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Bayesian event tree for long-term volcanic hazard assessment: Application to Teide-Pico Viejo stratovolcanoes, Tenerife, Canary Islands

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[1] In modern volcanology one of the most important goals is to perform hazard and risk assessment of volcanoes near urbanized areas. Previous work has been done to assess volcanic hazard in the form of event tree structures containing possible eruptive scenarios. Probability methods have been applied to these structures to estimate the long term probability for each scenario. However, most of these event tree models show restrictions in the eruptive scenarios they consider and/or on the possibility of having volcanic unrest triggered by other forces than magmatic. In this paper, we present a Bayesian event tree structure which accounts for external triggers (geothermal, seismic) as a source of volcanic unrest and looks at the hazard from different types of magma composition and different vent locations (as opposite to a central vent only). We apply the model to the particular case of Teide-Pico Viejo stratovolcanoes, two 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, situated on a densely populated island, one of the biggest tourist destinations of Europe, and for which limited geological and no historical data exist. Hence, the importance of volcanic hazard assessment for risk-based decision-making in land use planning and emergency management. A previous attempt to estimate the volcanic hazard for Teide-Pico Viejo has been done using an event tree structure based on Elicitation of Expert Judgment. The new method overcomes some limitations of the previous method, including human decision bias, epistemic and aleatoric uncertainties, restrictions on the segmentation complexity of the event tree structure, and automatically updating. The main steps are the following: (1) Design an extensive tree-shaped Bayesian network with possible eruptive scenarios following the case of Teide-Pico Viejo volcanic complex. (2) Build a Bayesian model to estimate the long term volcanic hazard for each scenario. (3) Apply the model to Teide-Pico Viejo stratovolcanoes. Finally, we compare the results with those from the Elicitation method applied before, as well as previous Bayesian event tree structures developed for other volcanoes.

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1. Introduction

[2] Assessing eruption risk scenarios in probabilistic ways has become a main challenge in modern volcanology [*Newhall and Hoblitt*, 2002; *Marzocchi et al.*, 2004, 2006, 2008; *Aspinall*, 2006; *Neri et al.*, 2008; *Martí et al.*, 2008a]. Volcanic risk is usually defined as the product of volcanic hazard, value and vulnerability, where volcanic hazard is the probability of any particular area being affected by a destructive volcanic event within a given period of time; the value is the number of human lives at stake, or the capital value (land, buildings, etc.), or the productive capacity (factories, power plants, highways, etc.) exposed to the destructive events; the vulnerability is a measure of the proportion of the value likely to be lost as a result of a given event [*Blong*, 2000].

[3] Short- and long-term eruption forecasting are defined based on the expected characteristic time in which the process shows significant variations. During a quiet phase of the volcano the time variations occur in time intervals significantly longer than during unrest. For the purpose of this paper, long-term forecasting refers to the time window before the volcanic system goes into unrest, and short-term forecasting refers to the unrest phase. Consequently, long-term forecasting is based on historical and geological data,

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and theoretical models, while short-term forecasting is complemented with continuous monitoring data.

[4] The complexity of any volcanic system and its associated eruptive processes, together with the lack of data that characterize many active volcanoes, particularly those with long recurrences, make volcanic hazard quantification very challenging, as there is often not enough observational data to build a robust statistical model.

[5] Despite the limitations in the construction of an event tree usually imposed by the lack of knowledge on the past and present behavior of active volcanoes, it is clear from the works previously cited and experiences on volcanic crises [*Aspinall and Cook*, 1998] that the construction of an event tree is a major step in the hazard assessment. Most of the research done so far is based on a deterministic approach for short-term forecasting [e.g., *Kilburn*, 2003; *Hill et al.*, 2001]. The alternative approach is probabilistic [e.g., *Newhall and Hoblitt*, 2002; *Aspinall and Woo*, 1994; *Marzocchi et al.*, 2004, 2006, 2008]. *Newhall and Hoblitt* [2002] proposed a general event tree scheme to estimate the probability of all the relevant possible scenarios of a volcanic crisis and, in general, to quantify the volcanic hazard and risk. Later, *Marzocchi et al.* [2008] developed a probabilistic tool for long- and short-term eruption forecasting based on Bayesian methodology and fuzzy logic using event trees.

[6] Event trees developed using Bayesian methodology assume that unrest is caused by internal (magmatic) triggers only. However, there are volcanic systems where unrest episodes and, occasionally, eruptions may also be caused by external triggers (geothermal, seismic) [*Tárraga et al.*, 2006; *Gottsmann et al.*, 2007; *Carniel et al.*, 2008]. In computing the long-term probability of an eruption if we only consider magmatic triggers as the source of the unrest we would be underestimating the total probability, since we need to account for the long-term probability that the eruption is originated by a geothermal unrest (when a hydrothermal system exists) or by a seismic unrest. On the other hand, event trees developed using elicitation of expert judgment have a human decision component which adds an additional source of bias to the model, require the event tree structure to be as simple as possible, do not account for the epistemic and aleatoric uncertainties and require the elicitation team to meet in order to update the probabilities each time new data arrive.

[7] In order to show the limitations of the previous attempts and the need for a more extensive structure we use the example of Teide-Pico Viejo stratovolcanoes, as they present alternative scenarios (i.e., nodes and branches) than those included in the previous event tree structures and may experience unrest triggered by external causes such as regional seismicity or oscillations in the hydrothermal system. Teide-Pico Viejo stratovolcanoes form one of the largest volcanic complexes in Europe, situated on the island of Tenerife, extensively populated and one of the main tourist destinations in Europe. There is scarce information on its past activity and the volcanoes have not shown clear signs of activity in historical times. However, it has produced several central and flank vent, effusive and explosive eruptions during the last 5000 years, the last one about 1000 years ago [*Carracedo et al.*, 2007]. It has permanent fumarolic activity at the summit of Teide volcano and the occurrence of a recent unrest episode [*Martí et al.*, 2009], reminds us that these volcanoes are presently quiescent, but potentially active and could erupt again in the near future. For this reason, research is needed to assess the volcanic hazard and forecast the range of potential volcanic eruptions. Since we rely on geological and geophysical data, aleatoric (stochastic) and epistemic (data or knowledge limited) uncertainties are significant, and we need to find a way to minimize them.

[8] The aleatoric (stochastic) uncertainty is a consequence of the intrinsic complexity of a system, hence our limitation in predicting the evolution of the system in a deterministic way. The aleatoric uncertainty introduces a component of randomness in the outcomes, regardless of our physical knowledge of the system. The epistemic uncertainty is directly related to our knowledge of the system and the quality and quantity of data we have about the system. The more data we have, the better we know the system and the lower the epistemic uncertainty [*Woo*, 1999].

