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Abstract

Most volcanic hazard studies focus on magmatic eruptions and their accompanying phenomena. However, hazardous volcanic events can also occur during non-magmatic unrest, defined as a state of volcanic unrest in which no migration of magma is recognised. Examples include tectonic unrest, and hydrothermal unrest that may lead to phreatic eruptions. Recent events (e.g. Ontake eruption, September 2014) have demonstrated that the successful forecasting of phreatic eruptions is still very difficult. It is therefore of paramount importance to identify indicators that define the state of non-magmatic unrest. Often, this type of unrest is driven by fluids-on-the-move, requiring alternative monitoring setups, beyond the classical seismic-geodetic-geochemical architectures. Here we present a new version of the probabilistic model BET (Bayesian Event Tree), called BET_UNREST, specifically developed to include the forecasting of non-magmatic unrest and related hazards. The structure of BET_UNREST differs from the previous BET_EF (BET for Eruption Forecasting) by adding a dedicated branch to detail non-magmatic unrest outcomes. Probabilities are calculated at each node by merging prior models and past data with new incoming monitoring data, and the results can be updated any time new data has been collected. Monitoring data are weighted through pre-defined thresholds of anomaly, as in BET_EF. The BET_UNREST model is introduced here, together with its software implementation PyBetUnrest, with the aim of creating a user-friendly, open-access, and straightforward tool to support short-term volcanic forecasting (already available on the VHub platform). The BET_UNREST model and PyBetUnrest tool are tested through three case studies in the frame of the EU VUELCO project.

Resumen extendido

La mayoría de los estudios sobre amenazas volcánicas tiene su enfoque en las erupciones magmáticas y fenómenos relacionados. Sin embargo, eventos volcánicos peligrosos pueden ocurrir durante una fase de unrest no-magmático, definido por el estado de unrest volcánico en el cual no se reconoce la migración de un magma. Ejemplos son unrest tectónico (capaz de causar preocupación independientemente del resultado posterior) y unrest hidrotermal, que puede resultar en erupciones freáticas. Eventos recientes (e.g. la erupción de Ontake en septiembre 2014) han demostrado que erupciones freáticas siguen siendo difícilmente previsibles. Por estas razones, es de extrema importancia de identificar señales que definen un estado de unrest no-magmático. Muchas veces, este tipo de unrest es instigado por fluidos-en-movimiento, y requiere la instalación de un sistema de monitoreo alternativo, más allá de la clásica arquitectura sismo-geodético-quimica. En este capítulo, presentamos la nueva versión del modelo probabilístico BET (Arbol de Eventos Bayesiano, por sus siglas en inglés), llamado BET_UNREST, específicamente desarrollado para incluir la previsión de unrest no-magmático y sus amenazas relacionadas. La estructura de BET_UNREST se difiere de la versión anterior BET_EF (BET para Previsión de Erupciones, por sus siglas en inglés), añadiendo un ramo dedicado para detallar los resultados amenazadores de unrest no-magmático. Las probabilidades están calculadas para cada nudo juntando modelos a priori y datos pasados con los datos nuevos, provenientes del monitoreo. Los datos de monitoreo están pesados mediante límites predefinidos de anomalía, como es el caso en BET_EF. El capítulo ilustra el modelo e instrumento con tres casos de estudio, dentro el marco del proyecto EU VUELCO:

(i) un análisis retrospectivo para el volcàn Popocatépetl, en donde no hay necesidad del ramo hidrotermal, debido al caràcter magmático; Popocatépetl quedó en unrest desde diciembre 1994 al presente. Para esta aplicación, BET_UNREST fue girado usando el Data Base de la UNAM (1997–2012), con una aplicación retrospectiva enfocando a prever erupciones mayores (columnas eruptivas >8 km) durante el período abril-junio 2013.
(ii) una aplicación basada en el ejercicio de simulacro en el Cotopaxi; en este caso se probó con BET_UNREST de manera retrospectiva, pero, esta vez, usando los datos inventados previstos durante el simulacro, junto a datos de input basado en la historia real del volcán preparados antes del simulacro. Ofrecimos la previsión de erupciones magmáticas resultantes del simulacro mismo.
(iii) el simulacro en casi tiempo-real organizado en el marco de VUELCO en Dominica (mayo 2015). El sistema volcánico de Dominica es “proto-tipo” para BET_UNREST debido a su carácter hidrotermal. Actividad freática/freatomagmática ocurrió durante el simulacro, cuando este resultado fue de hecho bastante probable según BET_UNREST (la probabilidad media de unrest hidrotermal fue de 0.73, mientras la probabilidad media de una erupción hidrotermal fue de 0.32). También comprobamos el uso de la probabilidad espacial, mediante mapas diferentes, de donde la apertura de una boca eruptiva es más probable, en el caso de erupciones magmáticas y freáticas.

. Con estos ejercicios, creemos arduamente de haber llevado BET un paso más cerca hacia una implementación completa en situaciones de crisis. Al final, BET_UNREST funcionó como se esperaba. Sin embargo, es importante de ser consiente de algunos puntos críticos que han salido de estas aplicaciones, para lograr más pruebas que pueden mejorar su “diseño” y comprobar su utilidad en casos reales en el futuro. BET_UNREST se introdujo junto a su implementación software PyBetUnrest con el objetivo de crear un instrumento de facil-uso, libre y diretto acceso (disponible a breve en el sitio web Vhub) para ayudar en la previsión de amenaza volcánica a corto-plazo.

