Journal of Volcanology and Geothermal Research 178 (2008) 543–552

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

A long-term volcanic hazard event tree for Teide-Pico Viejo stratovolcanoes (Tenerife, Canary Islands)

J. Martí [a,*], W.P. Aspinall [b], R. Sobradelo [a], A. Felpeto [c], A. Geyer [a], R. Ortiz [d], P. Baxter [e], P. Cole [f], J. Pacheco [g], M.J. Blanco [c], C. Lopez [c]

[a] *Institute of Earth Sciences "Jaume Almera", CSIC, Barcelona, Spain*
[b] *Department of Earth Sciences, Bristol University and Aspinall & Associates, Beaconsfield, UK*
[c] *National Geographical Institute (IGN), Madrid, Spain*
[d] *National Museum of Natural Sciences, CSIC, Madrid, Spain*
[e] *Institute of Public Health, University of Cambridge, UK*
[f] *Department of Geography, Coventry University, UK*
[g] *Centre for Volcanology, University of Azores, Portugal*

ARTICLE INFO

Available online 17 October 2008

Keywords:
Tenerife
Teide-Pico Viejo stratovolcanoes
event tree
expert elicitation judgement
hazard assessment

ABSTRACT

We propose a long-term volcanic hazards event tree for Teide-Pico Viejo stratovolcanoes, two complex alkaline composite volcanoes that have erupted 1.8–3 km^3 of mafic and felsic magmas from different vent sites during the last 35 ka. This is the maximum period that can be investigated from surface geology and also represents an upper time limit for the appearance of the first phonolites on that volcano. The whole process of the event tree construction was divided into three stages. The first stage included the determination of the spatial probability of vent opening for basaltic and phonolitic eruptions, based on the available geological and geophysical data. The second, involved the analysis of the different eruption types that have characterised the volcanic activity from Teide during this period. The third stage focussed on the generation of the event tree from the information obtained in the two previous steps and from the application of a probabilistic analysis on the occurrence of each possible eruption type. As for other volcanoes, the structure of the Teide-Pico Viejo Event Tree was subdivided into several steps of eruptive progression from general to more specific events. The precursory phase was assumed as an unrest episode of any geologic origin (magmatic, hydrothermal or tectonic), which could be responsible for a clear increase of volcanic activity revealed by geophysical and geochemical monitoring. According to the present characteristics of Teide-Pico Viejo and their past history, we started by considering whether the unrest episode would lead to a sector collapse or not. If the sector collapse does not occur but an eruption is expected, this could be either from the central vents or from any of the volcanoes' flanks. In any of these cases, there are several possibilities according to what has been observed in the period considered in our study. In the case that a sector collapse occurs and is followed by an eruption we considered it as a flank eruption. We conducted an experts elicitation judgement to assign probabilities to the different possibilities indicated in the event tree. We assumed long term estimations based on existing geological and historical data for the last 35 Ka, which gave us a minimum estimate as the geological record for such a long period is incomplete. However, to estimate probabilities for a short term forecast, for example during an unrest episode, we would need to include in the event tree additional information from the monitoring networks, as any possible precursors that may be identified could tell us in which direction the system will evolve. Therefore, we propose to develop future versions of the event tree to include also the precursors that might be expected on each path during the initial stages of a new eruptive event.

1. Introduction

Assessing eruption risk scenarios in a probabilistic way has recently become one of the main challenges of modern volcanology. The main reason for that is the need to look for 1) a straightforward way to assess the relative likelihoods of different ways in which a volcanic system may evolve in the future or more urgently when a new eruptive process starts; and 2) a simple way to transfer this information to the corresponding decision makers, without loosing essential information. In most cases, a logic-tree of volcanic events and impacts tends to be constructed on the basis of the volcanological scenarios that can be defined using the existing geological and historical volcanological records (Newhall and Hoblitt, 2002; Marzocchi et al., 2004; 2006). Probability weights for the various logic-tree branches are assigned

* Corresponding author. Institute of Earth Sciences 'Jaume Almera', CSIC, Lluis Sole i Sabaris s/n, 08028 Barcelona, Spain. Tel.: +34 934095410; fax: +34 934110012.
E-mail address: joan.marti@ija.csic.es (J. Martí).

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doi:10.1016/j.jvolgeores.2008.09.023

through statistical analysis of data or formal elicitation of expert volcanological judgement (Aspinall and Woo, 1994; Aspinall, 2006). An elicited risk assessment undertaken during a live volcanic crisis was conducted for Montserrat (Aspinall and Cook, 1998). Although previous experience shows that probabilities are not always well understood by decision makers or even by scientists, this is a necessary discipline to forecast and predict the complex and random behaviour of volcanic systems and quantify and explain the underlying uncertainty. Additionally, in the case of an actual volcanic crisis the statistical methodologies serve as a tool in the elaboration of a cost/benefit analysis, in relation to the decisions to be made by the authorities (i.e. emergency plans, evacuation). This should help them understand the complexities of the problem and envisage the potential consequences of making poorly informed decisions.

The construction of a probability event tree to estimate the volcanic hazard is based on the existence of a good volcanological record, allowing a precise reconstruction of the past history of the volcano. This allows us to determine eruption scenarios that can quantitatively define the future eruptive behaviour and potential impact of the volcano. However, problems arise when the knowledge of the past volcanological history is poor, the geochronological data are scarce and historical activity has not occurred or has not been recorded in the existing chronicles. Some recent eruptions such as those from Montserrat or Pinatubo have encountered this problem (Aspinall et al., 1998 and references therein; Newhall and Punongbayan, 1996). In these cases, the lack of knowledge of previous unrest and, more crucial, of the precursors of previous eruptive events, precludes using repetitive patterns of precursors to anticipate new eruptions (see Sandri et al., 2004).