[9] A first attempt to asses the volcanic hazard for Teide-Pico Viejo has been made by *Martí et al.* [2008a], following the 2004–2005 seismic volcanic crisis on Tenerife [*Martí et al.*, 2009], who have proposed an event tree using elicitation of expert judgment to assign a probability of occurrence to each possible eruptive scenario. However, the nature of the methodology applied required the event tree to be as simple as possible, grouping events which may require to be analyzed individually (e.g. origin of the unrest), and leaving out relevant nodes (e.g., type of composition of the magma). Also, despite the corrections applied according to the relative relevance (weight) of each expert, the method has still a strong human decision component which adds an additional source of bias to the final results.

[10] In this paper, we present an event tree structure which accounts for external triggers (geothermal, seismic) as additional sources of volcanic unrest and looks at the hazard from different types of magma composition and different vent locations. We then take the available geological data for Teide-Pico Viejo from the last 8 ka and run it through a Bayesian model built following this new event tree structure. The result is an estimation of the long-term probability for each possible scenario. We compare both Elicitation and Bayesian methods applied to Teide-Pico Viejo. Also, we compare the results from the Bayesian event tree developed here allowing for external triggers with previous Bayesian event tree structures. This is a new step in the development of useful tools for volcanic hazard assessment, but additional studies will be needed to define the precursors and monitoring parameters for each eruptive scenario in order to estimate the short-term probabilities.

2. Background Geology and Past Volcanic Activity in the Teide-Pico Viejo Volcanic Complex

[11] Teide-Pico Viejo stratovolcanoes started to grow about 180–190 ka in the interior of the Las Cañadas caldera (Figure 1). This volcanic depression originated by several vertical collapses of the former Tenerife central volcanic edifice (Las Cañadas edifice) following explosive emptying of a high-level magma chamber. Occasional lateral collapses of the volcano flanks also occurred and modified the resulting caldera depressions [*Martí et al.*, 1994; *Martí and Gundmundsson*, 2000]. The construction of the present

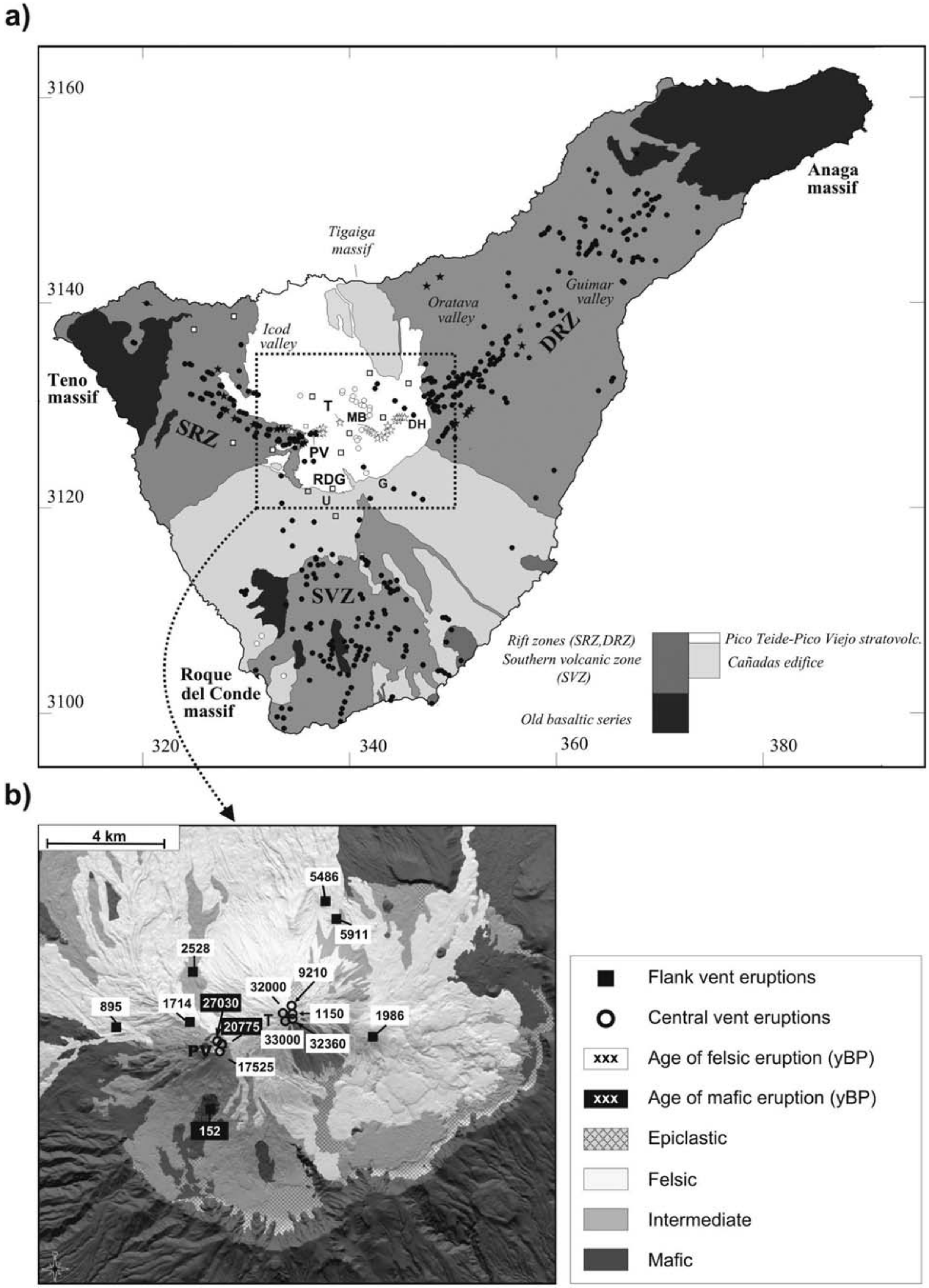
a)
3160
3140
3120
3100
320
340
360
380
Anaga massif
Tigaiga massif
Oratava valley
Guimar valley
Icod valley
Teno massif
DRZ
SRZ
SVZ
T
MB
DH
PV
RDG
G
U
Roque del Conde massif
Rift zones (SRZ,DRZ)
Southern volcanic zone (SVZ)
Old basaltic series
Pico Teide-Pico Viejo stratovolc.
Cañadas edifice
b)
4 km
5486
5911
2528
9210
32000
1150
895
1714
27030
20775
T
33000
32360
1986
PV
17525
152
Flank vent eruptions
Central vent eruptions
Age of felsic eruption (yBP)
Age of mafic eruption (yBP)
Epiclastic
Felsic
Intermediate
Mafic

Figure 1

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 [*Martí et al.*, 2008b].

[12] Eruptions at Teide and Pico Viejo stratovolcanoes have occurred from their central vents but also from a multitude of vents distributed on their flanks (Figure 1) [*Martí and Geyer*, 2009]. Mafic and phonolitic magmas have been erupted from these central and flank vents. The Santiago del Teide and Dorsal rift axes, the two main tectonic lineations currently active on Tenerife, probably join beneath the Teide-Pico Viejo complex [*Ablay and Martí*, 2000]. Some flank vents at the western side of Pico Viejo are located on eruption fissures that are subparallel to fissures further down the Santiago 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.

