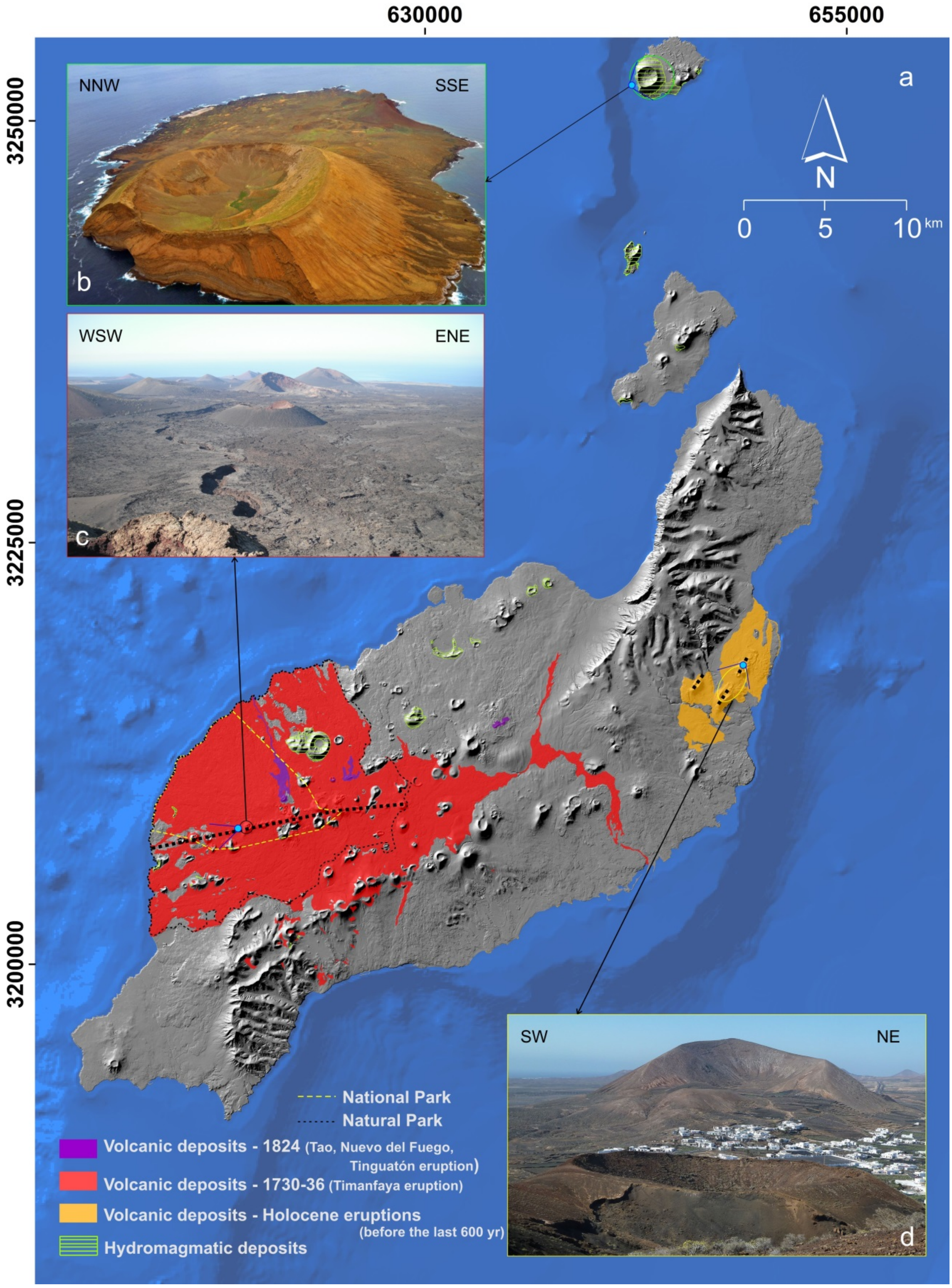

Figure 2. a) Historical eruptions (red, pink and yellow), and hydromagmatic edifices (green) on Lanzarote; b) Alegranza hydromagmatic cone with a diameter of 1.2 km; c) Timanfaya cones; d) Mt. Guenia and La Caldereta cones. Yellow and black dashed lines define the limits of the Timanfaya National Park and the Natural park, respectively.