Keywords (separated by '-') Volcanic unrest - Forecasting - Hydrothermal - Magmatic - Bayesian inference

Palabras clave (separated by '-') Unrest volcánico - Previsión - Hidrotermal - Magmático - Inferencia Bayesiana

The Need to Quantify Hazard Related to Non-magmatic Unrest: From BET_EF to BET_UNREST

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Abstract

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Keywords
Volcanic unrest · Forecasting · Hydrothermal · Magmatic · Bayesian inference

Palabras clave
Unrest volcánico · Previsión · Hidrotermal · Magmático · Inferencia Bayesiana

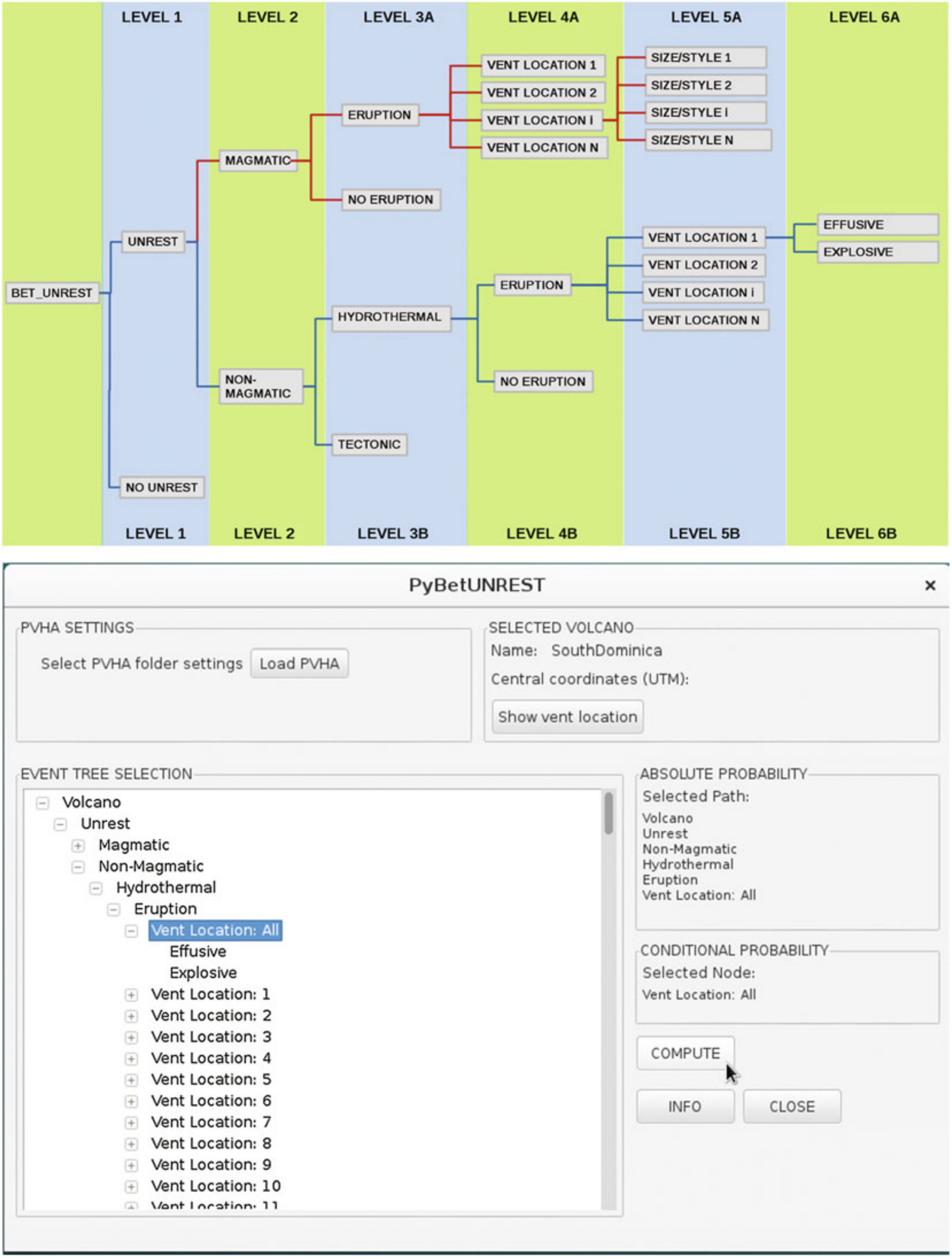
1 Introduction

Monitoring activities represent the main source of information to understand the behaviour of volcanic systems on short time-scales and, possibly, during emergency crises. In this framework, one of the main challenges of volcano monitoring is the identification and characterisation of the phase defined as “unrest”, which consists of a relevant physical or chemical change in the volcanic system with respect to its background behaviour, leading to cause for concern. Unrest can be due to several factors and depends on the local characteristics of each volcanic system, making it very difficult to find general features or patterns (Phillipson et al. 2013). Unrest may be followed by volcanic eruptions due to the movement of magma, but can also be associated with other dangerous phenomena: indeed, in addition to magma-related hazards (e.g., tephra fallout, lava flows, ballistics), hydrothermal and tectonic activities, without evidence for “magma-on-the-move”, can also lead to dangerous outcomes (i.e., flank collapses, gas emissions, phreatic explosions, lahars). Such hazardous events related to non-magmatic unrest are not easy to track and, in volcanic hazard evaluations, are sometimes underestimated (Rouwet et al. 2014). For instance, many volcanoes pass through a phase of hydrothermal unrest for years, decades or even centuries. Due to this long-term behavioural similarity, it is often difficult to recognise how hydrothermal unrest can lead to related hazards in the short-term. Where the driving agent and the main eruptive product is not magma, but water (liquid or vapour) and occasionally liquid sulphur, or gas, this type of unrest can lead to non-magmatic eruptions. On the other hand, non-eruptive hydrothermal unrest can also promote volcanic hazards after prolonged gas emissions, acidic fluid infiltration into aquifers, soils and the hydrologic network, or deformation induced by a rising fluid front (see Rouwet et al. 2014).

In this light, although most volcanic hazard assessments focus only on magmatic eruptions as potential hazard sources, hazardous events can also occur during non-magmatic unrest, which in this chapter is defined as a state of volcanic unrest in which no migration of magma is recognised. Examples of non-magmatic unrest include the tectonic (which causes concern independently on how it evolves and eventually ends), and hydrothermal unrest types; the latter may eventually lead to phreatic eruptions. Recent occurrences of phreatic eruptions (e.g. Ontake eruption, September 2014, Japan) have demonstrated that they are still very hard to anticipate from classical observations based on seismic-geodetic-geochemical monitoring architectures. For these reasons, it is of paramount importance to identify indicators that define the state of non-magmatic unrest. Often, this type of unrest is driven by "fluids-on-the-move", requiring alternative and innovative monitoring setups, beyond the classical ones.

