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Assessment and Modelling of Lava Flow Hazard on Lanzarote (Canary Islands)

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Abstract. This paper presents an evaluation of the lava flow hazard on Lanzarote (Canary Islands) by means of a probabilistic maximum slope model. This model assumes that the topography plays the major role in determining the path that a lava flow will follow. The area selected for containing future emission centres has been chosen taking into account the characteristics of the recent eruptive activity and the present activity of the island. The results of the simulations constitute hazard maps whose values at each point represent the probability of being covered by lava. These results are qualitatively analysed to provide some indication of the risk to the lifelines (electricity, drinking water etc.) of the island.

Key words: lava flow hazard, probabilistic maximum slope model, Lanzarote, Canary Islands.

Introduction

The volcanism of the Canary Islands began on the seafloor, at the Eocene-Oligocene boundary, and is still active (for a general description see Araña,1995; Araña and Ortiz,1991; Schmincke, 1982). Each of the islands displays singular characteristics in its geological history, with great differences in the age of the first subaerial eruptions (from 24 Ma for Fuerteventura and 17 Ma for Lanzarote to the 0.5 Ma for Hierro – see Cantagrel, 1988). Some islands, like Tenerife or Lanzarote seem to have been stable since emerging above sea level, while others have undergone significant vertical movements. This set of uplifted insular blocks is associated with the activity of an important fracture system in the dynamic framework of the expansion of the Atlantic (Araña and Ortiz, 1991, Ferraud *et al.*, 1985, Mezcua *et al.*,1992). These same fractures (roughly NE–SW, NW–SE and N–S) condition the alignment of some islands (Lanzarote-Fuerteventura) and the existence of well-defined volcanic cordilleras on islands such as Tenerife and La Palma.

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There is a great lithological variety amongst the islands and in different phases of their evolution (Araña, 1995; Ovchinnikova *et al.*, 1995). In the first stages of formation of all of these islands voluminous basaltic eruptions predominated and formed huge plateaux. This basaltic volcanism has continued with less intensity on all of the islands, except La Gomera, which has remained inactive for the last 5 Ma. In historic time (last 500 years) basaltic eruptions have been recorded on the islands of Lanzarote (1730–1736 and 1824), Tenerife (1704, 1706, 1798 and 1909) and La Palma (1585, 1646, 1677, 1712, 1949 and 1971) (see Romero, 1991). Only on the central islands of Tenerife and Gran Canaria have conditions been suitable for the creation of shallow magmatic chambers, above which large stratovolcanoes have formed.

The activity and variety of Canarian volcanism makes it necessary to take into account different volcanic hazards. The most serious are those associated with violent eruptions, although, with realistic criteria, today it would only be possible to consider this possibility in the present eruptive cycle of Teide on Tenerife, where a study of these hazards has already been carried out by Araña *et al.* (2000). Perhaps less hazardous, but very likely to cause damage on any island in the near future, are lava flows.

The analysis of lava flows as a volcanic hazard in the Canaries and the zoning of every island is of special importance for land planning and for the authorities and Civil Defence to take decisions in case of a crisis. The objective of this paper is to present a methodology for the identification of the zones that have the highest probability of being affected by lava flows, taking into account the location, extent and eruptive history of the source areas. The island of Lanzarote has been selected for the application of this model due to its recent eruptive history (Carracedo *et al.*, 1992) as well as because of its socio-economic conditions that require a rigorous evaluation of the potential volcanic hazards of the island.

Description of the Model

Different models have been used to simulate the path that a lava flow will follow over digital topographies. Ishihara *et al.* (1989) proposed a deterministic model that accounts for the non-Newtonian behaviour of the lava, mass conservation and radiative heat exchange with the atmosphere. Other approaches, based on the cellular automata techniques, are those by Barca *et al.* (1994) and Miyamoto and Sasaki (1997). An assessment of the lava flow hazard combining a deterministic model and a probabilistic analysis is presented in Wadge *et al.* (1994). A probabilistic model was used during the 1991–1992 eruption of Mt. Etna to evaluate the most probable paths for the lava (Barberi *et al.*, 1993; Dobran and Macedonio, 1992).