This is the case of Teide-Pivo Viejo twin stratovolcanoes, which form one of the largest active volcanic complexes in Europe. Since the current information on their past activity is scarce and they have not shown clear signs of activity in historical times, they could be classified as dormant volcanoes (Szakács, 1994; Connor et al., 2006). However, they have produced several central and flank vent, effusive and explosive eruptions during the last 5000 years, the last one having occurred about 1000 years ago (Carracedo et al., 2003, 2007). This, together with the presence of permanent fumarolic activity at the summit of Teide and the occurrence of a recent unrest episode (García et al., 2006, Gottsmann et al., 2006; Martí et al., in press), reminds us that Teide-Pico Viejo are potentially active volcanoes that could erupt again in the near future. Despite the potential risk that these volcanoes represent for the island of Tenerife, extensively populated and one of the main tourist destinations in Europe, much remains to be learned about Teide-Pico Viejo's eruptive history. The fact that many eruption mechanisms, magma compositions, and vent sites can be distinguished from their products (Ablay and Marti, 2000; Carracedo et al., 2007; Marti et al., 2008), complicates the definition of eruption scenarios and the establishment of eruption patterns that could be used as a guide to predict the future behaviour of these twin stratovolcanoes.

This paper presents a first attempt to construct a probability, long-term event tree for Teide-Pico Viejo stratovolcanoes. First, we study the possible location of future vents based on the available geological and geophysical data. Second, we analyse the different eruption types that have characterised the volcanic activity from Teide-Pico Viejo during the last 35 ka. And third, we create the event tree structure using the information obtained in the two previous steps and we define the formalised statistical procedure for the elicitation of expert judgement that should be used to assign a probability of occurrence to each branch of the event tree.

2. Background geology and past volcanic activity

Teide-Pico Viejo stratovolcanoes started to grow up about 180–190 ka ago at the interior of the Las Cañadas caldera (Fig. 1). This volcanic depression originated by several vertical collapses of the former Tenerife central volcanic edifice (Las Cañadas edifice) following explosive emptying of high-level magma chamber. Occasional lateral collapses of the volcano flanks also occurred and modified the resulting caldera depression (Martí et al., 1994, 1997; Martí and Gudmundsson, 2000). The construction of the present central volcanic complex on Tenerife encompasses the formation of these twin stratovolcanoes, which derive from the interaction of two different shallow magma systems that evolved simultaneously, giving rise to a complete series from basalt to phonolite (Ablay et al., 1998; Martí et al., 2008).

The structure and volcanic stratigraphy of the Teide-Pico Viejo stratovolcanoes were characterised by Ablay and Martí (2000), based on a detailed field and petrological study. More recently, Carracedo et al. (2003, 2007) have provided the first group of isotopic ages from Teide-Pico Viejo products, and Martí et al., 2008) analyses their explosive activity. The reader will find in these works a more complete description of the stratigraphic and volcanological evolution of Teide-Pico Viejo.

Teide-Pico Viejo stratovolcanoes mostly consist of mafic to intermediate products, being felsic materials volumetrically subordinate overall (see Martí et al., 2008, Fig. 1). Felsic products, however, predominate in the recent output of the Teide-Pico Viejo system. Eruptions at Teide and Pico Viejo stratovolcanoes have occurred from their central vents but also from a multitude of vents distributed on their flanks (Fig. 1). Mafic and phonolitic magmas have been erupted from these vents. The Santiago del Teide and Dorsal rift axes, the two main tectonic lineations currently active on Tenerife, probably join beneath Teide-Pico Viejo complex (Carracedo, 1994; Ablay and Martí, 2000). Some flank vents at the western side of Pico Viejo are located on eruption fissures that are sub-parallel to fissures further down the Santiago del Teide rift, and define the main rift axis. On the eastern side of Teide some flank vents define eruption fissures orientated parallel to the upper Dorsal rift.

The eruptive history of the Teide-Pico Viejo (see Fig. 7 in Martí et al., 2008) comprises a main stage of eruption of mafic to intermediate lavas that form the core of the volcanoes and also infill most of the Las Cañadas depression and the adjacent La Orotava and Icod valleys. About 35 ka ago the first phonolites appeared, and, since then, they have become the predominant composition in the Teide-Pico Viejo eruptions. Basaltic eruptions have also continued mostly associated with the two main rift zones. The available petrological data suggest that the interaction of a deep basaltic and a shallow phonolitic magmatic systems beneath central Tenerife controls their eruption dynamics (see Martí et al., 2008). Most of the phonolitic eruptions from Teide-Pico Viejo show signs of magma mixing, suggesting that eruptions were triggered by intrusion of deep basaltic magmas into shallow phonolitic reservoirs.

Phonolitic activity from Teide-Pico Viejo shows a recurrence of around 250–1000 years, according to the isotopic ages published by Carracedo et al. (2003, 2007). Phonolitic eruptions from Teide and Pico Viejo range in volume from 0.01 to 1 km^3 and have mostly generated thick lava flows and domes, some of them associated with minor explosive phases, and some subplinian eruptions, such as the Montaña Blanca at the eastern flank of Teide, 2000 years ago.

Some significant basaltic eruptions have also occurred from the flanks or the central vents of the Teide-Pico Viejo stratovolcanoes. All basaltic eruptions have developed explosive strombolian to violent strombolian phases leading to the construction of cinder and scoria cones and occasionally producing intense lava fountaining and violent explosions with the formation of ash-rich eruption columns. Violent basaltic phreatomagmatic eruptions have also occurred from the central craters of the Teide-Pico Viejo stratovolcanoes, generating high-energy, pyroclastic density currents.

According to Martí et al. (2008), the total volume of magma erupted in the last 35 ka is of the order of 1.5–3 km^3, 83%