[13] The eruptive history of the Teide-Pico Viejo 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 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, but also through some flank vents. 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 [*Martí et al.*, 2008b]. 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.

[14] 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 with sub-Plinian eruptions, such as the Montaña Blanca at the eastern flank of Teide, 2000 years ago [*Martí et al.*, 2008b].

[15] Some significant basaltic eruptions have also occurred from the flanks or the central vents of the Teide-Pico Viejo stratovolcanoes, with a recurrence of around 80–150 years according to the historic record. 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.

[16] According to *Martí et al.* [2008b], the total volume of magma erupted in the last 35 ka is of the order of 1.8–3 km^3, 83% 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 in the recent history of Teide-Pico Viejo.

[17] In summary, several possible eruptive scenarios can be envisaged for the Teide-Pico Viejo stratovolcanoes according to their most recent volcanological history (Figure 2). These include central and flank vent magmatic and phreatomagmatic eruptions of phonolitic and basaltic magmas, phreatic explosions, and sector collapses. All these scenarios may be preceded by unrest episodes of different origins and can generate a significant number of products (hazards). Each potential scenario is assigned a probability of occurrence.

3. Teide-Pico Viejo Bayesian Event Tree

[18] An event tree is a tree graph representation of events in the form of nodes and branches. Each node represents a step and contains a set of possible branches (outcomes for that particular category). The nodes are alternative steps from a general prior event, state, or condition through increasingly specific subsequent events to final outcomes. The event tree includes all relevant possible outcomes of volcanic unrest at progressively higher degrees of detail. In the Bayesian model developed here, one condition is that the branches in each node are mutually exclusive and exhaustive.

[19] To account for the possibility of flank vent eruptions (as opposed to only central eruptions), geothermal or seismic unrest (as opposed to only magmatic), phonolitic or basaltic composition (as opposed to no composition), and other relevant volcanic hazard possibilities for Teide-Pico Viejo, we have developed a new event tree structure that expands and complements the ones previously proposed by *Newhall and Hoblitt* [2002] and *Marzocchi et al.* [2004, 2006, 2008], where Bayesian methodology was applied, and by *Martí et al.* [2008a], where eliciting expert judgment was used.

[20] Figure 3 shows the Bayesian event tree developed for Teide-Pico Viejo stratovolcanoes based on the geological information gathered from Figure 2. All events in each node are assumed mutually exclusive and exhaustive; that is, they do not happen simultaneously, and the sum of probabilities of occurrence for different events in one node sums up to one.

Figure 1. (a) Simplified geological and topographic map of Tenerife illustrating the general distribution of visible vents. RDG, Roques de García; G, Guajara; T, Teide volcano; PV, Pico Viejo volcano; MB, Montaña Blanca; SRZ, Santiago rift zone; DRZ, dorsal rift zone; SVZ, southern volcanic zone. Black symbols, mafic and intermediate vents; white symbols, felsic vents; stars, historic and subhistoric vents; circles, other vents. Names and locations of landslide valleys are also shown. Coordinates refer to 20 km squares of the Spanish national grid (UTM). (b) Simplified geological map of the central part of Tenerife Island. Black squares and circles indicate flank and central vent eruptions, respectively. White boxes include the age in years B.P. of phonolitic events and black boxes those of mafic events. Not all the eruptions from Teide-Pico Viejo stratovolcanoes are included, only those dated by *Carracedo et al.* [2007].

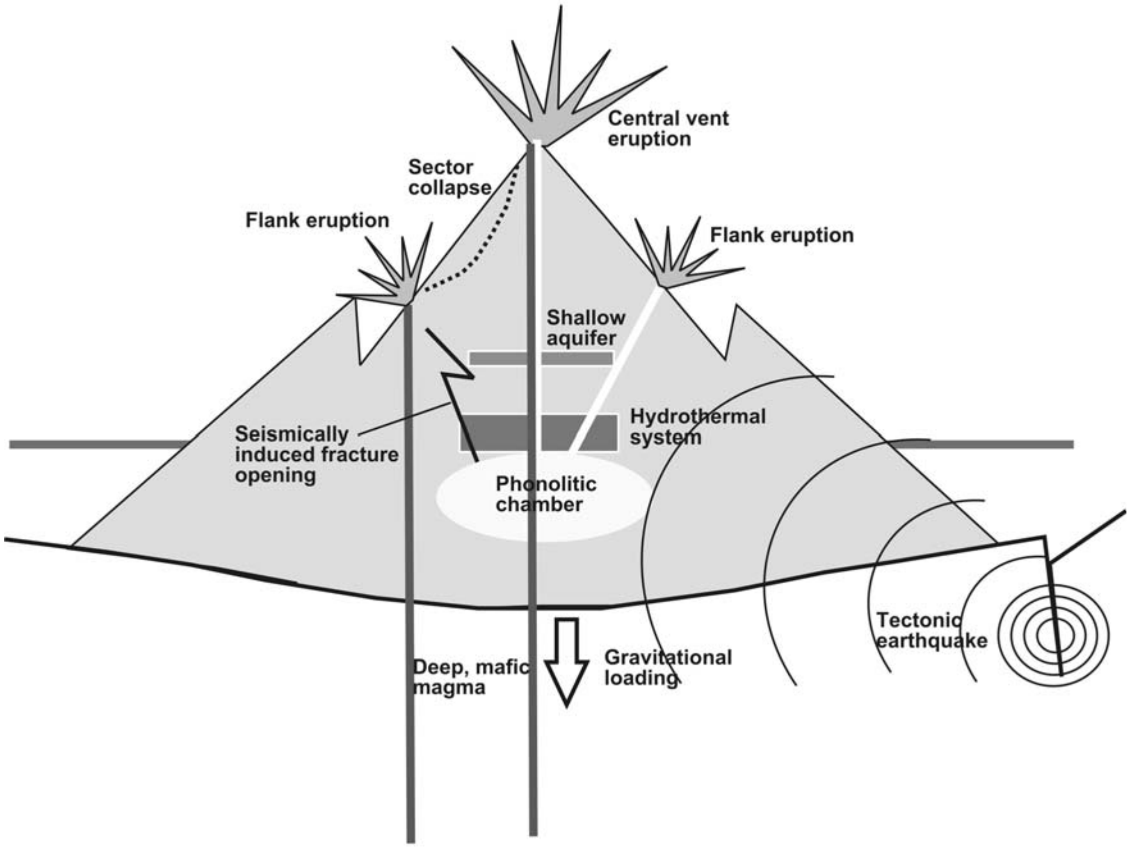

Figure 2. Schematic representation of the most relevant potential unrest and eruptive scenarios for Teide-Pico Viejo stratovolcanoes (see text for more explanation).

3.1. Node 1: Unrest

[21] Given that we have the capacity to differentiate the origin of the precursory signals, we define unrest as any modification of the background activity of the volcano recorded by the monitoring network and which may or may not be followed by an eruption of any kind.