Many of these models require a numerical parametrization of the physical properties of the lava (such viscosity) or of the eruption (such effusion temperature or eruption rate) that are very difficult to determine or even constrain in the case of Lanzarote. So, we have used a probabilistic approach that does not describe the evolution of the lava flow, but gives the probability of each point to be invaded by lava: a probabilistic maximum slope model.

This model assumes that the topography plays the major role on determining the path that a lava flow will follow. The determination of the probability of each point being invaded by lava is performed by computing several random paths by means of a Monte Carlo algorithm. These paths cannot propagate upwards and their probabilities are higher in the higher slopes.

Lets consider the topography represented by a mesh of squared cells whose value is the topographic height (h) of the cell (i.e. a DEM, Digital Elevation Model). If the flow is located in a cell ($i = 0$), the probability(P_i) that the flow enters into one of the eight surrounding cells ($i = 1, 2, \ldots, 8$) is:

$$P_i = \frac{\Delta h_i}{\sum_{j=1}^{8} \Delta h_j}, \qquad i = 1, 2, \ldots 8, \tag{1}$$

where Δh_i represents the difference in height between the cell where the flow is and each of its neighbours. In the estimation of this difference, a corrective factor (h_c) is added to the height of the cell where the flow is currently located. This parameter simulates the effect of the height of the lava flow and allows it to propagate over small topographic barriers, that can be real or only small errors in the generation of the DEM (Dobran and Macedonio, 1992). Therefore, Δh_i is evaluated from:

$$\begin{aligned} \Delta h_i &= h_0 + h_c - h_i \quad &&\text{if} \quad (h_0 + h_c - h_i) \geq 0 \\ \Delta h_i &= 0 &&\text{if} \quad (h_0 + h_c - h_i) < 0. \end{aligned} \tag{2}$$

From Equations (1) and (2) it is obvious that if the topographic height of cell i is higher than the corrected height of the cell where the flow is located, the probability of this flow to propagate to cell i is zero, implying the flow cannot propagate upwards.

A Monte Carlo algorithm is used to compute the selection of the cell where the flow will propagate. The flow will enter into cell i if:

$$S_{i-1} \leq n_{\mathrm{rnd}} < S_i, \qquad i = 1, 2, \ldots, 8, \tag{3}$$

where n_{rnd} is a random number between 0 and 1 and S_i is defined as:

$$S_i = \sum_{j=1}^{i} P_j, \qquad i = 1, 2, \ldots, 8, \tag{4}$$

$$S_0 = 0.$$

It is necessary to note that expression (3) could be false for any value of i. This means that the flow has entered into a ‘sink’, a cell whose corrected height is lower than that of the eight neighbours, and then the flow will stop. In the case of a real lava flow, this ‘sink’ would probably be filled and the flow would continue. To avoid stopping the flow in such a situation, the model evaluates Equations (3) and (4) for the sixteen cells which surround the original eight ones (still considering that cell $i = 0$ is that where the flow is located). If expression (3) is verified by any of these cells, the flow continues, otherwise it stops.

In this scheme, the flow could propagate until it reaches the limits of the computational area. To avoid this, a parameter named maximum flow length ($l_{\max}$) is included in the model and used to stop the flow when its length reaches $l_{\max}$.

Following this procedure, the computation of a possible path starts in the cell chosen as emission centre and its propagation is calculated with successive application of Equations (1) to (4). When many paths has been computed, the probability of each cell to be invaded by lava is calculated as the ratio between the number of paths that have crossed the cell and the total number of paths computed.

Application to Lanzarote Island

There have been only two historic (in the last 500 years) eruptions on Lanzarote: those of 1730 and 1824. The eruption of 1730 (Figure 1) is the most important eruption which has taken place in the Canary Islands in recorded history, and also one of the largest basaltic eruptions known to man. During the eruption, one cubic kilometre of lava was emitted, covering an area of approximately 200 km^2. It lasted six years, although there must have been alternation between periods of great activity and others of rest (Carracedo *et al.*, 1992).

The emission centres of historic eruptions are concentrated along a small strip. In this same zone the highest level of current local seismicity is also found. There are also strong thermal anomalies, with temperatures that reach 600°C at 12 m depth (Araña *et al.*, 1984). These facts and the distribution of the vents of recent (Series III and IV of Fuster *et al.*, 1968) eruptive events shown in Figure 2, allows a strip of 25 × 3 km to be defined as the most likely zone for the opening of new emission centres (Figure 3(a)).