In the last decade it has become crucial to provide forecasts of the possible outcomes of volcanic unrest, to give quantitative support and scientific advice to decision makers (e.g., Woo 2008; Marzocchi and Woo 2007, 2009). Because of this, event tree schemes have been proposed (e.g., Newhall and Hoblitt 2002; Marzocchi et al. 2004), and a few probabilistic tools based on event trees and Bayesian inference have been developed (e.g., BET_EF, Marzocchi et al. 2008; HASSET, Sobradelo et al. 2013) with the ability to quantify the probability of different possible outcomes related to magmatic unrest. However, the need for recognising and tracking the evolution of *any* type of volcanic unrest, and to quantify the probability linked to non-magmatic unrest as well, have led us, within the VUELCO project, to the development of a new probabilistic model, able to forecast both magmatic and non-magmatic hazardous events related to volcanic unrest: BET_UNREST. The BET_UNREST model is based on an event tree, whose structure is extended with respect to the previous schemes such as BET_EF (see the generalisation from BET_EF to BET_UNREST in Fig. 1, highlighted in red) by adding a specific branch to detail the track and outcome of non-magmatic unrest. Nonetheless, BET_UNREST adopts from BET_EF the Bayesian inferential paradigm and the ability to account both for long-term data (typically from the geological record) and short-term information from monitoring networks.

In this chapter, we briefly present the BET_UNREST model and its implementation in the PyBetUnrest software tool (Tonini et al. 2016), made with the aim of providing a user-friendly, open-access, and straightforward tool to handle probabilistic forecasts and visualise results, and that has already been included on the Vhub platform (https://vhub.org/resources/betunrest). The new event tree and tool are applied here as illustrative examples to the VUELCO target volcanoes Popocatépetl (Mexico), Cotopaxi (Ecuador) and Dominica (West Indies).



Name: SouthDominica

- Volcano
  - Unrest
    - Magmatic
    - Non-Magmatic
      - Hydrothermal
        - Eruption
          - Vent Location: All
            - Effusive
            - Explosive
          - Vent Location: 1
          - Vent Location: 2
          - Vent Location: 3
          - Vent Location: 4
          - Vent Location: 5
          - Vent Location: 6
          - Vent Location: 7
          - Vent Location: 8
          - Vent Location: 9
          - Vent Location: 10
          - Vent Location: 11

Selected Path:
Volcano
Unrest
Non-Magmatic
Hydrothermal
Eruption
Vent Location: All

Selected Node:
Vent Location: All

Fig. 1 The new event tree as defined for the BET_UNREST model (*on top*) and its visual implementation in the software PyBetUnrest (*on bottom*). The *red branch* corresponds to the previous BET_EF model

2 BET_UNREST Model and PyBetUnrest Tool

As with all the previous BET models (e.g., BET_EF, for short- and long-term eruption forecasting, Marzocchi et al. 2008; BET_VH, for long-term volcanic hazard associated to any potential hazardous phenomenon accompanying an eruption, Marzocchi et al. 2010; Tonini et al. 2015; BET_VHst, a model that merges the previous two, Selva et al. 2014), BET_UNREST performs probabilistic assessments in the frame of volcanic hazard analysis, based on an event tree scheme. The main novelty in the BET_UNREST event tree is the introduction, with respect to the BET_EF tree, of a new branch (Fig. 1) for exploring and forecasting the outcomes of *non-magmatic* unrest (Rouwet et al. 2014). Due to the resemblance of BET_UNREST to other BET models from a methodological and computational point of view, here we will only give a brief overview. The papers by Marzocchi et al. (2004, 2008) provide a more detailed description.

BET_UNREST probabilities are evaluated by a Bayesian inferential procedure, in order to quantify both the aleatory and epistemic uncertainty characterising the impact of volcanic eruptions in terms of eruption forecasting and/or hazard assessment. Such a procedure allows merging all the available information, such as models, a priori beliefs, past data from volcanic records and, when available, real-time monitoring data in order to include, in principle, all the knowledge about the considered volcanic system.

In general, the Bayesian inference procedure at the basis of BET_UNREST assigns a probability to each node, providing a framework where:

- probabilities are expressed through a probability density function (pdf), and not as a single number, to account for a best-evaluation value (for example the mean of the probability density function, representing a degree of aleatory uncertainty) and for a measure of the epistemic uncertainty (the dispersion of the pdf);
- the posterior pdf, at each node, is achieved by statistically combining, through Bayes' theorem, a prior probability distribution (usually coming from theoretical models and/or expert judgement) and information from the available data relevant for that node.

As in BET_EF, the probability $[\theta_k]$ at each node k is actually described by a statistical mixing of two pdfs, describing respectively the "so-called" long-term $[\theta_k^{\{\bar{M}\}}]$ and short-term $[\theta_k^{\{M\}}]$ regimes of the volcano as follows:

$$[\theta_k] = \gamma_k[\theta_k^{\{M\}}] + (1-\gamma_k)[\theta_k^{\{\bar{M}\}}]$$

where γ_k represents the weight in the interval [0,1] depending on the degree of unrest (Marzocchi et al. 2008). With such mixing, BET_UNREST switches between the two "regimes". In practice:

- When anomalies with respect to the volcano's background activity are not observed at time $t = t_0$, BET_UNREST relies on the so-called long-term information to assign the probabilities (hereinafter also referred to as background probabilities) at the various branches. Such background probabilities (i.e., $[\theta_k^{\{\bar{M}\}}]$) are based on theoretical models and information from the geological and eruptive record of the volcano studied, or of similar volcanoes, and describe the long-term frequencies of magmatic or non-magmatic unrest, and subsequent outcomes at these volcanic systems.
- When a clear state of unrest of whatever nature is detected at $t = t_0$ by BET_UNREST, the probabilistic assignment at all the successive nodes is based mainly on the monitoring information. In practice, monitoring data are transformed into subjective pdfs (i.e., $[\theta_k^{\{M\}}]$) relative to the occurrence of magmatic or non-magmatic unrest and the following branches. Actually, at some nodes, monitoring data are not considered as relevant (for example, in forecasting the size of an eruption, magmatic or not), and here BET_UNREST

continues to rely on theoretical models and long-term frequencies.

- When, at time $t = t_0$, BET_UNREST observes a “degree of unrest” (of whatever nature) without it being completely clear, the statistical mixing provides a resulting pdf which accounts for both the regimes, giving the short-term regime a weight equal to the degree of unrest, and to the long-term regime its complement.