[22] The previous event tree [*Martí et al.*, 2008a] started with the volcano at unrest (including external triggers), to make the event tree as simple as possible. That leaves out the computation of the probability of unrest and the origin of this unrest. The Bayesian methodology used here allows to further expand this node into two new branches, "unrest" and "no unrest" in a given time window τ, and add a new node which accounts for the origin of this unrest. When there is no unrest, we will compute the long-term probabilities based on past data, expert judgment, scientific beliefs, etc., using the Bayesian methodology as explained in section 4. This will allow us to estimate the absolute probability of a specific event given past information, for example, the long-term probability of a VEI 3 or less, basaltic, central vent, magmatic eruption with magmatic unrest in a given time window τ given information derived from past eruptions.

[23] Short-term probabilities could be computed in the event of some degree of unrest, provided that monitoring data were available. However, for the scope of this paper, we will only discuss long-term probabilities.

3.2. Node 2: Origin of the Unrest

[24] We define four types of unrest likely to happen in Teide-Pico Viejo stratovolcanoes: magmatic, geothermal, seismic, and other. Assuming in the future, in an optimal situation, we can define the precursors which identify the source of the unrest, it is crucial in a complex system like Teide-Pico Viejo to differentiate between unrest caused by internal triggers or caused by external triggers, which ultimately may condition the outcome and further development of the system. The previous Teide event tree grouped all types of unrest in a unique branch called "unrest", and previous event trees defined for other volcanoes consider so far only one type of unrest of magmatic origin. From the study of the different eruption types identified on Teide-Pico Viejo, we can deduce that all of them, including the phreatic episode [*Ablay and Martí*, 2000], require the presence of fresh magma, either mafic or felsic, at shallow depths in the volcanoes. However, we do not discard the possibility of starting an eruption process from an unrest directly associated with the hydrothermal system or even due to external triggers, such as regional tectonics, if eruptible magma is present in the system. In fact, the existence of an active hydrothermal system below Teide-Pico Viejo is evidenced by the presence of fumaroles and indirectly by geophysical data [*Pérez et al.*, 1996; *Coppo et al.*, 2008]. Volcanic unrest related to hydrothermal rather than to magmatic activity has been documented in similar volcanic

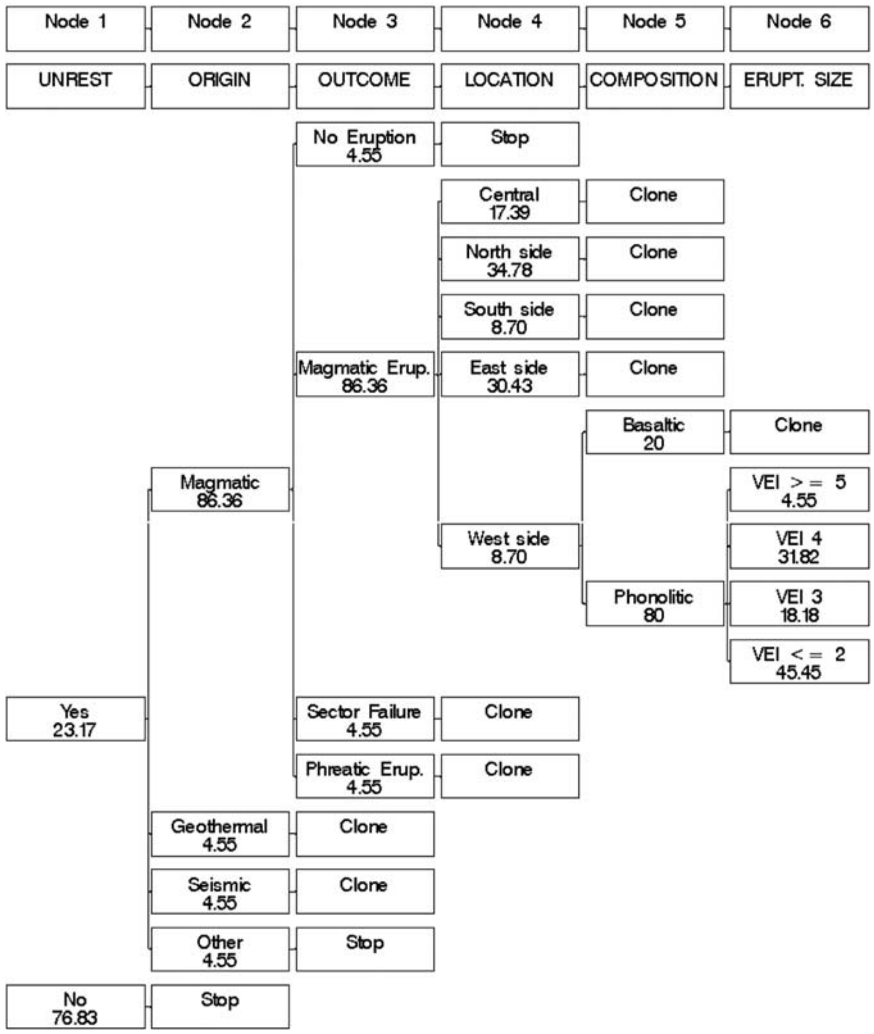

Figure 3. Bayesian event tree for Teide-Pico Viejo. The six steps of estimation progress from general to more specific events (left to right). Any branch ending with "clone" is identical to the detailed branch. Each branch contains the percent long-term absolute (posterior) probability of occurrence.

systems [*Gottsmann et al.*, 2003, 2007]. It is also important to mention that the interior of Tenerife is currently reacting to changes in the regional stress field or regional tectonics [*Carniel et al.*, 2008; *Tárraga et al.*, 2006; *Martí et al.*, 2009], so a seismic trigger for unrest cannot be ruled out.

[25] Volcanic unrest and subsequent eruption represent an increase of the internal pressure of the volcanic system. This pressure increase may be caused directly by intrusion of new magma and/or pressurization of the associated hydrothermal system, or indirectly by reducing the external loading by a sector collapse or opening of a fracture during a tectonic episode. Because we define unrest based on geophysical and geochemical signals recorded by the monitoring network, we accept that the unrest (i.e., the variation in this recorded signals) may derive from changes in the magma chamber due to intrusion of new (fresh) magma (magmatic unrest), changes in the hydrothermal system, having a magmatic origin or not (geothermal unrest) or changes in the host rock caused by regional seismicity (seismic unrest). However, there is also a possibility for a false unrest when non volcanic signals are recorded together with the volcanic ones. This is, for example, the case of variations in the recharge and extraction of meteoric water in/from the shallow aquifer inside the Las Cañadas caldera, which may cause changes in the gravity field, ground deformation, and even seismicity not related to any volcanic activity.

3.3. Node 3: Outcome of the Unrest

[26] We consider here the outcome of the unrest being of four different types:

[27] Type 1 is magmatic eruption which is triggered directly by a magmatic unrest, which may or may not be preceded by a sector failure, or triggered indirectly by a geothermal or seismic unrest, in which case, external decompression of the shallow volcanic system would be required. This could be achieved by sector failure or tectonic fracture opening.