The topography used in the application of the model to Lanzarote is a DEM with a cell size of 50 m. More than 9000 randomly distributed cells have been considered to be the possible emission centres (representing approximately 20% of the cells of the area of Figure 3(a)). The value assigned to the correction height is 3 m and the maximum flow length is 40 km (such a high value has been selected to allow the lava to reach the coast). The total number of paths calculated is 9 221 000 (value high enough, as further iterations produced no major changes to the pattern).

The simulation has been performed twice: the first one (simulation 1) considering that all the cells in the area have the same probability of being emission centres, and the second (simulation 2) considering that the probability in the area decreases from the main axis outwards (Figure 3(b)) following:

$$P(x) = e^{-(x^2/\lambda^2)}, \tag{5}$$

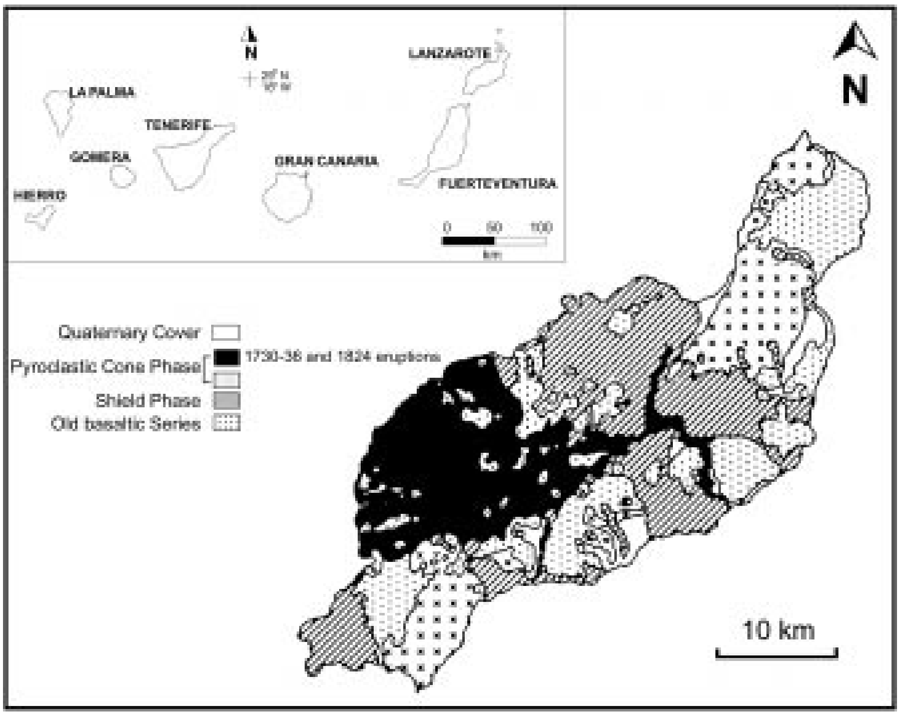

Figure 1. Simplified geological map of Lanzarote (from Marinoni and Pasquare, 1994).