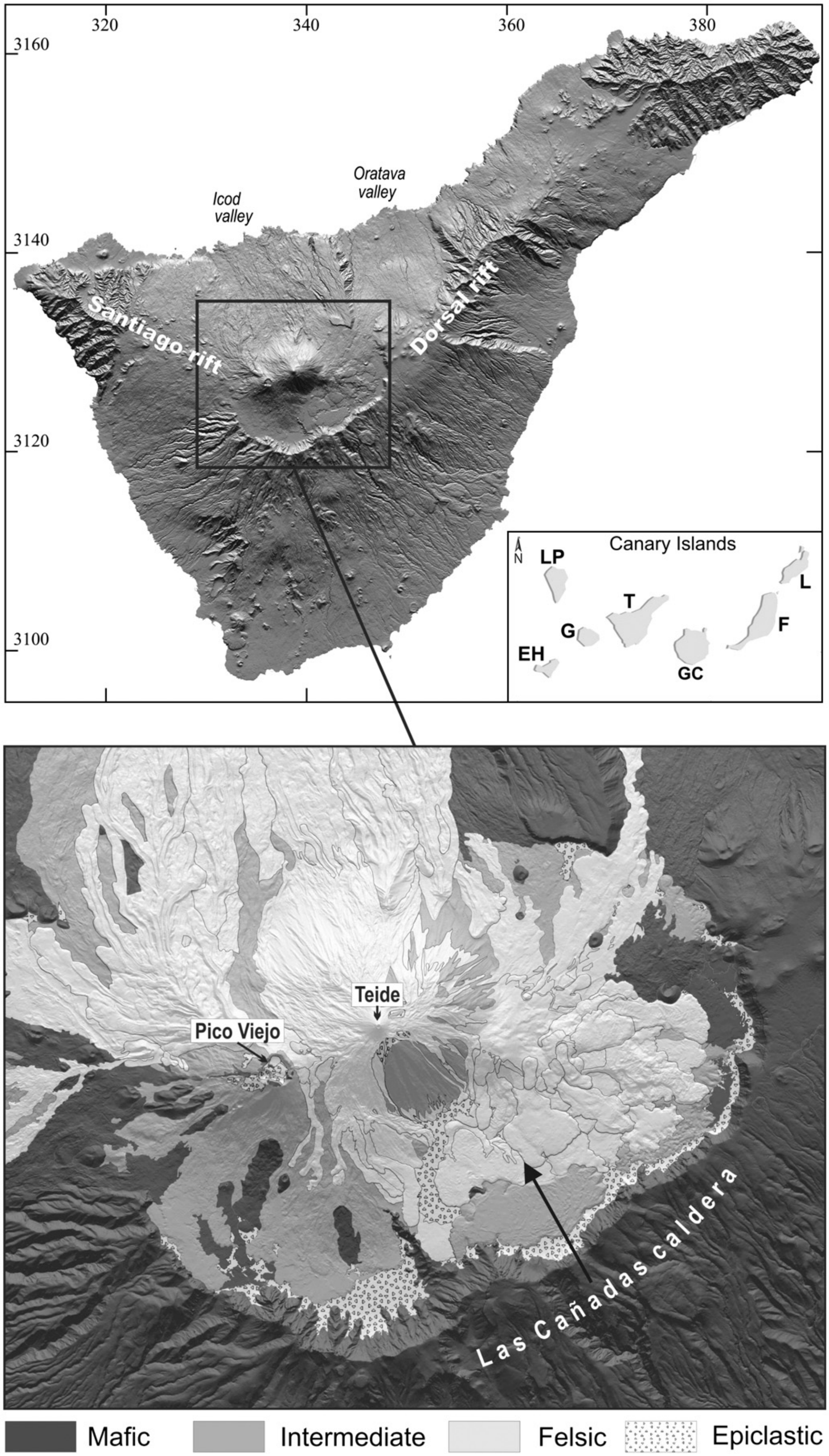

Fig. 1. Simplified geological map of Teide, based on Ablay and Martí (2000). Eruptive products from the Teide-Pico Viejo stratovolcanoes are identified according to their composition (mafic, intermediate and felsic). Pre-Teide_Pico Viejo rocks are undifferentiated (darkest grey). LP: La Palma; EH: El Hierro; G: Gomera; GC: Gran Canaria; T: Tenerife; L: Lanzarote; F: Fuerteventura.

corresponding to phonolitic magmas, while the rest includes basaltic and intermediate magmas. Therefore, phonolitic eruptions have been less frequent but much more voluminous than basaltic eruptions. All phonolitic activity has been concentrated at the central vents and flanks of the Teide-Pico Viejo stratovolcanoes. Basaltic eruptions during this period have also occurred through the rift zones.

3. The Teide-Pico Viejo event tree

The event tree for the Teide-Pico Viejo stratovolcano was established using a methodology similar to that proposed by Newhall and Hoblitt (2002) and Marzocchi et al. (2004, 2006), and following a similar systematic and structure than in Neri et al. (2008). However, a significant difference with regard to these previous models is due to the fact that in previous cases only the possibility of central vent eruptions is considered, i.e. there is only one possible vent, while in Teide-Pico Viejo many vent sites are possible, including central and flank vents, having significantly different hazard implications. In addition, the stratigraphic record from Teide and Pico Viejo shows that both volcanoes may either behave independently or erupt simultaneously (Ablay and Martí, 2000). Therefore, we had to include in our event tree, at initial stages in the estimation process, the possible vent locations, in addition to all possible outcomes of the volcanic unrest. We include all possible options for the evolution of volcanic unrest, even those that have a very low probability of occurrence but which have been recognised in the geological record of Teide-Pico Viejo. Compared to the previous models (Newhall and Hoblitt, 2002; Marzocchi et al., 2004; Neri et al., 2008), we built our probability event tree to include the first phases of the long-term volcanic hazard estimation, since we have only geological data and no relevant historical or monitoring data is available. Hence, the subsequent risk branches, such as sectors affected, distance of runouts, exposure or vulnerability cannot be properly estimated in this paper.

3.1. Location of future vents

The first stage involves an analysis of the potential location of future vents. Teide-Pico Viejo have undergone several flank and central vent eruptions and these have been of basaltic and phonolitic composition, without any apparent structural or petrological pattern that could explain such random eruption behaviour (Martí et al., 2008). The lack of a good surveillance network makes the identification of future vents more challenging than in other similar volcanoes. It has been generally assumed that future eruptive activity on Tenerife, if any, should be of basaltic nature, far from the central Teide system, and generate short lava flows and small cinder cones (Carracedo et al., 2003, 2007). However, there are no scientific reasons to rule out the possibility of an eruption, basaltic or phonolitic, from Teide-Pico Viejo. On the contrary, all the petrological, geochronological and volcanological data available, suggest that Teide_Pico Viejo cannot be considered as extinct volcanoes at all (Ablay and Martí, 2000; Martí et al. (2008) and that they could erupt again in the near future, even in a violent way.