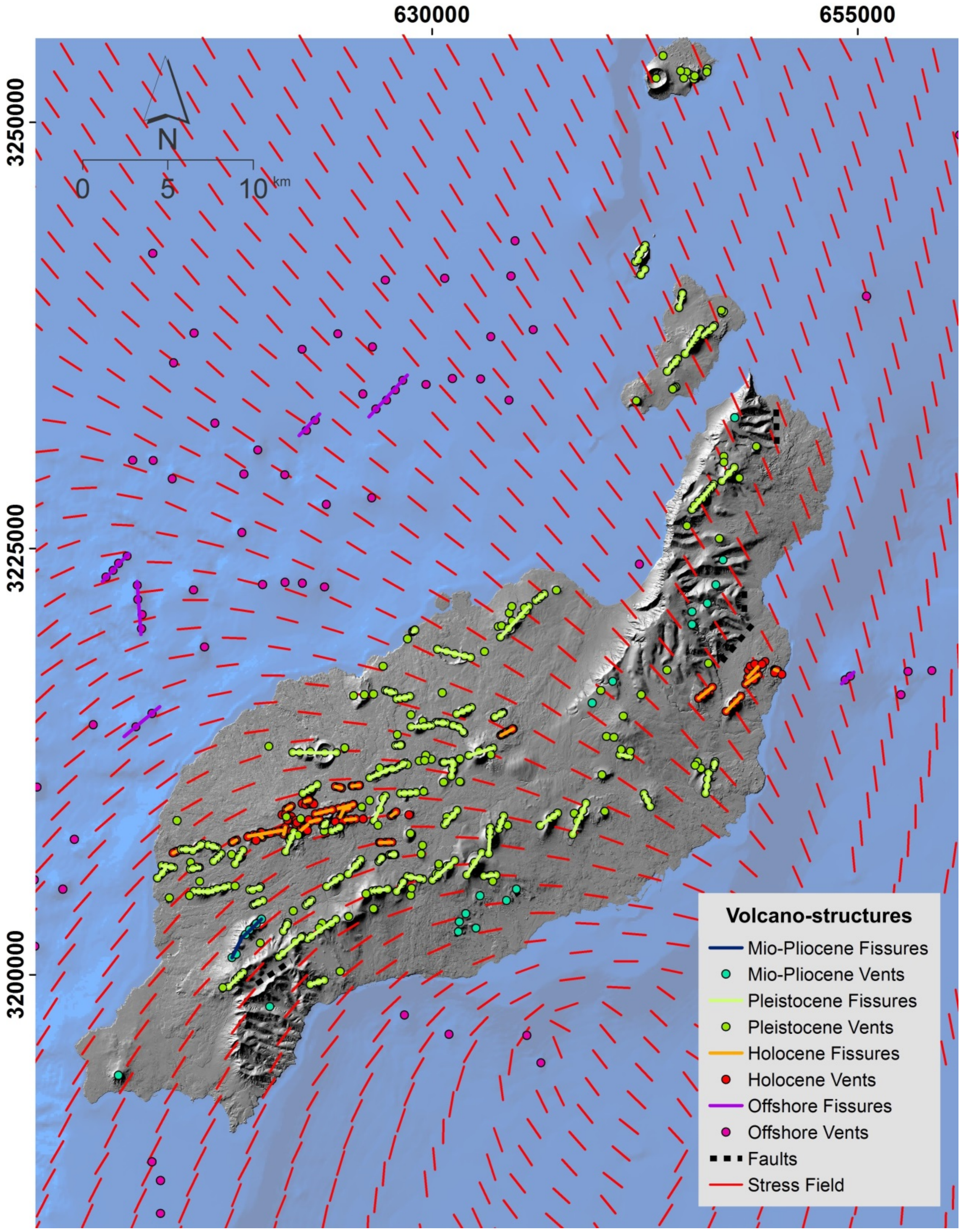

Figure 3. Volcano-structural datasets defined for Lanzarote and used for evaluating spatial probability. Maximum compressive horizontal stress trajectories are also indicated (red lines).