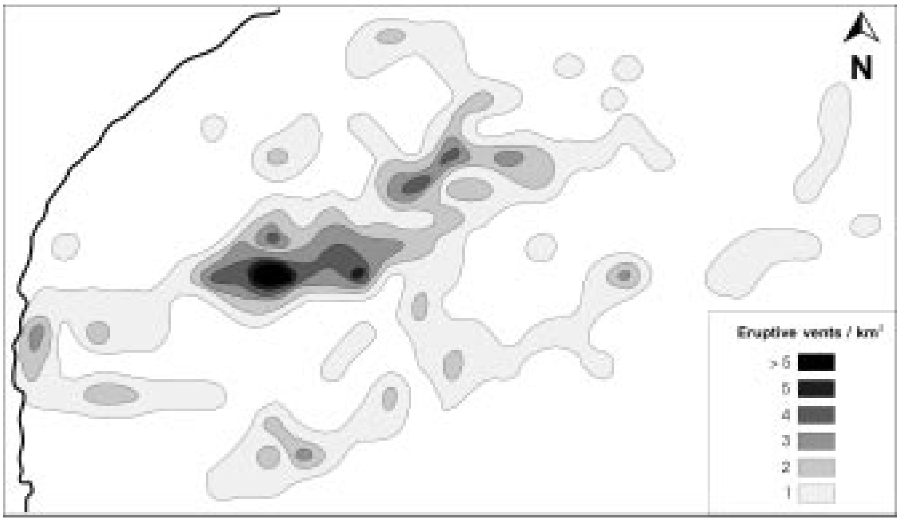

Figure 2. From Carracedo *et al.* (1992), the number-density distribution of vents of recent eruptives centres (Series III and IV of Fuster *et al.*, 1968) on the western part of Lanzarote.

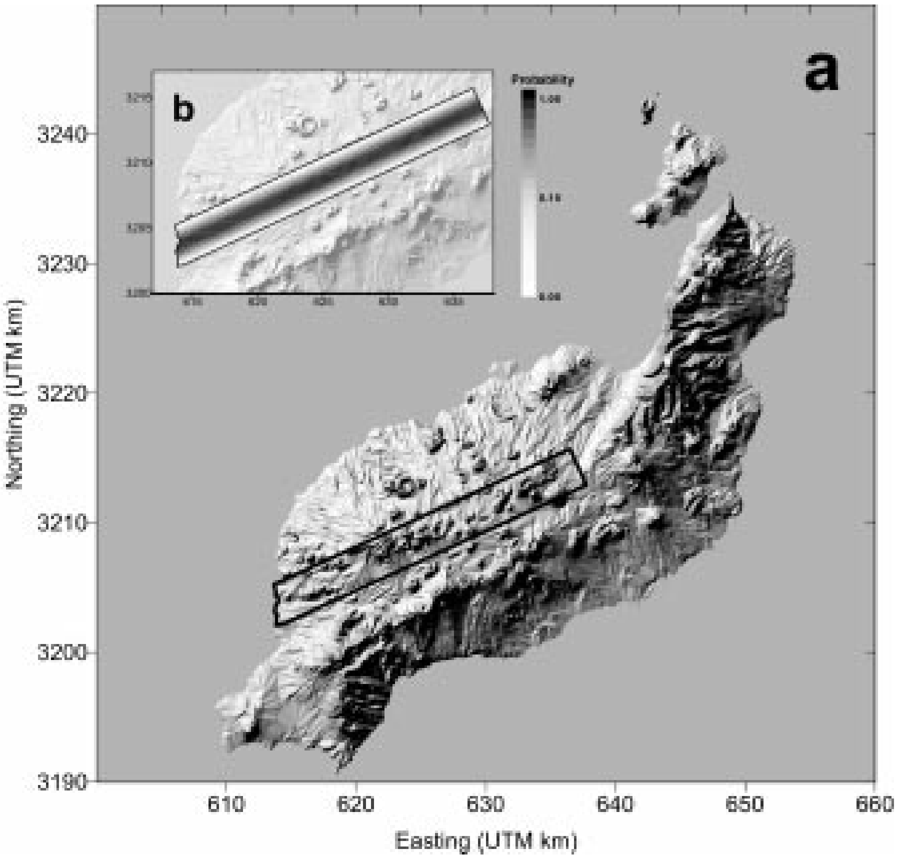

Figure 3. (a) Area selected for containing emission centres. The background is a shaded image of Lanzarote's topography. (b) Probability of each point being an emission centre for simulation 2.

where P represents the probability of a point located at x km from the main axis being an emission centre, and λ is a parameter that has been assigned a value of 0.7 km (one quarter the width of the area selected).

The results of both simulations are shown in Figures 4(a) and 5. Although both figures appear to be similar, the probabilities are significantly different in many areas. Figure 6 clearly shows these differences, since it represents the difference between both simulations, cell by cell, expressed as percentage of the higher value of both simulations. As can be seen, this difference is small in the most probable paths, but there are some areas where the difference is very high. This implies that these areas are mainly affected by the centres located at the edges of the area of Figure 3(a).