[28] When the unrest is geothermal or seismic, for a magmatic eruption to occur we would need a sector collapse first or fracture opening to decompress the whole system, so when we talk about a magmatic eruption originated by a geothermal or seismic unrest, we assume that a sector failure

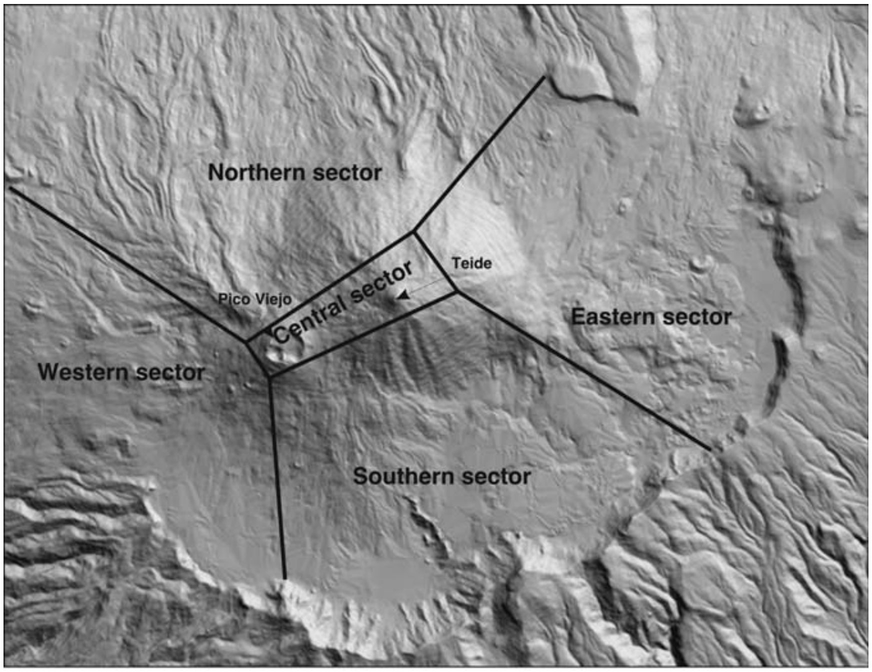

Figure 4. Digital elevation model (DEM) of the central part of Tenerife Island showing the sectors distribution used to define the different source areas of the hazardous events (eruptions, sector collapses, lahars, etc.) considered in the event tree.

or a tectonically induced fracture opening have previously occurred.

[29] Type 2 is sector failure, which is triggered by a magmatic, geothermal or a seismic unrest. In this branch the outcome is the sector collapse itself, not being followed by an eruption. A sector failure followed by a magmatic eruption is considered in the previous branch (magmatic eruption), caused indirectly by a magmatic unrest which triggered a sector collapse.

[30] Type 3 is phreatic eruption, which is triggered by unrest of any type, where no magma is involved in the eruption.

[31] Type 4 is no eruption. There is unrest but no further outcome develops.

3.4. Node 4: Location

[32] Teide-Pico Viejo has undergone several flank and central vent eruptions without any apparent structural or petrological pattern that could explain such random eruption behavior [*Martí et al.*, 2008b; *Martí and Geyer*, 2009]. The lack of a good surveillance network and detailed knowledge on past activity makes the identification of future vents more challenging than in other volcanoes better known and monitored (e.g., Vesuvius, Popocatépetl).

[33] *Martí and Geyer* [2009] show that the main control on the pathway of phonolitic magma between the shallow magma chamber and the surface is exerted by the stress field distribution around and above the chamber, this being a function of the shape and depth of the magma chamber. Comparison of these results with the available geological and geochronological information suggests that the number of flank eruptions that occurred on Teide-Pico Viejo during the time period considered (last 8000 years) is slightly higher than that of the central vent eruptions.

[34] With respect to previous work [*Martí et al.*, 2008a], this node is an expansion of the node "location" by segmenting the "flank vent" branch. Aside from the central vent location, we segmented the flank vent location into "north," "south," "east," and "west". Further segmentation is possible. The reason for this is that the impact of the different hazards that have occurred from each eruption may differ significantly depending on the exact location of the vent. The abrupt topography of the Teide-Pico Viejo and their surroundings, together with the presence of important topographic barriers such as the Cañadas caldera wall, impose a different level of hazard and risk depending on what side of the volcano the eruption occurs. The north side of the volcano is the area that poses the greater risk, due to the densely populated area and lack of any topographical protection from gravity driven flows.

[35] Hence, node 4 location segments the area around Teide-Pico Viejo volcano complex into five sectors (Figure 4): central, north, south, east, and west.

3.5. Node 5: Composition

[36] Unlike previous event trees, the composition node is a new contribution. Teide-Pico Viejo's eruptive activity has been associated with both mafic (basaltic, tephri-phonolites) and felsic (phono-tephrites and phonolites) magmas. Hence, the magma composition will determine two main types of eruptions, basaltic or phonolitic, and they will have different hazard implications, as phonolitic magmas are associated with more violent eruptions than basaltic magmas.

[37] There are two feeding systems in Teide-Pico Viejo that should be associated with different precursors. These will allow us to determine if the eruption is going to be associated with the phonolitic or the basaltic system. This conditions where the eruption is going to take place and the

composition of the erupting magma, which will influence the level of hazard and the magnitude of the eruption. Phonolitic eruptions are more common in the central vents of Teide-Pico Viejo and their flanks, while basaltic eruptions are randomly distributed on the stratovolcanoes but also inside the caldera. It is obvious that outside and inside the caldera basaltic volcanism is tectonically controlled by the rift systems, which also affects the plumbing systems that allow deep magma to rise into the central complex [*Ablay and Martí*, 2000; *Martí et al.*, 2008b]. However, the structural constraints of the rift system that allow basaltic magma to reach the surface in Teide-Pico Viejo are still not clear. Therefore in terms of forecasting future eruptions from Teide-Pico Viejo it will be crucial to clearly distinguish between precursory activity of basaltic and phonolitic magmas. Thus, the composition in node 5 could be of two types: basaltic or phonolitic. The importance in distinguishing these two outcomes for node 5 is the different level of hazard that is associated with each one [*Martí et al.*, 2008b].

3.6. Node 6: Size

[38] Teide-Pico Viejo's eruptive activity has produced a large variety of eruption types and magnitudes. This node represents the magnitude of the eruption in terms of the volcanic explosive index (VEI), categorized here in four possible outcomes: VEI ≥ 5, VEI = 4, VEI = 3, VEI ≤ 2.

[39] Basaltic eruptions recorded in the geological record of Teide-Pico Viejo mostly correspond to Strombolian to violent Strombolian eruptions (VEI 2, VEI 3), while phonolitic eruptions may generate eruptions of VEI 5 or higher. The hazards that this wide range of eruptions have generated in the past and may produce in the future is rather variable and include lava flows and lahars of different volumes and run out distances, ash fallout, pumice-lapilli fallout, ballistic bombs and pyroclastic density currents.