In this way, during a phase of unrest, the past data have less (null, in the case of complete unrest) importance. The short term hazard/eruption forecasting depends exclusively on the translation of observed anomalies into pdfs describing all the branches of the event tree. This is done, separately at each node, by weighting monitoring data through pre-defined thresholds of anomaly (Marzocchi et al. 2008) and converting the resulting “degree of anomaly” into a best-evaluation probability, to which a degree of variance is associated (Fig. 2). This is a very simple and intuitive procedure, in which the basic assumptions are:

1. the first anomaly detected is the most informative
2. subsequent anomalies contribute less and less to the increase of the degree of anomaly
3. strong non-linear coupling among anomalies are neglected.

At each node, BET_UNREST evaluates the following probabilities (see also Fig. 1) by means of Bayesian inference (we give the acronyms used throughout the chapter to indicate the probability at each node in brackets):

- *Unrest*: probability ($P(U)$) of unrest in the time period $[t_0; t_0 + |]$, given the monitoring observations at time $t = t_0$; the time window | is defined by the user;
- *Magmatic unrest*: probability ($P(MU)$) that the unrest is due to “magma-on-the-move”, given the unrest;
- *Magmatic eruption*: probability ($P(MEr)$) of a magmatic eruption, given magmatic unrest; the following sub-branches mirror the BET_EF structure, so we point the reader to Marzocchi et al. (Marzocchi et al. 2008) for them;
- *Non-magmatic unrest*: this is the complementary of the *Magmatic unrest* branch, so by definition is the probability of non-magmatic unrest, given an unrest;
- *Hydrothermal unrest*: probability ($P(HU)$) of hydrothermal unrest, given a non-magmatic unrest;
- *Tectonic unrest*: this is the complementary of the *Hydrothermal unrest* branch, so it describes the probability ($P(TU)$) of a tectonic unrest, given a non-magmatic unrest;
- *Hydrothermal eruption*: probability ($P(HEr)$) of a hydrothermal eruption, given a hydrothermal unrest;
- *Vent of hydrothermal eruption*: here we explore the spatial probability of vent opening in a hydrothermal eruption, given a hydrothermal eruption occurring; this node is an extension with respect to the event tree proposed in Rouwet et al. (2014);
- *Size of hydrothermal eruption*: probability of an explosive hydrothermal eruption, given a hydrothermal eruption occurring from a specific vent; its complementary branch is the effusive hydrothermal eruption.

In order to keep the structure of BET_UNREST as simple as possible, an effort has been made to maintain, where possible, a dichotomic branching into complementary (i.e., exhaustive and mutually exclusive) events. This is why the *Unrest* node does not branch directly into magmatic, hydrothermal and tectonic, but first it branches into magmatic-or-not. This allows a simplification in the evaluation of short-term probabilities. In particular, with this type of ramification, the user defines which monitoring measurements (plus thresholds and weight) affect the pdf of one of the two branches; the pdf of the complementary branch then comes automatically.

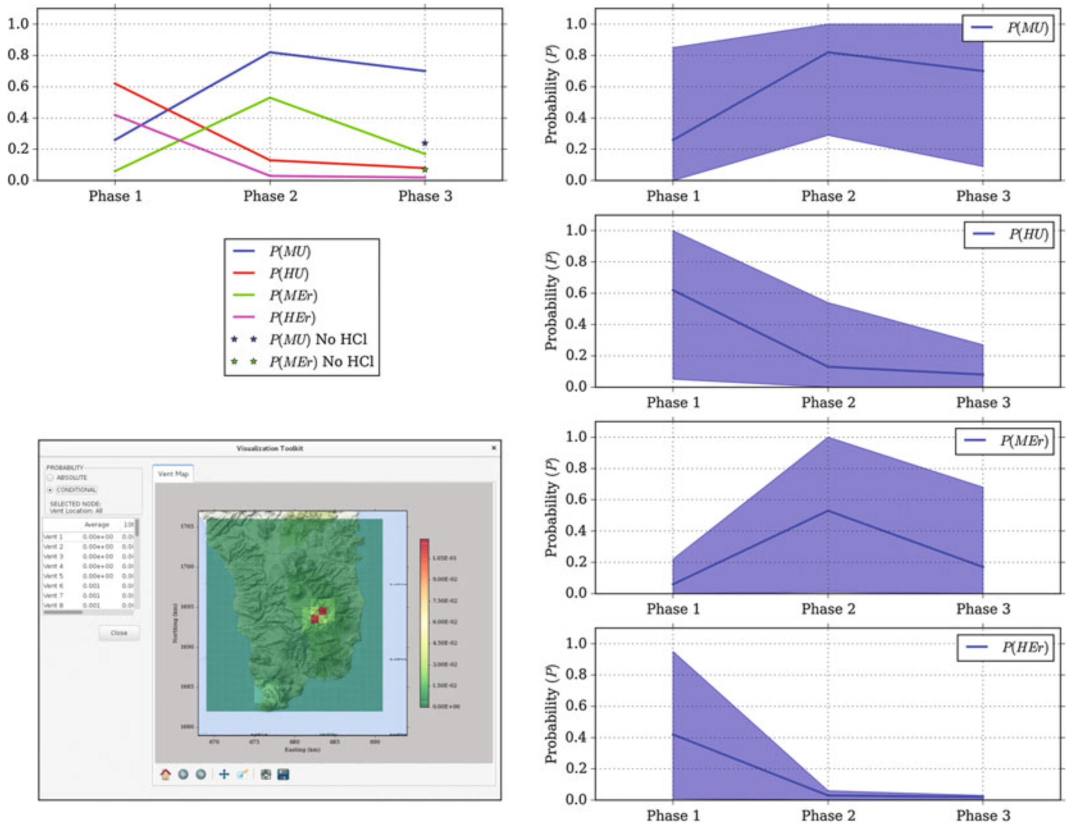


Fig. 2 This figure explains how monitoring measures are transformed into a best-evaluation probability at a given node of the event tree. First, a monitoring measure x_i is translated in a degree of anomaly z_i according to a selected anomaly function $\mu(\cdot)$ (**a**). In the above example, a measure below x_1 is considered background, above x_2 is anomalous, and in between it has a certain degree of anomaly. After collecting the degree of anomaly for all parameters considered at the node, we combine them using a weighted average (ωi is the weight of the i-th parameter) in order to obtain the total degree of anomaly (**b**). Then the total degree of anomaly is transformed into an average probability using a predefined function, in BET_UNREST, we use the function in (**c**). The parameters, weights, and thresholds are selected by the user, possibly through expert opinions' elicitation. Figure modified from (Marzocchi and Bebbington 2012)

The new BET_UNREST model is applied here with its software implementation PyBetUnrest presented in Tonini et al. (2016), which aims to provide an open and usable tool to bridge between the scientific community and decision makers, with a graphical user interface which allows the exploration of the event tree and the visualisation of the results (see Fig. 1). This solution was also implemented in the VHub cyber-infrastructure (http://vhub.org/resources/betunrest). In the present PyBetUnrest tool only one file needs to be adapted when new monitoring information is gathered. This structure makes PyBetUnrest extremely fast and user-friendly during crisis situations. More on the technical background of the BET_UNREST model and PyBetUnrest tool can be found in the VUELCO Deliverable 7.3 (at http://vhub.org) and in Tonini et al. (2016).