In terms of risk (see following section) the paths labelled A in Figure 4(a) are especially interesting. In order to refine the simulation in this area, another simulation (simulation 3) was performed with a DEM with a cell size of 25 m,

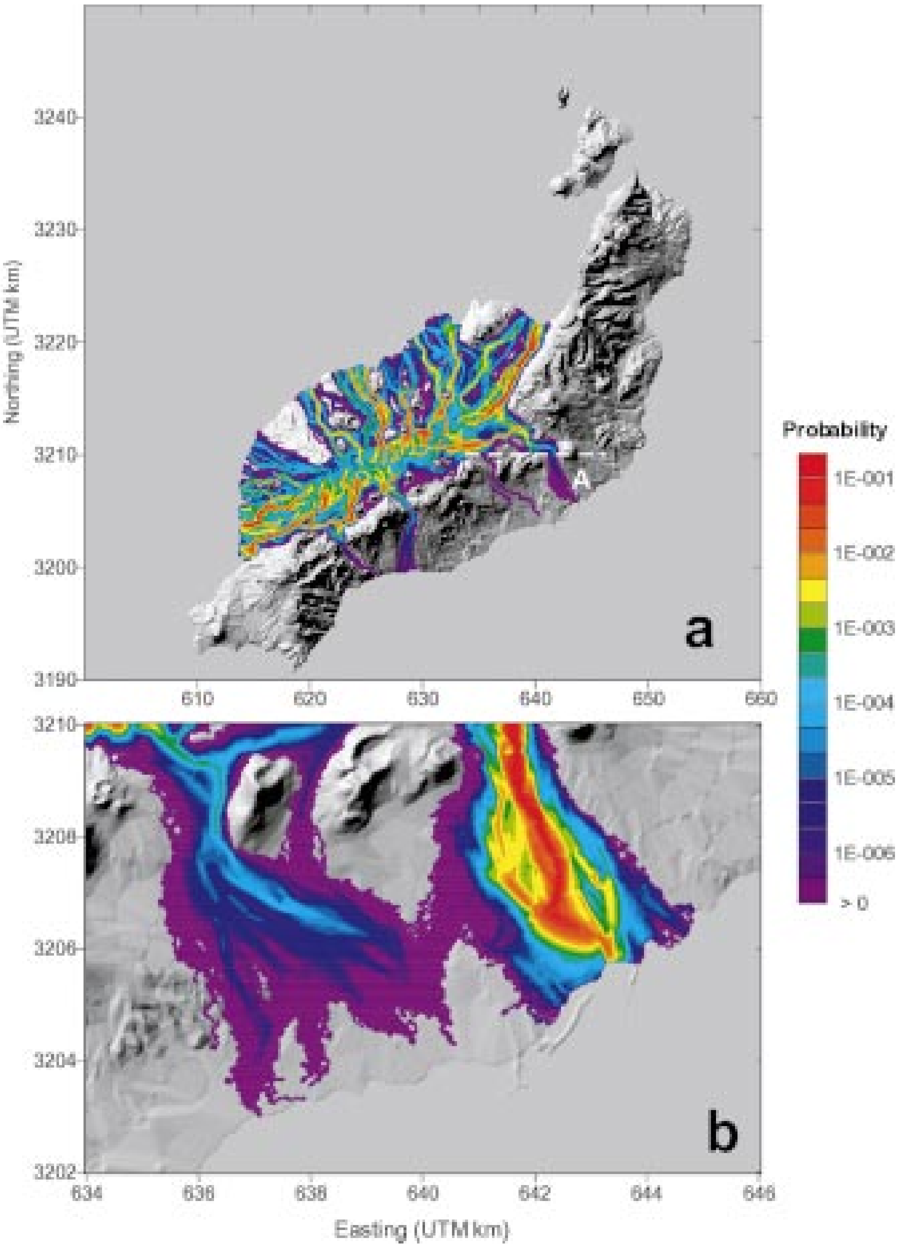

Figure 4. (a) Result of simulation 1: probability of being invaded by lava for the emission centres located in area of Figure 3(a) over a DEM with cell size of 50 m. Letter A marks the paths that go to Arrecife area. Dashed line represents the location of the emission centres considered in simulation 3. (b) Refined simulation in Arrecife area (simulation 3), over a DEM with a cell size of 25 m. The emission centres considered are those located on the dashed line of Figure 4(a) with a probability equal to the results of simulation 1.