4. Bayesian Model for Teide-Pico Viejo Event Tree

[40] In Bayesian statistics, probability has the subjective interpretation. Bayesians use probability to make statements about the partial knowledge available concerning some underlying process or "state of nature" (unobservable or as yet unobserved) in a systematic way. The fundamental principle of Bayesian statistics is that what is known about anything that is incompletely or imperfectly known is described by a probability or probability distribution.

[41] Bayesians regard both the observed data y and the unknown parameters θ as random variables. Posterior inference about θ is then conditional on the particular realization of y actually observed.

[42] This is in contrast to classical inference, where only the data are regarded as random, while parameters θ are treated as fixed but unknown. Classical inference is not just conditional on the observed data, but on what might have been observed under repeated sampling.

[43] Suppose we have data y and unknowns θ. We posit a model which specifies the likelihood $p(y|\theta)$.

[44] From a Bayesian point of view, θ should have a probability distribution reflecting our uncertainty about it, and as y is known, should be conditional on θ.

[45] Therefore, our knowledge about θ is expressed through its posterior distribution $p(\theta|y)$:

$$p(\theta|y) \propto p(\theta) \times p(y|\theta) \tag{1}$$

$$\text{posterior} \propto \text{prior} \times \text{likelihood} \tag{2}$$

4.1. Prior Distribution

[46] The prior distribution, $p(\theta)$, expresses our uncertainty about θ before seeing the data. The posterior distribution, $p(\theta|y)$, expresses our uncertainty about θ after seeing the data.

[47] The only requirement for the prior distribution is that it should represent the knowledge about θ before observing the current data. The prior can be specified entirely subjectively, depend on past data or be weak or noninformative.

[48] We model the prior distribution for the jth event at the kth node with a Dirichlet distribution, which is the generalization of the Beta distribution [*Marzocchi et al.*, 2008]:

$$\theta_{prior_k} \approx Di_{J_k}(\alpha_{k1}, \alpha_{k2}, .., \alpha_{kJ_k}) \tag{3}$$

where J_k is the number of possible mutually exclusive and exhaustive events at the kth node, and α_{k1}, α_{k2},.., α_{kJ_k} are the parameters of the distribution in that particular node. The choice of the Dirichlet (Beta) distribution is itself rather subjective. In general, theoretical models, a priori beliefs, and/or expert elicitation give estimation of the expected average of the prior distribution that represents the "best guess". Further details on this choice are given by *Marzocchi et al.* [2004].

[49] The expected value (mean) E and variance V of the priori random variable (equation (3)) from the kth node and the nth event, which follows a Dirichlet distribution, are

$$E[\theta_{kn}] = \frac{\alpha_{kn}}{\left(\sum_{i=1}^{J_k} \alpha_{ki}\right)} \tag{4}$$

$$V[\theta_{kn}] = \frac{\alpha_{kn}\left(\sum_{i=1}^{J_k} \alpha_{ki} - \alpha_{kn}\right)}{\left(\sum_{i=1}^{J_k} \alpha_{ki}\right)^2 \left(\sum_{i=1}^{J_k} \alpha_{ki} + 1\right)} \tag{5}$$

The expected value of those distributions represents an estimation of the aleatoric uncertainty, i.e., the intrinsic (and unavoidable) random variability due to the complexity of the process. The dispersion around the average (i.e., the variance) represents an estimation of the epistemic uncertainty, due to our limited knowledge of the process. The estimation of the epistemic uncertainty is very important for correct comparison between the probabilities of different hazards, and the confidence limits that are ascribed to them [*Woo*, 1999]. The variance can be seen as a sort of "confidence degree" of our a priori information, i.e., an evaluation of the epistemic uncertainties. The confidence degree is set up by writing the variance in terms of "equivalent number of data" (λ_k) [*Marzocchi et al.*, 2008]

$$\lambda_k = \sum_{i=1}^{J_k} \alpha_{ki} - J_k + 1 \tag{6}$$

And then,

$$V[\theta_{kn}] = \frac{E[\theta_{kn}](1 - E[\theta_{kn}]}{\lambda_k + J_k} \quad (7)$$

[50] The higher λ_k, the larger our confidence on the reliability of the model. Hence, we need more past data to modify significantly the prior, but if we believe that the prior is poorly informative, λ_k is small, and so even a small number of past data can drastically modify the prior. In our case, we will use the minimum value for λ_k which is 1, i.e., the maximum possible epistemic uncertainty, since some of the past geological records we have are not accurate.

4.2. Likelihood Function

[51] The likelihood function allows us to use the past data (y_k) at node k to modify the a priori beliefs or priori distributions. In our model the data for each event in each node is a random variable that follows a multinomial distribution, which is the generalization of the binomial distribution. In our case, we have

$$[y_k|\theta_k] \approx Mu_{J_k}(y_{k1}, y_{k2}, .., y_{kJ_k}; \theta_k) \quad (8)$$

Where J_k is the number of possible mutually exclusive and exhaustive events at the kth node. Note this distribution assumes the data of the set y_k are independent and identically distributed.

4.3. Posterior Distribution

[52] Since the Dirichlet and Multinomial are conjugate distributions, the posterior distribution for θ_k is still a Dirichlet:

$$\theta_{posterior_k} \approx Di_{J_k}(\alpha_{ki} + y_{ki}, \forall i = 1..J_k) \quad (9)$$

where the parameter α_{ki} will be determined by

$$\alpha_{ki} = E[\theta_{ki}](\lambda_{ki} + J_k - 1) \quad (10)$$

[53] As discussed before, $E[\theta_{kn}]$ is the central value inferred by a priori models and/or of the theoretical beliefs, and will account for the aleatoric uncertainty, while λ_{ki} controls the confidence at which $E[\theta_{kn}]$ is considered a reliable estimate and will account for the epistemic uncertainty. Both these parameters will be inputs to the model.

4.4. Total Probability

[54] Once we have all the probability density functions for each branch in each node and the conditional probability assessment calculated, we combine all these probabilities to estimate the total long-term probability of a particular event. For example, the long-term probability of having a magmatic unrest with central vent basaltic eruption in the time interval (t_0, $t_0 + \tau$) is

$$P(U \cap \mathrm{Mo} \cap \mathrm{Me} \cap \mathrm{C} \cap \mathrm{B}) = \theta_{\mathrm{post_U}} \theta_{\mathrm{post_{Mo}}} \theta_{\mathrm{post_{Me}}} \theta_{\mathrm{post_C}} \theta_{\mathrm{post_B}} \quad (11)$$

where U is unrest, Mo is magmatic origin, Me is magmatic eruption, C is central, and B is basaltic.