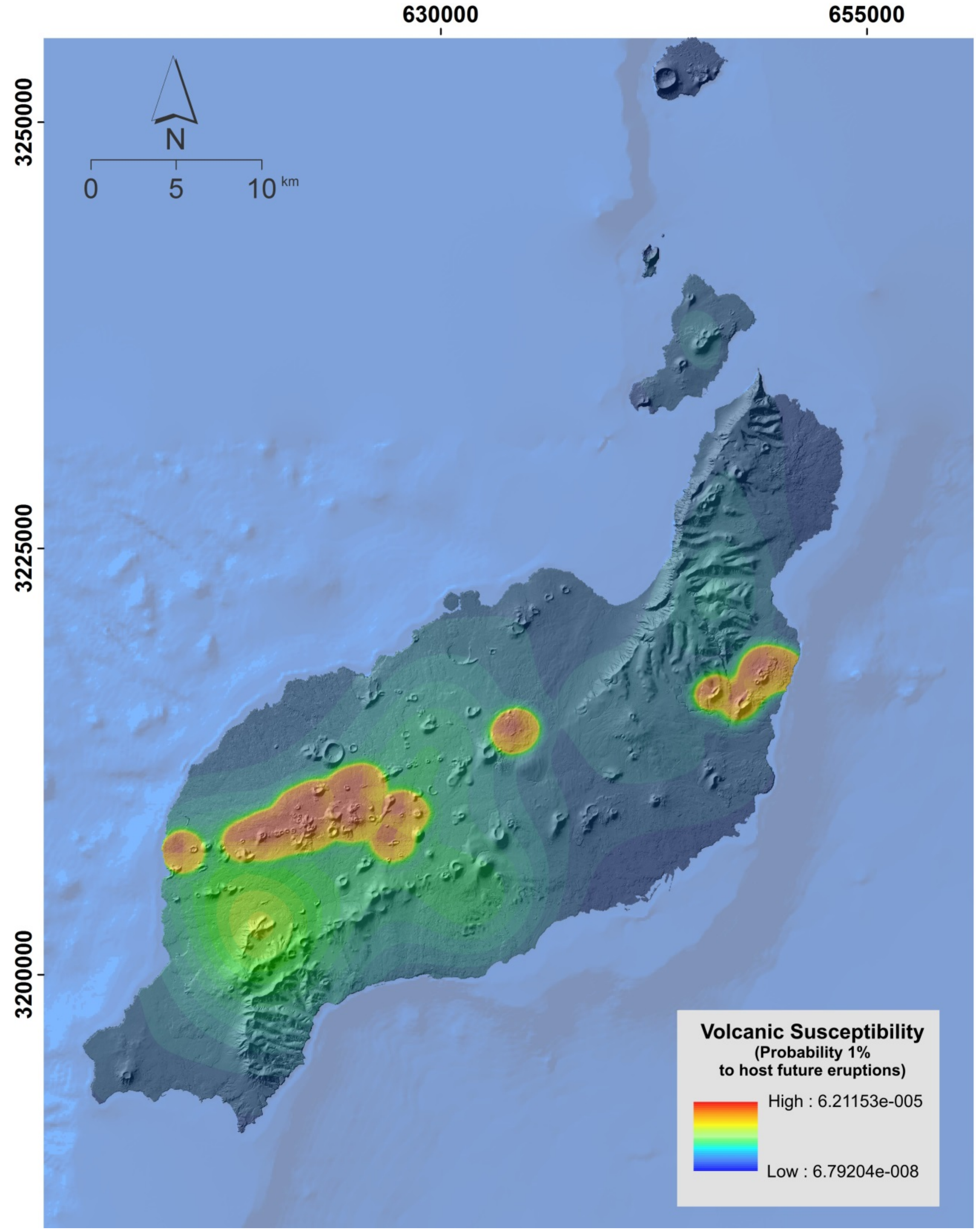

Figure 4. Volcanic susceptibility map of Lanzarote Island. The highest probability (0.00006) of new vent opening is obtained along a NE-SW area. High probabilities are also observed in the South of the island.