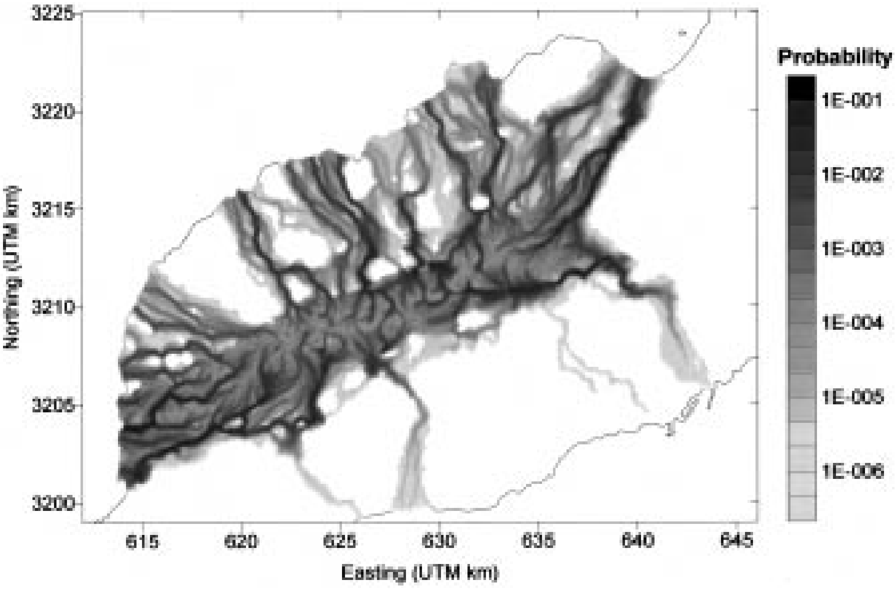

Figure 5. Result of simulation 2: probability of being invaded by lava for the emission centres located in area of Figure 3(a) with probability of Figure 3(b), over a DEM with a cell size of 50 m.

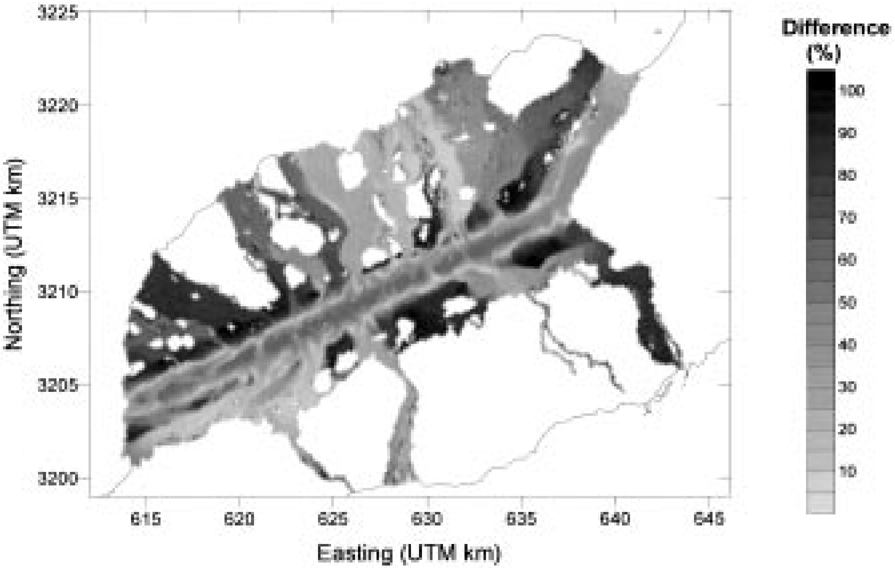

Figure 6. Difference between results of simulations 1 and 2 expressed as percentage of the higher value of both simulations.