In addition to field studies (Ablay and Martí, 2000), numerical experiments have been used to investigate the possible factors that determine the occurrence of either a central or a flank eruption at Teide-Pico Viejo. We have considered a wide range of situations in which the main physical conditions of the volcanic system have been changed (topography, size, depth and shape of the magma chambers, presence of deviatoric stresses, internal structure of the volcano) (Martí et al., 2006). The results obtained show that the main control on the pathway that phonolitic magma will follow to leave the shallow chamber and reach the surface is exerted by the stress field distribution around and above the chamber, being this a function of the shape and depth of the magma chamber. An alternative explanation is that the magma follows paths around any massive blockage such as recent intrusions. In the case of basaltic eruptions, which are fed by much deeper magmas, we think that a structural control resulting from the interaction between the rift systems and the central complex, rather than the geometry and location of the pressure source at depth, determines the exact location of the vent(s) in each eruption. Comparison of these results with the available geological (Ablay and Martí, 2000) and geochronological (Carracedo et al., 2003, 2007) information suggests that the number of flank eruptions occurred on Teide-Viejo during the time period considered is slightly higher than that of the central vent eruptions.

3.2. Eruption types and eruption scenarios

The second stage in the construction of the Teide-Pico Viejo event tree involved the identification and characterisation of all the effusive and explosive eruption types that have been associated with the Teide-Pico Viejo central complex during the last 35 ka. This is the maximum period that we can investigate from surface geology and also represents an upper time limit for the appearance of the first phonolites on that volcano. Despite this could be regarded as a long time interval because the record of older events is incomplete, it gives

Table 1
Description of the main characteristics of the eruption types (largest or most explosive event) that have occurred from the Teide-Pico Viejo complex during the last 35 ka (see Martí et al., 2008, for more information)

Eruptive type	VEI	DRE km^3	Composition	Vent location	Recurrence period	Eruption phases and products
Strombolian	1–2	0.001–0.03	Mafic/felsic	Any	80–200 years >25 events	Fine ash/lapilli dispersion through short eruption columns (<1 km), proximal coarse lapilli, scoria and spatter from fire fountains (up to 300 m), some ballistics, frequent lava flows
Violent strombolian	2–3	0.01–0.2	Mafic/felsic	Any	200–500 years ? >5 event	Fine ash/lapilli dispersion through eruption columns up to 2 km high, proximal coarse lapilli, scoria and spatter from fire fountains (up to 600 m), abundant ballistics (up to 1 m across), frequent lava flows
Sub-plinian	3–4	0.01–0.5	Felsic	Any	400–2000 years ? ≥3 events	Eruption column up to 10 km high, pumice fall deposit, some ballistics, emplacement of lava flows and domes at the beginning and end of the eruption
Phreatic	?	?	?	Pico Viejo Caldera	? 1 event	Large ballistics (up to 1 m across) at distances of several km from the vent
Phreatomagmatic	2–3	0.001–0.01	Mafic	T-PV old and present central vents	? ≥4 events	Radial/directed distribution of ballistic breccias and pyroclastic surges up to 10 km from the vent, lahars
Mainly effusive (lava flows, clastogenic lavas and domes)	0–1	0.01–1	Felsic	any	300–1000 years ? >14 events	Thick (up to 40 m) massive lava flows (up to 15 km in length), clastogenic lavas and domes. Occasional occurrence of associated bock and ash deposits (and related debris flows and lahars) caused by gravitational collapse of lavas flows and/or domes.

us a minimum estimate. Teide-Pico Viejo's eruptive activity has been associated with both, mafic (basalts, tephri-phonolites) and felsic (phono-tephrites and phonolites) magmas, and has produced a large variety of eruption types: mostly effusive (lavas and/or domes), strombolian, violent strombolian and sub-plinian magmatic eruptions, as well as phreatomagmatic eruptions of mafic magmas and phreatic explosions. There is no any apparent control on the style of the eruption by the vent location, so that we assumed a priori that similar eruptions can occur from both flank and central vents on Teide-Pico Viejo. The set of eruptive types we have included in the event tree represents the largest or the most explosive event that occurs in the course of an eruption that might include many events and eruption styles. Table 1 summarises the characteristics of the main Teide-Pico Viejo eruption types. A more detailed description of the eruptive activity of Teide-Pico Viejo is given in Martí et al. (2008).

3.3. Event tree structure

The third stage included the generation of the event tree (nodes and branches) using the information obtained in the two previous stages, to later assign a probability of occurrence to each branch using the elicitation of expert judgement procedure presented in the next section. As for other volcanoes (Newhall and Hoblitt, 2002; Marzocchi et al., 2004, 2006; Neri et al., 2008), the estimation was carried out for all the branches of each node for the Teide-Pico Viejo event tree, progressing from general to specific events (Fig. 2). From the study of the different eruption types identified on Teide-Pico Viejo, we can deduce that all of them, including the phreatic episode from Pico Viejo (Ablay and Martí, 2000) require the presence of fresh magma, either mafic or felsic, at shallow depths in the volcanoes. However, we did not discard the possibility of starting an eruption process from an unrest directly associated with the hydrothermal system or event due to external triggers, such as regional tectonics, if eruptible magma is present in the system. Therefore, we assumed a precursory step as an unrest episode, regardless of it is magmatic, hydrothermal or tectonic, characterised by an anomalous increase of seismic activity, ground deformation, gravity changes, gas emissions, and so on. We started by considering whether the unrest episode could lead to a sector collapse that then could trigger an eruption or not. If an eruption is expected regardless of the existence of sector collapse, this could be from the central vent (s) (either Teide or Pico Viejo) or from any of the volcano's flanks. In any of these cases, there are several possibilities, mainly controlled by the composition (mafic or felsic) of the erupting magma,