5. Long-Term Hazard at the Nodes for Teide-Pico Viejo Event Tree Based on Existing Data: Computation and Results

[55] Suppose we have 80 time windows investigated ($n_1 = 80$) out of which 18 have had unrest ($y_{11} = 18$, $y_{12} = 62$), and we want to compute the long-term probability of unrest in the next time window τ (each time window 100 years long) using Bayesian Inference. According to equation (9) the posterior probability follows a Dirichlet distribution of parameters (α_{11} + 18) and (α_{12} + 62), where $\alpha_{11} = \alpha_{12} = 1$ (equation (10)), $E[\theta_{11}] = E[\theta_{12}] = 0.5$ (prior weight) and $\lambda_{11} = \lambda_{12} = 1$ (data weight). Hence, the long-term probability of having an unrest in the next time window is the expected value of a random variable that follows a Dirichlet distribution with parameters (1 + 18) and (1 + 62), which by definition (equation (4)) is

$$\frac{\alpha_{11} + y_{11}}{(\alpha_{11} + y_{11}) + (\alpha_{12} + y_{12})} = \frac{1 + 18}{1 + 1 + 80} = 0.2317$$

[56] Using R, a free language and environment for statistical computing and graphics (available at http://www.r-project.org/), a code has been developed to apply the above Bayesian model to the Teide-Pico Viejo data (code available upon request). Table 1 shows 18 eruptions recorded geologically for the last 8000 years, using a time window of 100 years, we have 18 events in the last eighty time windows. Table 2 shows the input data for the model.

[57] There are no historical records to know if there where any false alarms. We assume that all the eruptions geologically documented here where preceded by volcanic unrest. Hence, during the 80 time windows of 100 years each, there were 18 episodes of unrest versus 62 of no unrest.

[58] The probability function named ltvh, programmed in R, computes the long-term probability vector (Table 2) for each node and is defined as

$$\mathrm{ltvh} = f(pb1, pb2, pb3, pb4, pb5, pb6, y1, y2, y3, y4, y5, y6) \quad (12)$$

where $pb1$,.., $pb6$ are the $J_k \times 2$ matrices containing the $E[\theta_{ki}]$, λ_{ki} parameter information for each node (k = 1,…, 6) and each event within each node (i = 1,..,J_k) (Table 2, prior and data weight values). Weights are equally distributed based on the assumption of noninformative priors; $y1$,.., $y6$ are the vectors with the geological and geophysical data for each node, each vector is of dimension 1 × J_k (Table 2, past events values).

[59] Because of the fact that each volcano is unique, we cannot use validation data from analogs. To validate the model, we used the previous model BET_EF already published [*Marzocchi et al.*, 2008] and verified that the new extended model yields the same results as the former one when the same parameters are given. After the model has been validated for accuracy of the results, we present some examples and interpretations.

Table 1. Geological Records of Eruptions at Teide-Pico Viejo Volcanic Complex for the Last 8000 Years[a]

Eruption	Year	Node 1 Unrest	Node 2 Origin	Node 3 Outcome	Node 4 Location	Node 5 Composition	Node 6 Size
Chahorra	1798	Yes	Magmatic	Magmatic Eruption	West Side	Basaltic	VEI ≤ 2
Mta Reventada	895 B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Basaltic	VEI ≤ 2
Lavas Negras	1150 B.P.	Yes	Magmatic	Magmatic Eruption	Central	Phonolitic	VEI 3
Roques Blancos	1714 B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Phonolitic	VEI 4
Mta Blanca	2000 B.P.	Yes	Magmatic	Magmatic Eruption	East Side	Phonolitic	VEI 3
PV surges	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	Central	Basaltic	VEI ≤ 2
Hoya del Cedro	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Phonolitic	VEI 4
Mta Majua	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	South Side	Phonolitic	VEI ≤ 2
Mta de la Cruz	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	East Side	Phonolitic	VEI ≤ 2
Arenas Blancas	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	East Side	Phonolitic	VEI ≤ 2
Mta Los Conejos	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	East Side	Phonolitic	VEI ≤ 2
Bocas de Maria	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	East Side	Phonolitic	VEI ≤ 2
Mta Las Lajas	(2528–2000) B.P.	Yes	Magmatic	Magmatic Eruption	East Side	Phonolitic	VEI ≤ 2
El Boqueron	2528 B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Phonolitic	VEI 4
Cañada Blanca	(5911–2528) B.P.	Yes	Magmatic	Magmatic Eruption	Central	Phonolitic	VEI 3
Abejera Baja	5911 B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Phonolitic	VEI 4
Abejera Alta	5486 B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Phonolitic	VEI 4
Pico Cabras	(7900–5486) B.P.	Yes	Magmatic	Magmatic Eruption	North Side	Phonolitic	VEI 4

[a]Data are from *Ablay and Martí* [2000], *Carracedo et al.* [2007], and J. Martí (unpublished data, 2009–2010). Since there are no historical records, we assumed that an episode of unrest corresponds to each eruption geologically documented.

[60] The event tree on Figure 3 shows the long-term probabilities computed with the model presented above, this is, the posterior probabilities computed as shown in section 4.3. This probabilities are also shown in Table 2 and are then used to compute the total long-term probability for each eruptive scenario (equation (11)) as explained in section 4.4. Some examples are shown below.

[61] According to our model, the long-term probability of a basaltic central vent magmatic eruption with magmatic unrest in the next time window is 0.2317 × 0.8636 × 0.8636 × 0.1739 × 0.20 = 0.6%. That is, the probability of an unrest (0.2317) times the probability that this unrest is magmatic (0.8636) times the probability that this magmatic unrest derives into a magmatic eruption (0.8636) times the probability that this magmatic eruption is central (0.1739) times the probability that the composition is basaltic (0.20) is 0.6%. Similarly, the long-term probability of a phonolitic central vent magmatic eruption with magmatic unrest in the next time window is 0.2317 × 0.8636 × 0.8636 × 0.1739 × 0.80 = 2.4%, 4 times the probability of a central magmatic eruption of basaltic composition.

[62] The branch called "yes" in the tree node "unrest" refers to episodes of unrest that could either derive into false alarm or into eruption. Even though we assume the 18 geologically documented eruptions followed unrest, the model also computes a probability of false alarm, this is, having an unrest which does not derive into an eruption: 0.2317 × 0.0455 × (0.8636 + 0.0455 + 0.0455) = 1.01%.

[63] The probability of "No Eruption" would be the sum of the probability of a false alarm, this is, 1.01%, plus the probability of a false unrest (0.2317 × 0.0455 = 1.05%), plus the probability of no unrest of the volcanic system (76.83%).