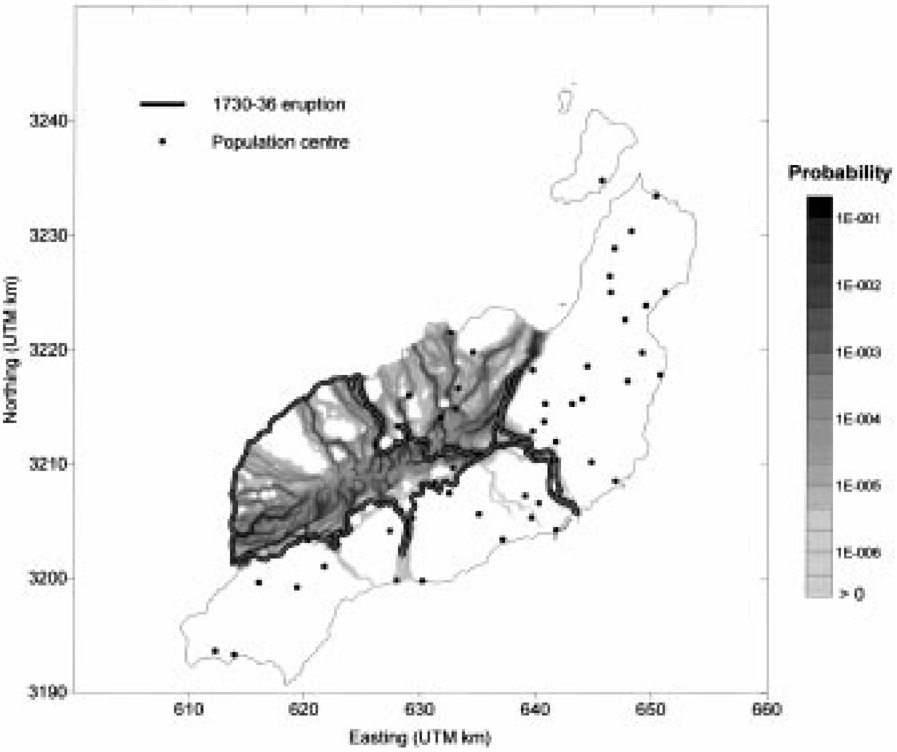

Figure 7. Main population centres (black points) and area covered by the 1730–1736 eruption (thick black and white line). The background image is the result of simulation 1 (same as Figure 4(a)).

height correction of 3 m and maximum flow length high enough to let the flows reach the sea. The emission centres considered are those cells along the dashed line in Figure 4(a), line that should be crossed by any flow that could reach the area of interest, and their probability are the result of simulation 1. This means that the result of this simulation is equivalent to performing simulation 1 on a DEM with a cell size of 25 m but considering only those centres that can affect the area of interest. Due to this artifact, the probability values of this simulation cannot be compared with those of simulations 1 and 2, as they represent the probability of each cell being covered by lava when flows from the emission area cross the dashed line in Figure 4(a). The results of simulation 3 are shown in Figure 4(b).

Discussion of the Results and Conclusions

Figure 7 superimposes the main centres of population over the probability map of Figure 4(a). Although this figure cannot be considered a risk map, it does give some indication about the possible impact of a future eruption. The possible eruption would mainly affect lesser populated areas of the island, which were largely covered by the lavas from 1730 eruption (thick line in Figure 7). The low population in this area is due to the fact that it constitutes the National Park of Timanfaya. The main tourist areas are centred on the south and east coasts of the island, and would be practically unaffected.

As noted earlier, the paths lettered A in Figure 4(a) are especially significant because, although their probabilities are not very high, they lead directly to Arrecife, the capital of the island, where more than the 40% of the population of the island live. Its surroundings are also critical as the main lifelines (power plant, water purifier, harbour and fuel deposits) are located there. This has historically been the centre of the resources of the island as a lava flow formed a natural protective port, around which Arrecife grew up.

This result is important as it shows that it is necessary to carefully design emergency plans to defend this part of the island from the invasion of lava using canals and barriers (Barberi *et al.*, 1993; Abersten, 1984). These plans should also take into account that if the lava did reach the power plant and/or water purifier, the rest of the island could be deprived of drinking water or electricity. As a consequence, future expansion of these lifelines should not be located near the present ones and should take into account analyses like present in this paper to determine their locations.

References

Abersten, L.: 1984, Diversion of a lava flow from its natural bed to an artificial channel with the aid of explosives, Etna 1983. *Bull. Volcanol.* **47**(1), 167–177.

Araña, V., Díez-Gil, J.L., Ortiz, R., Yuguero, J., 1984, Convection of geothermal fluids in the Timanfaya volcanic area, Lanzarote, Canary Is. *Bull. Volcanol.* **47**, 667–677.