So far BET_UNREST and PyBetUnrest have not yet been blindly tested in real-time during an actual volcanic crisis, but only retrospectively (Tonini et al. 2016) at Kawah Ijen (Indonesia), for the time period 2010–2012 (after a learning period based on the observations from 2000 to 2010). The term "blindly" signifies that the rules of BET_UNREST (the long-term pdfs, and the monitoring parameters, thresholds and weight at the different nodes) are set *before* the beginning of the application, on different data (the *learning* dataset), and then the model is applied untouched to new data (the voting dataset), typically covering a different time period (as in the case of Tonini et al. 2016).

In the next section of this chapter, results and performances of the new model and tool will be discussed and validated by analysing the unrest crises for VUELCO target volcanoes Popocatépetl, Cotopaxi and Dominica through blind applications of BET_UNREST. The latter two applications show the results of the VUELCO crisis simulation exercises held in Quito (November 2014) and Dominica (May 2015).

3 BET_UNREST Applications

3.1 Popocatépetl, Mexico: A Retrospective Application Based on the Popo-DataBase

Here we apply the BET_UNREST model to Popocatépetl Volcano (Mexico), based on a catalog of monitored parameters of the 1994-ongoing eruptive period. Popocatépetl volcano awakened in December 1994, after almost 48 years of volcanic quiescence. Since 1994, Popocatépetl volcano has been one of the most active volcanoes in the world, and magmatic activity has been nearly constant. This fact raises the need to first redefine the concept of volcanic unrest for Popocatépetl, as BET_UNREST, at the *Unrest* node, requires indicative parameters to verify if the given volcano is in a state of unrest, or not. In *stricto* sensu, Popocatépetl has remained at least in a state of unrest, or even magmatic or eruptive unrest, since 1994, as its common manifestations are dome growth and vulcanian eruptive phases. The continuous state of unrest is reflected by the decision to never decrease the level of alert from orange to green (traffic light, De la Cruz-Reyna and Tilling 2008). Nevertheless, many of these eruptions are of no cause of concern (so, no unrest in *lato* sensu), neither for volcanologists nor for population. On the other hand, a practical scope of the BET_UNREST application at Popocatépetl is to forecast *major* eruptions, which can be considered a deviation from its current background activity. During the past 23,000 years, nine Plinian eruptions occurred at Popocatépetl (Mendoza-Rosas and De la Cruz-Reyna 2008), while, since 1994, three eruptions with an eruption column >8 km have occurred. No Plinian eruptions have occurred during the 1994-ongoing eruption cycle, and thus none of the past Plinian eruptions have been monitored. For practical purposes, we thus define a *major* eruption for Popocatépetl as an eruption *with an eruption column >8 km*, as they are recorded during the current monitoring period. These eruptions have caused ash fall in the Puebla-Mexico City metropolitan area, thus having an impact on human activity. We aim at finding precursory signals for major eruptions (>8 km, VEI 3) for the period 1997–2012 (the learning period), and test the BET_UNREST retrospectively, using monitoring data of the volcanic activity observed during 2013 (the voting period). The time window, |, is defined as 1 month.

In Table 1 we report the activity carried out 24/7 with regards to monitoring at Popocatépetl, available as short-term information for unrest, origin of unrest and eruption. However, for the time period 1994–2012, the available data (as listed in Mendoza-Rosas, *VUELCO deliverable 5.1*), are restricted mainly to seismicity (VT, tremor, number of events) and visual observations (i.e. number of eruptions, column height). No real-time SO_2 flux is available for our purpose, and deformation data would need further processing. Regarding past data (long-term information for unrest, origin of unrest, and eruption), there have been 13 unrest episodes, and constant unrest since December 1994 (so, a priori probability to be in a state of unrest for the next month is about 85%). Out of the 13 unrest episodes, 6 were due to magma-on-the-move (magmatic unrest), of which 3 lead into a

Table 1 Activity carried out 24/7 as regards monitoring at Popocatépetl

Observations	4 cameras for visual observations
	5 three-component seismic stations
	5 BB seismic stations
	1 video camera + microwaves
	1 doppler radar
	3 biaxial inclinometers
	Geochemical observations (3 sites)
Routine actions	Automatic alarm for anomalies in seismicity
	Cell phone messages to personnel
	Comité Técnico Cientifico Asesor UNAM/CENAPRED
	Reports by SMS to population

magmatic *major* eruption. The monitoring parameters listed in Table 2, along with respective thresholds and weight, have been identified in the UNAM (Universidad Nacional Autónoma de México) database for the period 1997–2012, and used to set BET_UNREST for Popocatépetl. The volcano is a stratocone with a higher probability of an eruption to occur from the central vent. For the period of observation (1997–2012) all eruptions were magmatic and occurred at the central crater. The a priori spatial distribution of vent opening is assigned as in Table 3. As a prior model to define the size/style of magmatic eruptions we take the power law from Simkin and Siebert (1994). As past data we take the Mendoza-Rosas and De la Cruz-Reyna (2008) catalog for the past 23,000 years, and assume it to be complete for VEI >= 2 (Table 3).