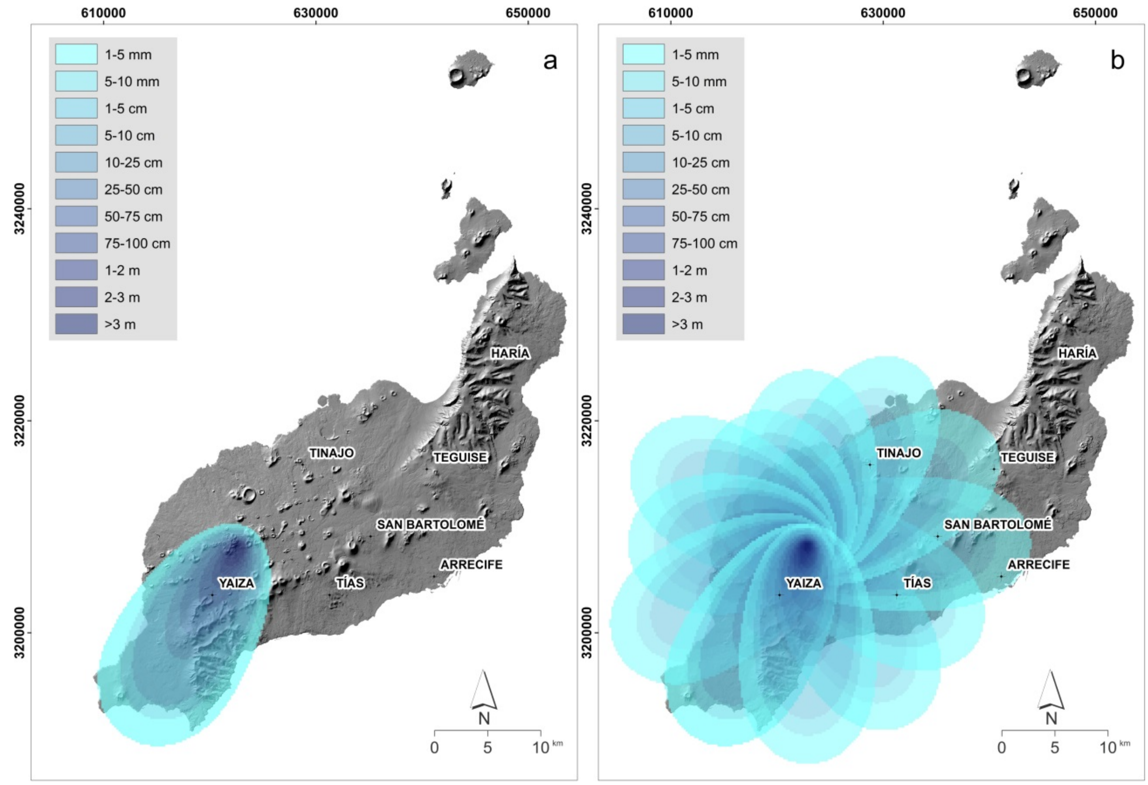

Figure 5. Fallout scenarios at the highest probability vent for the NE wind direction and for the entire wind rose directions performed with VORIS 2.0.1. a) NE wind simulation assuming a Strombolian eruption; b) 1824 eruption. Main localities have been placed in order to show which ones would be affected by the ashfall dispersion.