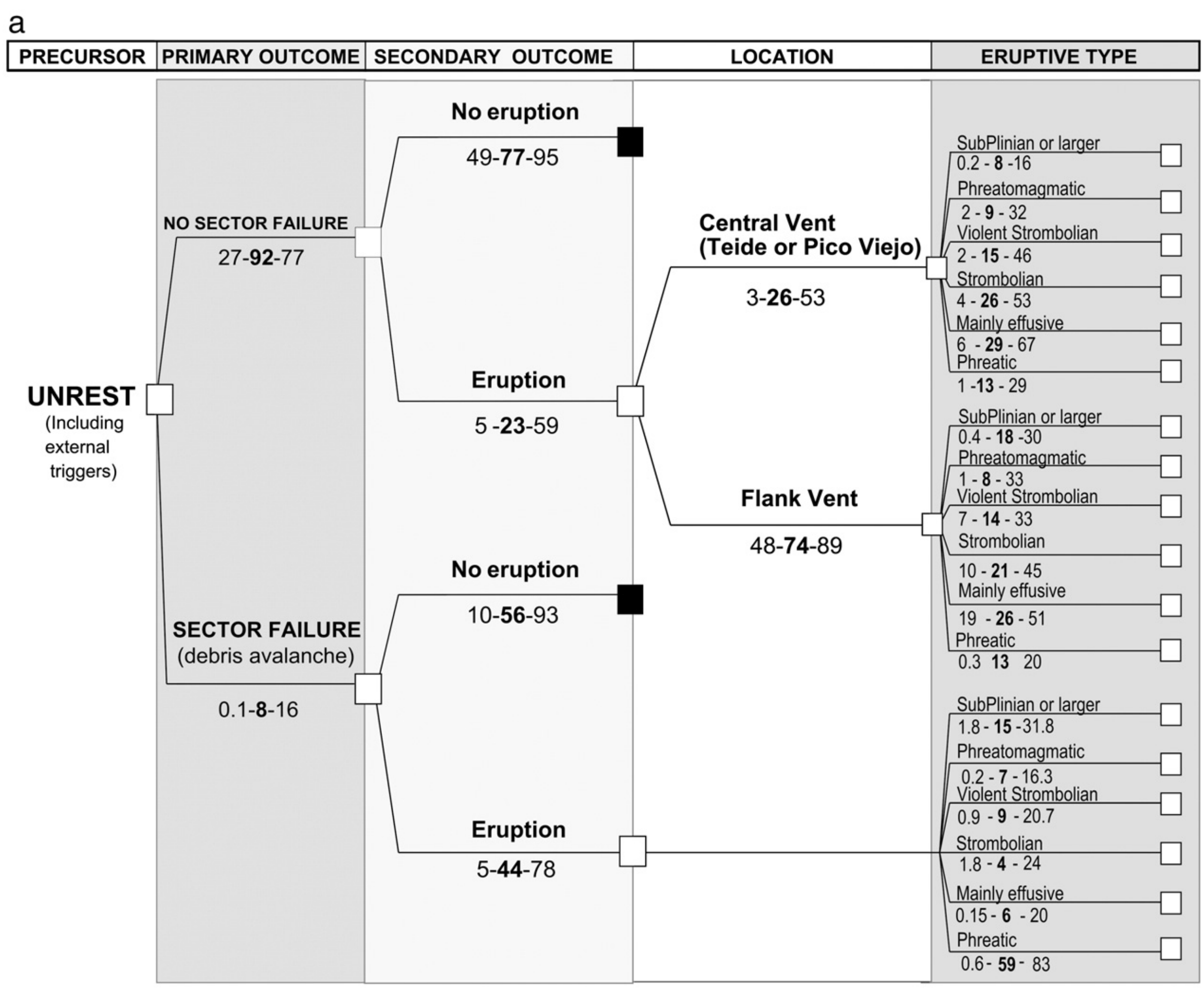

Fig. 2. The volcanic event tree for Teide-Pico Viejo. Six stages of eruptive progression from general to more specific events (from left to right) are presented. Nodes from which subsequent multiple different outcomes (branches) of the eruptive process are possible at each stage are indicated by white squares. Nodes that represent the termination of a particular process are represented by black squares. a) shows an overview of the primary branches of Teide-Pico Viejo event tree as far as eruptive style. The set of eruptive types we have included in the event tree represents the largest or the most explosive event that occurs in the course of an eruption that might include many events and eruption styles. Expanded tree details including hazards are shown for: b) the scenario of a central vent eruption; c) the flank vents scenario; and, d) the case of a magmatic eruption triggered by sector failure. In addition to the authors of the paper, the following scientists have also participated in the experts elicitation judgement: J. Andujar, A. Bertagnini, R. Chioni, O, Cornellà, A. Folch, A. M. Garcia, MJ. Jimenez, Neri, T. Ongaro, G. Queiroz, M. Rosi, L. Sandri, C. Soriano, R. Spence, F. Teixidó, M. Todesco, G. Toyos, G. Zuccaro.

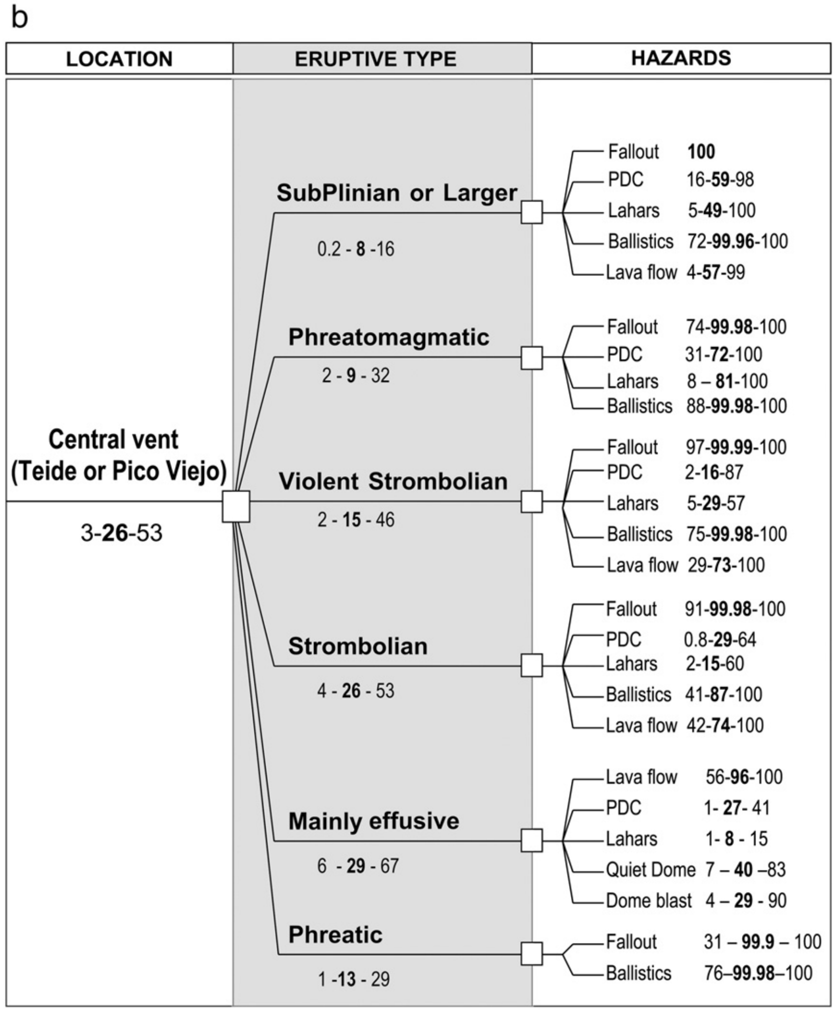

Fig. 2 (*continued*).

according to what has been observed in the period considered in our study. The construction of our event tree continued with the inclusion in the following sequence of nodes and branches of the different possible eruptions and related hazards that may occur from Teide-Pico Viejo (see Table 1 and Fig. 2a–d).