We retrospectively applied BET_UNREST for the voting period April–June 2013, in which respectively 10, 11 and 2 eruptions of 2, 3 and 4 km-high columns were observed. No *major* eruption occurred. Observed anomalies include ash eruptions up to 130/day (all with columns <4 km), seismic tremor, incandescence in the crater/dome, and VT events (but no shallow event with depth <5 km). There was no anomalous deformation, no dome growth, and no SO_2 data available. Results of $P(MEr)$ for the retrospective application period (weekly updated) are

Table 2 Monitoring parameters set for BET_UNREST at Popocatépetl

	Parameters
Unrest	– # exhalations with ash (<4 km) > 20/day – Tremor Y/N – Increase VT Y/N
Magmatic unrest	– Incandescence dome Y/N, weight 2 – Duration tremor >6000 s, weight 1 – SO_2 >2000 t/d, weight 1
Magmatic eruption	– Dome growth Y/N – SO_2 >9000 t/d – Tectonic EQ > M5.5 (along the coast/arc Michoacán-Chiapas) Y/N – Incandescent debris Y/N – Change in # tremor Y/N – VT depth <5 km – Increase # VT >M2 Y/N – Duration tremor >30,000 s (inertia 2 months) Y/N – Increase # ash eruptions >2000–4000 (inertia 2 months) – Deformation Y/N

Table 3 *Left Part:* Spatial probability of vent opening for magmatic eruptions assigned for BET_UNREST at Popocatépetl: best guess a priori values. No past data are used. *Right Part:* Parameters of the magmatic eruption size distribution assigned for BET_UNREST at Popocatépetl: best guess a priori values and past data

Spatial probability of vent opening in magmatic eruptions		Size of magmatic eruption		
Vent location	A priori probability (best guess values; equivalent number of data = 1)	Size	A priori (best guess values; equivalent number of data = 1)	Past data
Central vent	0.99	VEI 1	0.83	975
North flank	0.0025	VEI 2	0.14	13
East flank	0.0025	VEI 3	0.023	3
South flank	0.0025	VEI 4	0.0038	7
West flank	0.0025	VEI $\geq$ 5	0.0008	2

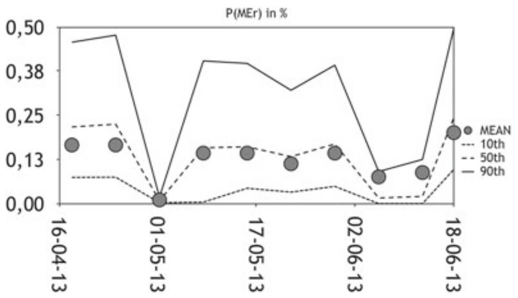


Fig. 3 Time history of probability (expressed in percentage) to have a magmatic eruption in the retrospective analysis at Popocatépetl

presented in Fig. 3. For the whole period, *P* (*MEr*) of a *major* eruption (>8 km eruption column) was <1% per month.

3.2 Cotopaxi, Ecuador: Retrospective Application Inspired by the VUELCO Simulation Exercise in Quito

A volcanic unrest simulation exercise for Cotopaxi volcano (5872 m.a.s.l.) was performed on November 13th, 2014 in Quito, Ecuador. The ice-capped stratovolcano, with an andesitic to rhyolitic composition, is one of the most active and hazardous volcanoes in Ecuador. Historic eruptions at Cotopaxi produced large lithic-rich pyroclastic flows, ash flows, lava flows as well as large lahars (Barberi et al. 1995; Hall and Mothes 2008; Biass and Bonadonna 2011). Some lahars reached the Pacific Ocean at >200 km distance (Aguilera et al. 2004; Pistolesi et al. 2013). Recent unrest periods at Cotopaxi occurred in 1975–1976 and 2001–2002 and were characterised by increased fumarolic activity, elevated seismicity and edifice deformation (Molina et al. 2008). Fumarolic activity is a concern due to the heat transfer that may affect the ice cover resulting in non-eruptive debris flows or lahars.

A still unstable version of PyBetUnrest was set up (along with parameters and thresholds at each node for Cotopaxi volcano derived from monitoring information) before the simulation exercise, based on the available data in the literature up to the beginning of the simulation (the learning period stopped with the beginning of the exercise), in order to preliminarily test its value in decision support by providing near-real time probabilities of (i) the occurrence of unrest, (ii) the origin and nature of unrest and (iii) eruptive activity. However, during the simulation, the reports from the "volcano team" did not reflect the real eruptive and unrest history of Cotopaxi, as the past activity for the simulation was "invented". A different setting of BET_UNREST (and consequently of

PyBetUnrest) on site was not possible due to the lack of time and the still premature customisability of the tool. This obliged us to set up and run the old BET_EF tool during the exercise (Constantinescu et al. 2015). Obviously, this prevented us from providing probabilistic assessment of non-magmatic events during the exercise at Cotopaxi: this would have been possible with BET_UNREST, enabling the calculation of probabilities for hydrothermal unrest and hydrothermal eruptions (*P*(*HU*) and *P*(*HEr*)). Nevertheless, the unrest scenario proposed by the "volcano team" (Bulletins 1–5) did not emphasise a significant state of hydrothermal unrest, which, on the one hand, made our output less biased in not providing an evaluation for *P*(*HU*) and *P*(*HEr*); but on the other hand this simulation was probably not the best case to test BET_UNREST.

Here, we will re-run BET_UNREST and PyBetUnrest at Cotopaxi retrospectively for the unrest phases described in the five bulletins provided by the "volcano team" during the simulation exercise and using the BET_UNREST setup prepared prior to the simulation based on the *real* past activity of the volcano (Table 4). The time window | was set to 1 month. In Table 5 we show the probabilities resulting from the run of the code, after each bulletin:

(1) *Phase 0: The background activity of Cotopaxi (NO anomalies)*: results are based on the past activity of Cotopaxi, with all observation within background limits.
(2) *Phase 1 (Bulletin 1)*: the observed anomalies in this phase were limited to an increase in seismic activity compared to background level. Such an increased is indicative, according to pre-set parameters, of magma-on-the-move (*P*(*MU*) = 0.68). The considerable uncertainty is summarised by the 10th to 90th percentiles confidence interval.
(3) *Phase 2 (Bulletin 2)*: the observed anomalies in this phase were: a drastic increase in seismicity, an increase in SO_2 emission (5 times background levels), and a crater thermal anomaly. As a consequence, the mean *P* (*MU*) increases, along with a decrease in the associated uncertainty.
(4) *Phase 3 (Bulletin 3)*: the observed anomalies in this phase were: an increase in VT and LP events, occurrence of tremor, appearance of new fumaroles, an increase in SO_2 emission, and an increase in the crater thermal anomaly. As a consequence, the *P*(*MU*) is similar to Bulletin 2, but the *P*(*HU*) increases slightly, due to the new fumaroles.
(5) *Phases 4 and 5 (Bulletins 4 and 5)*: the observed anomalies in these phases were similar, and included: intense fumarolic activity, occurrence of hybrid seismic events, an increase in SO_2 emission, and an increase in the crater thermal anomaly. As a consequence, *P*(*MEr*) increases from 0.21 (phase 3) to 0.57, combined with a lower uncertainty.