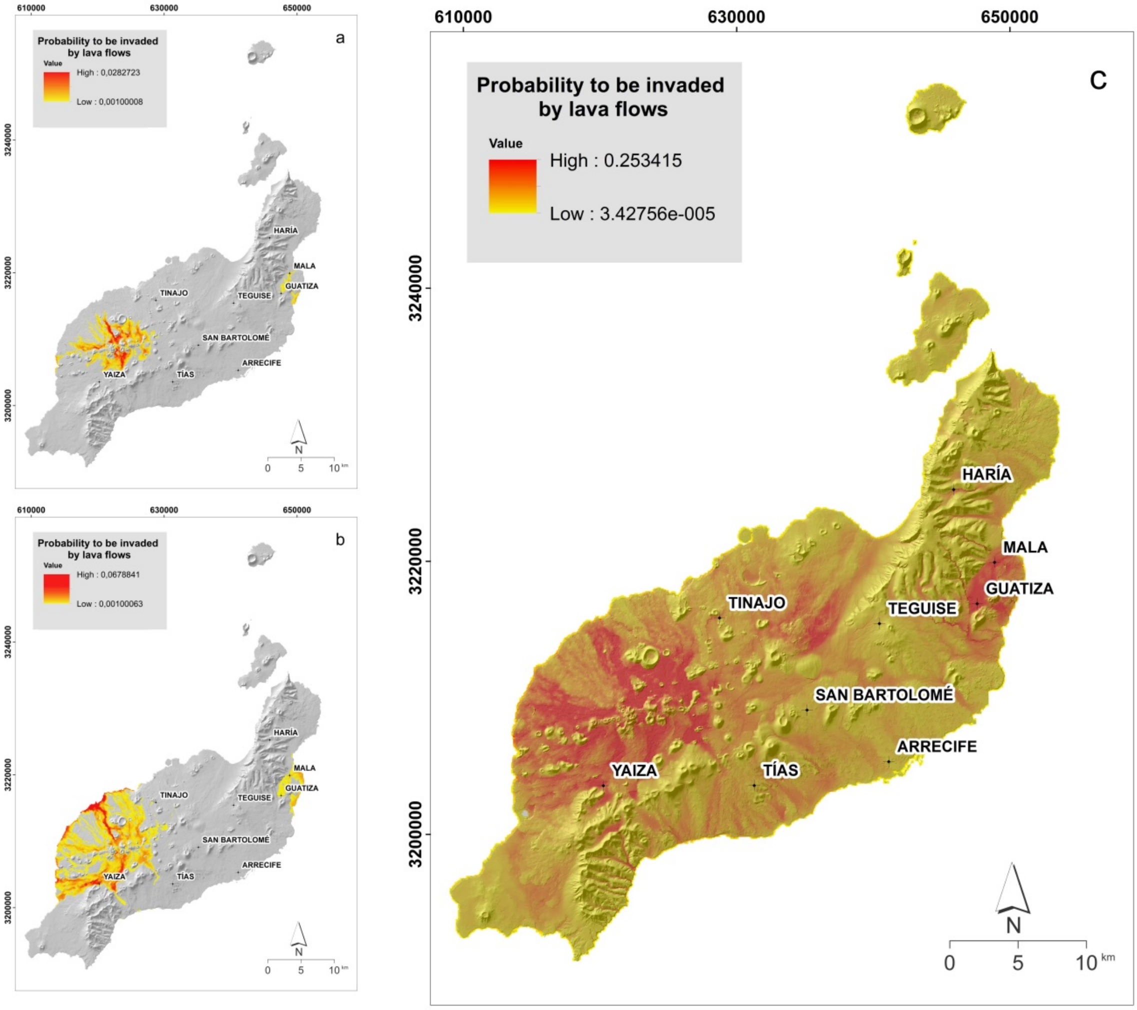

Figure 6. Lava flow scenarios for Lanzarote performed with VORIS 2.0.1. a) Timanfaya scenario; b) 1824 eruption scenario; c) Total lava flow map. Red colours are those areas with the highest probability to be invaded by lava flows.