As we have indicated before, it would be premature at this stage to continue the construction of the Teide-Pico Viejo event tree adding the corresponding steps concerning the potential impacts of each hazard, as there is still some basic information missing. However, the structure proposed will allow the event tree to be extended at any moment and to adapt it for a short-term hazard assessment when information from volcano monitoring from Teide-Pico Viejo will be available.

3.4. Statistical methodology: the Teide-Pico Viejo expert elicitation procedure

The ultimate aim of a volcanic hazard event tree is to assign probabilities to the different eruption possibilities or scenarios that we can envisage from the eruption history of the volcano and our knowledge of other analogous volcanoes. An event tree aims to quantitatively estimate both long- and short-term volcanic hazard. In order to achieve this objective, we use a methodology based on Elicitation of Expert Judgement. In particular, the so-called Classical Model developed in Delft (Bedford and Cooke, 2001). Other statistical procedures as well as other methods to elicit expert judgements are available. The Classical Model is a performance-based formalised procedure for the elicitation of expert judgements which allows to derive uncertainty distributions over model parameters using expert judgement. This approach provides a basis for weighted averaging of subjective opinions. The weights are derived from the experts' calibration and information performances, measured by the so-called “seed” variables (Aspinall, 2006).

Within the EXPLORIS Project, the approach adopted for parameterising event probability nodes on event trees was to elicit values from colleagues (see Fig. 2a–d) in a structured manner, and to use Cooke's (1991) ‘classical model’ mentioned above — implemented in the computer program EXCALIBR (Cooke and Solomatine, 1990) — for the quantification of the corresponding collective scientific uncertainty. The classical model is unique in that it embodies a performance-based expert scoring scheme, by which weights are ascribed to individual experts on the basis of empirically determined calibration and informativeness scores. The expert's assessments are treated as statistical hypotheses and the probability at which these hypotheses would be rejected is used to provide a score for calibration (under the assumption that the calibration variables are independent realisations of the experts' distributions). A second factor, the ‘informativeness’ of the expert, is defined as the relative information of his or her distributions with respect to some specified background measure. The theory of strictly proper scoring rules is used to combine calibration and informativeness scores expressed as a product, and from these results the so-called performance-based ‘decision-maker’ is formed from a weighted combination of the judgements of the group of experts involved.

In EXPLORIS, the processing of group elicitations utilised a variant of the EXCALIBR application in which the power of the statistical

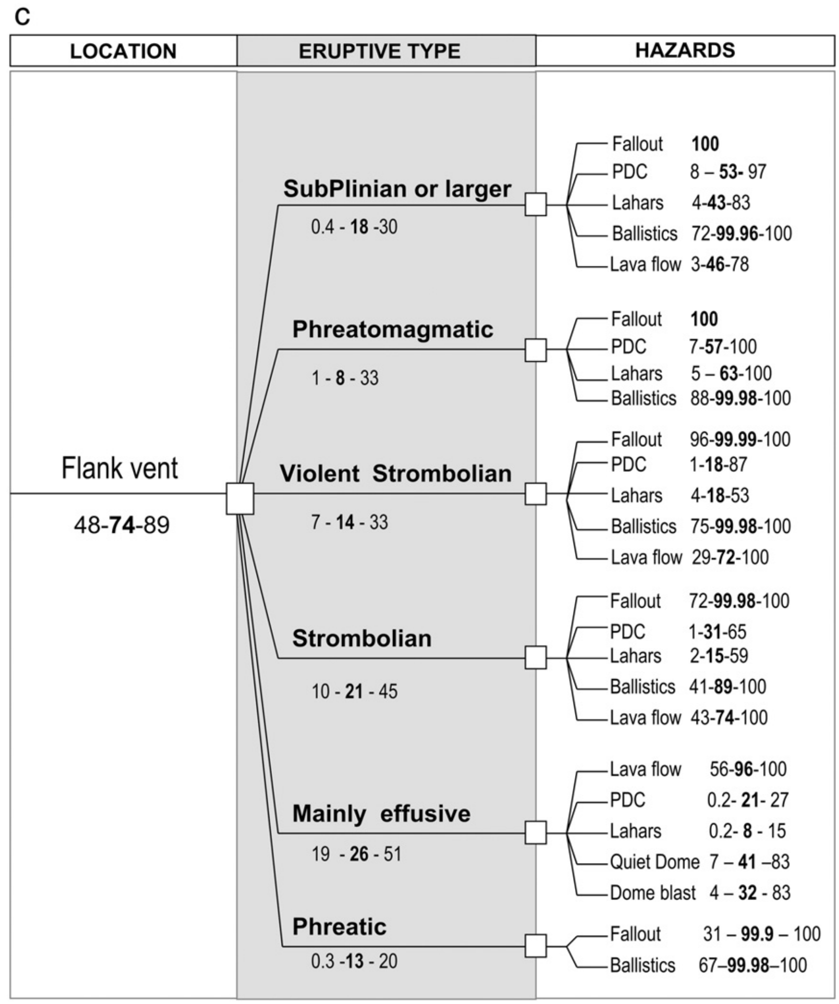

Fig. 2 (*continued*).

hypothesis test and the significance level for rejection were adjusted so that all participants obtained some positive weight for their opinions; this approach is termed ‘constrained optimisation weighting’ (Aspinall, 2006). The purpose of doing this was to limit the chances that any individual expert might be unduly penalised in their measured performance just as a result of any particular property or bias in the set of seed questions that had been selected for calibration. Thus, the outcome of an EXCALIBR calibration exercise is a set of numerical scores for the panel of experts involved, each individual's score representing his or her empirical success in making uncertainty judgements about known parameters or values. Within all the EXPLORIS volcano groups, there was a tendency for the majority of participants to be over-confident in their judgements, and to receive reduced relative weighting accordingly — this is a widespread characteristic of almost all groups of experts, in any scientific or engineering discipline. However, the EXCALIBR procedure accounts for such traits in an objective and traceable way and provides a rational and neutral pooling of diverse opinions.