3.3 Dominica, West Indies, Lesser Antilles: VUELCO Simulation Exercise, Dominica, May 2015

Dominica is characterised by hydrothermal activity manifested as thermal springs (up to boiling temperature), boiling-temperature fumarolic emissions (e.g. Valley of Desolation) and a crater lake, known as 'Boiling Lake', with a particular hydrodynamic behaviour (Fournier et al. 2009; Joseph et al. 2011; Rouwet et al. 2017). No high-temperature manifestations occur on the island, so no clear evidence of active magmatic degassing exists at the present time.

The simulation exercise, and consequently the BET_UNREST application, for the VUELCO target island of Dominica mainly focused on an unrest scenario for the southern part of the island. The purpose of the exercise was to test the tracking/assessment of an unrest period, and the decision making process undertaken by the scientific advisory group and local authorities.

Due to the hydrothermal character of Dominica, the application of BET_UNREST is

Table 4 Monitoring parameters set for BET_UNREST at Cotopaxi

Node-parameter#	Parameter and threshold(s) (Y/N indicates a Boolean observation)
Unrest-parameter 1	LP/month (205–335) (Garcia-Aristazabal 2010)
Unrest-parameter 2	VT/month (24–32) (Garcia-Aristazabal 2010)
Unrest-parameter 3	M Tectonic EQ (3–4)
Unrest-parameter 4	SO_2 (Y/N)
Magmatic unrest-parameter 1	EQ depth (>4.5–5.5 km)
Magmatic unrest-parameter 2	Deep VLP (Y/N)
Magmatic unrest-parameter 3	T fumarole (>119 °C)
Magmatic unrest-parameter 4	Appearance of acidic gas (Y/N)
Magmatic unrest-parameter 5	VT/month (>32)
Magmatic unrest-parameter 6	Increased deformation (Y/N)
Magmatic unrest-parameter 7	VLP + LP together (Y/N)
Magmatic unrest-parameter 8	Harmonic LP tremor (Y/N)
Magmatic unrest-parameter 9	SO_2 flux (t/d) (>100–350)
Magmatic eruption-parameter 1	sudden stop (Y/N)
Magmatic eruption-parameter 2	SO_2 flux (t/d) (>2000–2500)
Magmatic eruption-parameter 3	Tornillos (Y/N)
Hydrothermal unrest-parameter 1	New fumarole (Y/N)
Hydrothermal unrest-parameter 2	Anomalous glacier volume decrease (defrosting) (Y/N)
Hydrothermal unrest-parameter 3	LP/month (>205–335) (Garcia-Aristazabal 2010)
Hydrothermal eruption-parameter 1	Increase in T of fumarole (>120–200 °C)
Hydrothermal eruption-parameter 2	Increase in extension of fumarolic field (Y/N)
Hydrothermal eruption-parameter 3	Inflation of fumarolic field (Y/N)
Hydrothermal eruption-parameter 4	Landslides in hydrothermal areas (Y/N)
Hydrothermal eruption-parameter 5	New/extension of alteration areas (Y/N)

highly suited. *Before* the simulation exercise, the PyBetUnrest tool was set for Dominica, based on (1) existing literature of the past volcanic activity (2) insights on the current hydrothermal activity (3) discussion-based expert elicitation sessions (4 sessions at SRC and 1 at INGV-Bologna) and (4) exchanges with local experts in order to fine-tune the code with the monitoring parameters. We remark that all of this was done *prior* to the start of the simulation exercise (the learning period stopped at the beginning of the simulation exercise, as for Cotopaxi), and again no hindsight tuning was made. The long-term setup of PyBetUnrest is done by filling up a configuration file that includes the a priori and past data specifically for Dominica, whose main information is summarised in Table 6. The short-term information is listed in Table 7 (parameters and thresholds identified prior to the exercise onset, see above). Further details on the Dominica simulation exercise and on the BET_UNREST application are given in Constantinescu et al. (under review).

During the simulation exercise (May 14–15, 2015) three phases of changes in volcanic activity, each with a duration of six months, were distributed by the “volcano team” to the operators of the unrest crisis. The reports included four

Table 5 Resulting probabilities from retrospective application of BET_UNREST at Cotopaxi

		P(U)	P (MU)	P (MEr)	P(HU)	P (HEr)
Phase 0 (Background)	Mean	0.005	0.002	0.0005	0.001	0.0006
	10th percentile	0.0013	0.0002	0	0	0
	50th percentile	0.004	0.001	0.0002	0.0006	0.0002
	90th percentile	0.009	0.004	0.001	0.003	0.001
Phase 1	Mean	1	0.68	0.18	0.08	0.02
	10th percentile	1	0.07	0	0	0
	50th percentile	1	0.84	0.02	0.001	0
	90th percentile	1	1	0.69	0.30	0.04
Phase 2	Mean	1	0.83	0.22	0.05	0.013
	10th percentile	1	0.27	0	0	0
	50th percentile	1	1	0.04	0	0
	90th percentile	1	1	0.75	0.13	0.008
Phase 3	Mean	1	0.80	0.21	0.13	0.07
	10th percentile	1	0.14	0	0	0
	50th percentile	1	1	0.04	0.002	0.0003
	90th percentile	1	1	0.72	0.54	0.22
Phase 4 and 5	Mean	1	0.81	0.57	0.12	0.07
	10th percentile	1	0.23	0.02	0	0
	50th percentile	1	1	0.65	0.0004	0.0002
	90th percentile	1	1	1	0.49	0.28

types of observations: (1) seismic bulletin, (2) GPS, (3) geothermal monitoring data, and (4) other observations.