Table 2. Long-Term Probability Estimation for Each Branch of the Event Tree Using Bayesian Inference and Geological Records[a]

Node	Node Type	Branch	Past Events	Prior Weight	Data Weight	Probability (%)
1	unrest	yes	18	0.5	1	0.2317
1	unrest	no	62	0.5	1	0.7683
2	origin	magmatic	18	0.25	1	0.8636
2	origin	geothermal	0	0.25	1	0.0455
2	origin	seismic	0	0.25	1	0.0455
2	origin	other	0	0.25	1	0.0455
3	outcome	Magmatic Eruption	18	0.25	1	0.8636
3	outcome	Sector Failure	0	0.25	1	0.0455
3	outcome	Phreatic Eruption	0	0.25	1	0.0455
3	outcome	No Eruption	0	0.25	1	0.0455
4	location	Central	3	0.2	1	0.1739
4	location	North	7	0.2	1	0.3478
4	location	South	1	0.2	1	0.087
4	location	East	6	0.2	1	0.3043
4	location	West	1	0.2	1	0.087
5	composition	Basaltic	3	0.5	1	0.2
5	composition	Phonolitic	15	0.5	1	0.8
6	size	VEI ≥ 5	0	0.25	1	0.0455
6	size	VEI4	6	0.25	1	0.3182
6	size	VEI3	3	0.25	1	0.1818
6	size	VEI ≤ 2	9	0.25	1	0.4545

[a]Past events are based on the geological records for the last 80 time windows (each time window is 100 years) shown in Table 1. Weights for the priori, aleatoric, and epistemic uncertainties are equally distributed across branches of the same node based on the assumption of noninformative priors.

Thus, the long-term probability of not having an eruption in the next time window is 78.89%.

[64] To compute the long-term probability of having a magmatic eruption of any origin in the next time window, we have to consider all the sources that can trigger a magmatic eruption (magmatic, geothermal or seismic unrest). This is, the long-term probability of having a magmatic eruption caused by (1) a magmatic unrest (0.2317 × 0.8636 × 0.8636 = 17.28%), (2) a geothermal unrest (0.2317 × 0.0455 × 0.8636 = 0.91%), (3) a seismic unrest (0.2317 × 0.0455 × 0.8636 = 0.91%). Thus, the long-term probability of having a magmatic eruption in the next time window is 19.10%.

6. Discussion and Conclusions

[65] We have developed a new event tree model for long-term volcanic hazard assessment based on Bayesian methodology and that represents a step forward with respect to previous attempts based on the same methodology or the elicitation of expert judgment. We have applied this new model to the particular case of Teide-Pico Viejo stratovolcanoes, but it may be applied to other active volcanoes.

[66] In comparison with previous event trees based on Bayesian methodology [*Newhall and Hoblitt*, 2002; *Marzocchi et al.*, 2008], the model presented here accounts for the possibility of the unrest being caused by external triggers (geothermal, seismic), and adds new nodes with two additional sources of volcanic hazard based on the composition of the magma and different vent locations. With respect to event trees based on elicitation of expert judgment [*Neri et al.*, 2008; *Martí et al.*, 2008a] the new model does not have the additional source of bias that the human decision component adds to the final results of the elicitation method, controls for the epistemic and aleatoric uncertainties, and allows the level of segmentation and complexity of the event tree structure to be as complete and extensive as needed, with the only requirements of mutually exclusive and exhaustive events in each node. It also permits to automatically update the probabilities when new data arrive or the system becomes active and monitoring data on precursors exist, as opposed to the eliciting method which requires the group of experts to meet each time new data arrive to update the probabilities. However, during a volcanic crisis, Elicitation and Bayesian models are needed and the elicitation team should provide input and interpretation to the probabilities from the updated Bayesian model.

[67] In order to understand the differences between this new model of event tree and the previous ones, let us to consider the example presented in this paper. With respect to previous hazard assessment, we have expanded the existing event tree for Teide Pico Viejo [*Martí et al.*, 2008a] and estimated the long-term probability of an eruption when this can be caused by internal as well as external triggers, considered magma composition as an additional source of hazard and segmented the flank vent location into four lateral locations. To do this, we have used Bayesian methodology applied to a more detailed and complete event tree scheme. By doing this, we have been able to account for additional eruptive scenarios that were not contemplated before and more accurately estimate the long-term probabilities of an eruption within a given time window.

[68] Therefore, in a volcanic system like the one formed by the Teide-Pico Viejo stratovolcanoes we may consider different possibilities of unrest, each one with its associated probability. However, if we do not contemplate the possibility of an unrest caused by external triggers, types 2 and 3 in the example presented in section 5 to compute the probability of having a magmatic eruption would be set to zero, and the total probability of having a magmatic eruption would be computed only for the case of the unrest being magmatic, in the example in section 5, this is (17.28%). In this case, the result should be the same as the one computed with the BET_EF [*Marzocchi et al.*, 2008], where the weight assigned to the branches "geothermal" and "seismic" in node 2 "origin" would be zero and all the weight would go for the remaining two branches "magmatic" and "other". However, in the future some volcanic systems may want to considered the possibility of an eruption caused by external triggers, as we have done here for Teide-Pico Viejo, in which case this new event tree could be applied to that volcano. On the other hand, if we consider only the origin of the unrest being magmatic on a volcanic system with an hydrothermal system underneath or high seismic activity, then we are underestimating the volcanic hazard of an eruption, as the probability of an eruption originated by a geothermal or seismic unrest would be embedded in the residual probability of "other" origin and not taken into account. This would happen if we use the above mentioned BET_EF model to compute the probability of a magmatic eruption in Teide-Pico Viejo, which yields a 17.28% versus the 19.10% computed with our model, since the former only considers internal (magmatic) triggers.

[69] Assuming the same probability of unrest than in our Bayesian event tree, and using the Eliciting event tree made for Teide-Pico Viejo to compute the probability of an eruption [*Martí et al.*, 2008a], we get ((unrest) 0.2317 × (no sector failure) 0.92 × (eruption) 0.23) + ((unrest) 0.2317 × (sector failure) 0.08 × (eruption) 0.44) = 5.72%, while the probability of an eruption computed with the Bayesian model, as explained in section 5, is 19.10%, more than 3 times higher.

[70] Despite these differences between the different methods, we believe that Expert Elicitation and Bayesian Inference complement each other and must be used simultaneously during volcanic crises, where Bayesian approach provides a way to quick and automatically update the final probabilities, but the lack of information on precursors and triggers for each branch makes it impossible to automatically compute the short-term probabilities. Further research is needed to define the precursors and automate the Bayesian event tree to be used in the short term.

[71] Our event tree does not include a node with all the different geological hazards from the eruption (lahars, pyroclastic flow, ash fall, etc.) because these events can happen simultaneously, and hence are not mutually exclusive, which is one of the conditions we made on the Bayesian model. Again, further work is needed to address this issue. However, the method accounts for the aleatoric (intrinsic) and epistemic (due to scarce knowledge) uncertainties, allowing us to merge theoretical models, geological data, and expert elicitation exercises to assign a long-term probability to each eruptive scenario in a more realistic manner.

[72] The new method allows us to estimate the long-term probability during a quiet period of the volcano, being useful for land use policy, and will be of use for estimating and automatically updating the short-term probabilities when monitoring data are obtained during unrest.

[73] Although this method is specifically applied to the Teide-Pico Viejo stratovolcanoes in Tenerife, it can be used with other similar volcanoes as it offers a wider structure in comparison with previous event trees that have a more restricted structure and do not include some relevant eruptive scenarios which are likely in the Teide-Pico Viejo but also in many other composite volcanoes.

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