In the case of Teide-Pico Viejo, more than 30 experts (Fig. 2) from the EXPLORIS project participated in the elicitation process. For every node on the Teide-Pico Viejo event tree, the experts provided their individual opinions as the relative likelihoods of occurrence of the alternative pathways for the way the course of the eruption could progress, and these opinions are pooled using the weights obtained from the EXCALIBR calibration procedure. The outcomes of this process are recorded as numerical probability values on the event tree shown on Fig. 2a–d. On each branch, the results are given as three numbers: the median probability (i.e. 50 percentile value for the distribution of opinions provided by the group), together with corresponding 90% credible interval bounds (i.e. approximate 5 percentile and 95 percentile distributional values). This way of representing the collective scientific uncertainty associated with forecasting volcanic hazards is uniquely different to that of other approaches, and gives formal, quantitative expression to all the uncertainties involved, essential for any comprehensive probabilistic risk assessment.

In the particular case of Teide-Pico Viejo, due to the lack of information on their past geology and recent volcanic activity, two questions where posed to the referees regarding the nodes with two branches of the first steps of eruptive progression (outcome and location) (Fig. 2a). This makes a significant difference compared to other event trees, such as the one for Vesuvius (Neri et al., 2008), from which there is a good set of data and most of the experts know the corresponding volcanoes very well. In such cases, only one question (three percentiles) is asked for one branch since the three percentiles of the other branch are simply the complement. In our case, the reason to elicit both probabilities and their complement in separate questions for binary branches is due to the general lack of knowledge on Teide-Pico Viejo and, consequently, as a way to test the expert understanding of the method and the volcano, just looking at how stable the paired answers were. Consequently, in our example the credible intervals do not need to be complementary. Although, the resulting numbers from the Teide-Pico Viejo elicitation were not always very consistent, we decided to show them as a first indication of the great uncertainty we have to deal with when working with a poorly known volcano.

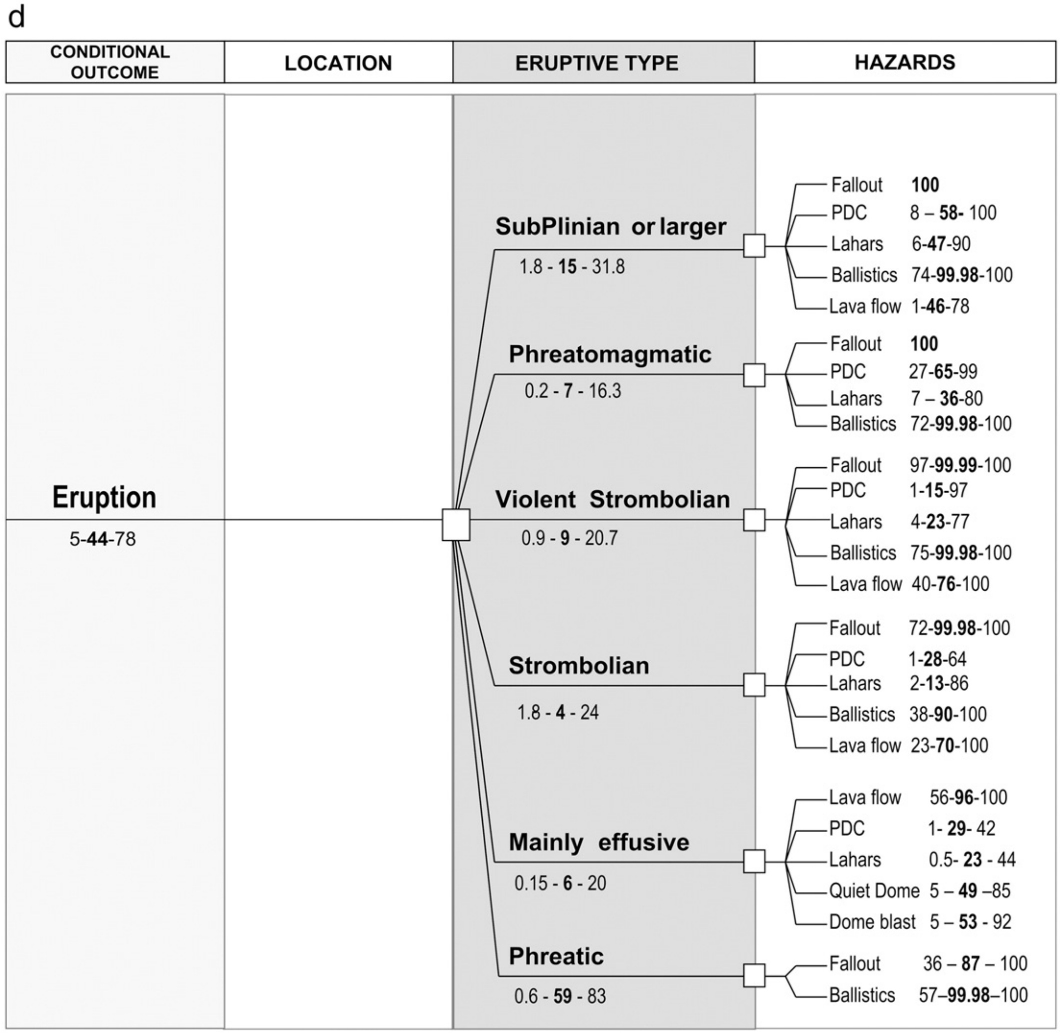

Fig. 2 (*continued*).