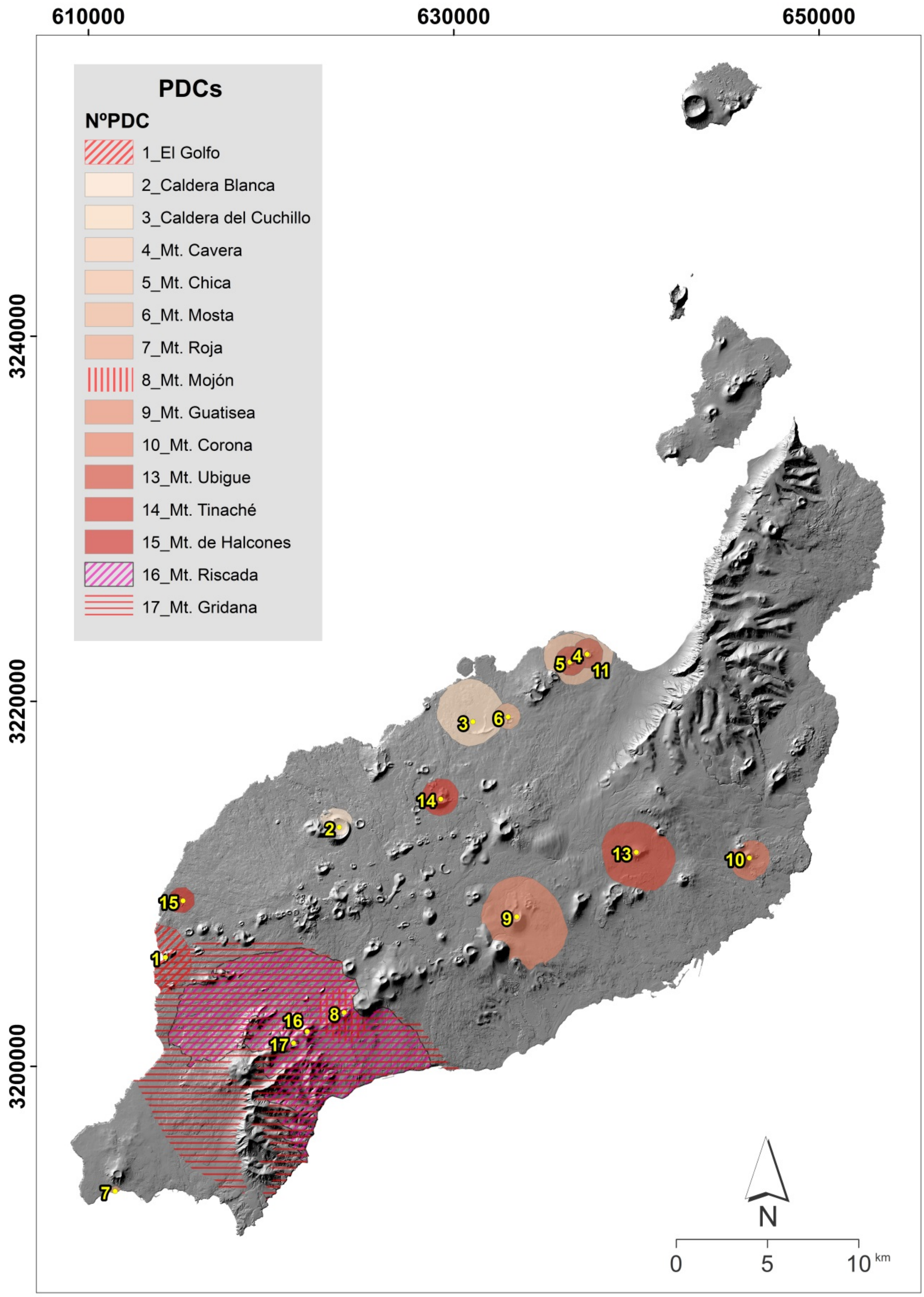

Figure 7. PDC scenarios performed with VORIS 2.0.1. Covered areas with different collapse equivalent heights (Hc) and collapse equivalent angles (θ) (see the text for more detail). Different symbols (dashed, filled and coloured) have been used to show the limits of each PDC. Yellow dots indicate the simulation starting point.