Araña, V. and Ortiz, R.: 1991. The Canary Islands: Tectonics, magmatism and geodynamic framework, in A. B. Kampunzu and R. T. Lubala (eds), *Magmatism in Extensional Structural Settings. The Phanerozoic African Plate*, Springer-Verlag, Berlín, pp. 209–249.

Araña, V.: 1995, Notes on Canarian Volcanism, in J. Martí and J. Mitjavila (eds), *A Field Guide to the Central Volcanic Complex of Tenerife (Canary Islands)*, Serie Casa de Los Volcanes, **4**. Cabildo de Lanzarote, pp. 3–17.

Araña, V., Felpeto, A., Astiz, M., Gómez, F., García, A., and Ortiz, R.: 2000, Zonation of the main volcanic hazards in Tenerife (Canary Islands), *J. Volcanol. Geotherm. Res.* (in press).

Barberi, F., Carapezza, M. L., Valenza, M., and Villari, L., 1993, The control of lava flow during the 1991–1992 eruption of Mt. Etna, *J. Volcanol. Geotherm. Res.* **56**, 1–34.

Barca, D., Crisci, G. M., Di Gregorio, S., and Nicoletta, F., 1994, Cellular Automata for simulating lava flows: a method and examples of the Etnean eruptions, *Transport Theory and Statistical Physics* **23**(1–3), 195–232.

Cantagrel, J. M.: 1988, Quel age ont les iles Canaries, in *Le magmatisme Mesozoique a Actual de La Plaque Afrique*, CIFEG, pp. 62–71.

Carracedo, J. C., Rodríguez, E., and Soler, V.: 1992, The 1730–1736 eruption of Lanzarote, Canary Islands: a long high-magnitude basaltic fissure eruption, *J. Volcanol. Geotherm. Res.* **53**, 239–250.

Dobran, F. and Macedonio, G.: 1992, Lava modelling contributions of the Volcanic Simlation Group during the 1991–1992 eruption of Mt. Etna. VSG Report 92-7, GNV-CNR, Giardini, Pisa, Italy.

Ferraud, G., Gianneni, G., Campredon, R., and Stillman, C.: 1985, Geochronology of some Canarian dike swarms: contribution to the volcano-tectonic evolution of the archipelago, *J. Volcanol. Geotherm. Res.* **30**, 159–162.

Fuster, J. M., Fernandez Santin, S., and Sagredo, J., 1968, Geología y Volcanología de las Islas Canarias, Lanzarote. Inst. Lucas Mallada, CSIC. Madrid.

Ishihara, K., Iguchi, M., and Kamo, K., 1989, Numerical simulation of lava flows on some volcanoes in Japan, in J. H. Fink (ed.), *Lava Flows and Domes*, IAVCEI Proceedings in Volcanology, Springer-Verlag, New York. pp. 174–207.

Marinoni, L. B. and Pasquare, G.: 1994, Tectonic evolution of the emergent part of a volcanic ocean island: Lanzarote, Canary Islands, *Tectonophysics* **239**, 111–135.

Mezcua, J., Buforn, E., Udías, A., and Rueda, J.: 1992, Seismotectonics of the Canary Islands, *Tectonophysics* **208**, 447–452.

Miyamoto, H. and Sasaki, S.: 1997, Simulating lava flows by an improved cellular automata method, *Computers and Geosciences* **23**, 283–292.

Ovchinnikova, G., Belyatskii, B., Vasileva, I., Levskii, L.; Grachev, A., Araña, V., and Mitjavila, J.: 1995, Sr-Nd-Pb Isotope characteristics of the mantle sources of basalts from the Canary Islands, *Petrology* **3,** 172–182.

Romero, C.: 1991, Las manifestaciones volcánicas históricas del Archipiélago Canario. Univ. La Laguna, 2 Vols. 1391 pp.

Schmincke, H. U.: 1982, Volcanic and chemical evolution of the Canary Islands, in U. Von Rad, K. Hinz, M. Sarnthein and E. Seibol (eds), *Geology of the Northwest African continental margins*, Springer, Berlin Heidelber New York, pp. 273–306.

Wadge, G., Young, P. A. V., and McKendrick, I. J.: 1994, Mapping lava flow hazards using computer simulation, *J. Geophys. Res.* **99**(B1), 489–504.