The following are examples of some of the group's judgements for scenarios relating to the next eruption of Teide-Pico Viejo. According to Fig. 2a, if unrest occurs, it is considered 11.5× more likely that no sector failure will ensue (conditional probability given unrest=92%) than a sector failure (conditional probability=8%) will happen. Note that the probabilities we discuss refer to the 50 percentile confidence level. On this basis, it is concluded there is a 1-in-12.5 chance of a sector failure, given unrest. Of course, these probabilities would be updated in the light of data, observations or evidence that is detected in relation to the unrest episode, when it develops.

Moving across the tree on Fig. 2a, if an eruption should occur, the collective view is that a flank eruption (conditional probability=74%) is 2.8× more likely than a central vent eruption (conditional probability=26%). Again, these values are based solely on the available geological data and interpretations of that incomplete data, and could easily be modified by indicators from emerging unrest (e.g. seismological data suggesting dike propagation at a flank location).

If the next eruption of Teide-Pico Viejo is from a central vent (Fig. 2b), the expert elicitation provides the following guidance about relative likelihoods of the eruptive style that may ensue, assuming that the possible eruption scenarios are mutually exclusive: the most likely scenario is either a mainly effusive eruption (conditional probability=29%) or a Strombolian intensity explosive eruption (conditional probability=26%). Less likely next are either a Violent Strombolian scenario (conditional probability=15%) or an eruption of predominantly phreatic activity (conditional probability=13%). The other possible scenarios are a Phreatomagmatic eruption (conditional probability=9%) or a sub-Plinian or larger eruption (conditional probability=8%). Although these last two are the least likely possibilities, neither is judged to be highly unlikely — either has a chance of about 1-in-10 of being experienced in a future central vent eruption.

On Fig. 2b–d the last columns of the Teide-Pico Viejo event tree in its present form, show the hazards that could accompany each of the different eruptive style scenarios. Here, the relevant individual conditional probabilities are not exclusive, as more than one hazard may be present in any one eruption episode. The overall likelihood of any particular hazard being manifest in the next eruption of Teide-Pico Viejo, whatever its eruptive style or vent location, can be calculated by summing up the compounded conditional probabilities across all those branches which lead to a termination node with that hazard.

The next stage in the enhancement of the Teide-Pico Viejo event tree should be to expand it to add further branches that represent factors important for risk assessment, such as flow directivity and run-out distances, for example. As with the initial eruptive scenario stages of the Teide-Pico Viejo event tree, described here, these further elements can also be derived from expert judgement, but in this case extensively informed by physical modelling results, as well as the geological record. This said, the rational quantification of scientific uncertainty remains the key reason for adopting a formalised expert elicitation approach.

With the data and knowledge currently available for Teide-Pico Viejo, the median probabilities and their uncertainty spreads, shown on Fig. 2a–e, are expected to be stable against most plausible alternative interpretations if no new information emerges, in which case they can be modified significantly. For instance, if unrest develops, many of the conditional probabilities on the Teide-Pico Viejo event tree could change in response to the occurrence of precursors that are robust indicators of certain aspects of forthcoming activity. In this sense, any volcanic event tree should be regarded as an evolving, organic object, which requires attention (and pruning) as new information emerges.

4. Discussion and conclusions

We propose a volcanic hazard event tree for Teide-Pico Viejo that shows all possible outcomes of volcanic unrest at progressively higher degrees of detail. The construction of the current version of the Teide-Pico Viejo event tree is based on the past eruptive history of the volcano and corresponds to its long-term volcanic hazard assessment. Moreover, the Teide-Pico Viejo event tree can be easily extended to account for short-term hazard assessment (in case of volcanic crisis) when precise monitoring data from the volcano will be available.

The Teide-Pico Viejo event tree has been constructed following previous models (Newhall and Hoblitt, 2002; Marzocchi et al., 2004, 2006; Neri et al., 2008) and it is based on similar concepts. It uses a statistical approach based on Expert Judgement Elicitation to ascribe the appropriate probabilities and to determine the corresponding uncertainty for the different possible events that could occur, based on available past geological data. We have conducted this process among the participants of the EXPLORIS project using the performance-based Classical Model for expert judgement elicitation. However, there is a significant difference between the present Teide-Pico Viejo event tree and the reference models we have used in its construction. This difference relates to the need to allow for several possible vent sites, instead of a single one as is the case in the previous models. The actual location of the vent will condition the resulting hazards and, in particular, their potential impacts, as the vent position will determine the area affected by each volcanic process. This is clear in the case of Teide-Pico Viejo from which eruptions have occurred not only from the central vent area but also from any of its flanks. Therefore, we have included in our event tree a new step for the progression of the eruption that considers the location of the eruptive vent. However, it is important to remark that this is correct for the present situation but if we get to the future step of hazard to specific location, the central vs flank distinction will not be specific enough.

The Teide-Pico Viejo event tree considers all possible volcanic processes that could occur according to the available past information, even those with a low probability of occurrence. In this sense, we have to mention that the structure of the event tree has to be simple but as informative as possible. We have to keep in mind that a volcanic hazard event tree has to be prepared for showing to decision makers, who will not necessarily be familiar with volcanic or probabilistic terminology. The role of scientists should be just to advise decision makers, so that if a possible outcome is not shown in the event tree and it finally occurs, scientists could be regarded as at fault.

Volcanoes are complex, non-linear natural systems that rarely follow a constant pattern of behaviour. Although we can establish some general eruptive patterns for certain group or types of volcanoes, each volcano will at the end behave in its own particular way, different from the others. In the case of Teide-Pico Viejo, as in many other volcanoes around the World, the information we have on its past eruptive history and on its present state of activity is incomplete, and requires much more effort before being more confident that we can precisely forecast its future behaviour. This said, the event tree we have presented in this paper is a contribution to advancing and rationalising our current knowledge on Teide-Pico Viejo, and to providing a useful tool to help the society increase its confidence that any future threat of the volcano is properly assessed, according to the main objectives of the EXPLORIS project.

Acknowledgements

This research has been funded by the EC EXPLORIS (EVR1-2001-00047) and MEC TEGETEIDE (CGL2004-21643-E) projects. JM is grateful for the MEC grant PR-2006-0499. We warmly thank all the participants in the EXPLORIS project who have collaborated in the elicitation of expert judgement process for Teide-Pico Viejo. We thank Augusto Neri, Chris Newhall and Roberto Santacrocce for their detailed and constructive reviews.

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