The translation of the reported bulletins into the values for the selected parameters in the BET_UNREST for Dominica setup were reported back to the team of experts in real-time during the simulation. In Table 8 we provide the probabilities resulting from the run of the code after each bulletin. In Fig. 4 we also provide the time evolution of some of the most relevant probability distributions, across all the time periods spanned by the simulation exercise in Dominica. For each bulletin, among the output

Table 6 Set up of BET_UNREST at Dominica in terms of long-term information

	A priori mean (equivalent n data in brackets)	Past data
Unrest	0.5 (1)	Past data (successes) = 14 Past data (total) = 608
Magmatic	0.5 (1)	Past data (successes) = 13 past data (total) = 14
Magmatic eruption	0.58 from Phillipson et al. (2013) (1)	Past data (successes) = 0 Past data (total) = 13
Magmatic vent location	file	file
Hydrothermal vent location	file	file
Size distribution (Magmatic)	Dome extrusion: 0.83 Small explosive: 0.14 Large explosive: 0.03 (1)	Dome extrusion: 0 Small explosive: 5 Large explosive: 2

Some of the data are too many to be listed (this is indicated by the label “file” in the table). They can be provided in the form of files on request

Table 7 Monitoring parameters set for BET_UNREST at Dominica

Node–parameter#	Parameter and threshold(s) (Y/N indicates a boolean observation)
Unrest-parameter 1	Increased CO_2 flux above background (Y/N)
Unrest-parameter 2	Increase in T of hot springs and/or fumaroles (Y/N)
Unrest-parameter 3	Changes in H_2O/CO_2 (Y/N)
Unrest-parameter 4	Appearance of new fumaroles and/or hot springs (Y/N)
Unrest-parameter 5	Vegetation die back (Y/N)
Unrest-parameter 6	Appearance of LPs and hybrid EQs (Y/N)
Unrest-parameter 7	Large regional tectonic event (M > 7) (Y/N)
Unrest-parameter 8	Number of VTs [if >10/day for two weeks]
Unrest-parameter 9	Detectable ground deformation (Y/N)
Magmatic unrest-parameter 1	Increase in C/S, or decrease after increase (Y/N)
Magmatic unrest -parameter 2	Detectable SO_2, HCl, HF (Y/N)
Magmatic unrest-parameter 3	Extreme increase in T [>300 °C]
Magmatic unrest-parameter 4	Any VLPs (Y/N)
Magmatic unrest-parameter 5	No. of LPs after significant VT swarms (#/day) (>5–10)
Magmatic unrest-parameter 6	Consistent increase in No. of VTs for 1 month (Y/N)
Magmatic unrest-parameter 7	Deep VTs [>8 km] (#/week) (4–5)
Magmatic unrest-parameter 8	Detectable radial deformation (localized-coherent signal) (Y/N)
Magmatic unrest-parameter 9	Surface deformation (island wide, >6 cm in over 6 months) (Y/N)
Magmatic eruption-parameter 1	Decreasing C/S after increase (Y/N)
Magmatic eruption-parameter 2	Increase in Cl, Br, F content in hot springs/pools (Y/N)
Magmatic eruption-parameter 3	Decrease in H_2O/CO_2 and/or H_2S/SO_2 and/or SO_2/HCl (Y/N)
Magmatic eruption-parameter 4	Phreatic activity (Y/N)
Magmatic eruption-parameter 5	Large thermal anomaly [incandescense] (Y/N)

(continued)

Table 7 (continued)

Node–parameter#	Parameter and threshold(s) (Y/N indicates a boolean observation)
Magmatic eruption-parameter 6	Landslides in hydrothermal areas (Y/N)
Magmatic eruption-parameter 7	Acceleration of VTs, LPs, hybrids [weekly] (Y/N)
Magmatic eruption-parameter 8	Presence of harmonic tremor (Y/N)
Magmatic eruption-parameter 9	Shallowing of VTs hypocenters in the ediffice or shallow depths [<3 km] (Y/N)
Magmatic eruption-parameter 10	Sudden reversal of activity (Y/N)
Hydrothermal unrest-parameter 1	Anomalous behavior of Boiling Lake [overflow, lower or higher T than usual, no return of lake, etc.] (Y/N)
Hydrothermal unrest-parameter 2	Changes in hydrothermal features (Y/N)
Hydrothermal unrest-parameter 3	Increase in B and/or NH_4 concentration in waters (Y/N)
Hydrothermal unrest-parameter 4	Increase in CH_4/CO_2 (fumaroles) (Y/N)
Hydrothermal unrest-parameter 5	Increase in T of fumaroles (Y/N)
Hydrothermal eruption-parameter 1	Increase in T of fumaroles (fuzzy 120–200 °C)
Hydrothermal eruption-parameter 2	riSe of water level in pools/overflow of BL (Y/N)
Hydrothermal eruption-parameter 3	Increase in extension of fumarolic field (Y/N)
Hydrothermal eruption-parameter 4	Muddy pools (Y/N)
Hydrothermal eruption-parameter 5	Boiling/bubbling of pools that previously didn't (Y/N)
Hydrothermal eruption-parameter 6	Inflation of fumarolic field (Y/N)
Hydrothermal eruption-parameter 7	Landslides in hydrothermal areas (Y/N)
Hydrothermal eruption-parameter 8	New/extension of alteration areas (Y/N)

Table 8 Resulting probabilities from real-time application of BET_UNREST at Dominica during VUELCO simulation exercise

		P(U)	P(MU)	P(MEr)	P(HU)	P(HEr)	P(TU)
Phase 1	mean	1	0.26	0.06	0.62	0.42	0.12
	10th percentile	1	0	0	0.05	0.01	0
	50th percentile	1	0.06	0	0.73	0.32	0
	90th percentile	1	0.85	0.22	1	0.95	0.5
Phase 2	mean	1	0.82	0.53	0.13	0.03	0.05
	10th percentile	1	0.29	0.01	0	0	0
	50th percentile	1	1	0.56	0.001	0	0
	90th percentile	1	1	1	0.54	0.06	0.06
Phase 3	mean	1	0.70 (0.24)	0.17 (0.07)	0.08	0.02	0.22
	10th percentile	1	0.09	0	0	0	0
	50th percentile	1	0.87	0.02	0	0	0.08
	90th percentile	1	1	0.68	0.27	0.03	0.80

In bracket estimates of mean values without including HCl anomaly in Phase 3

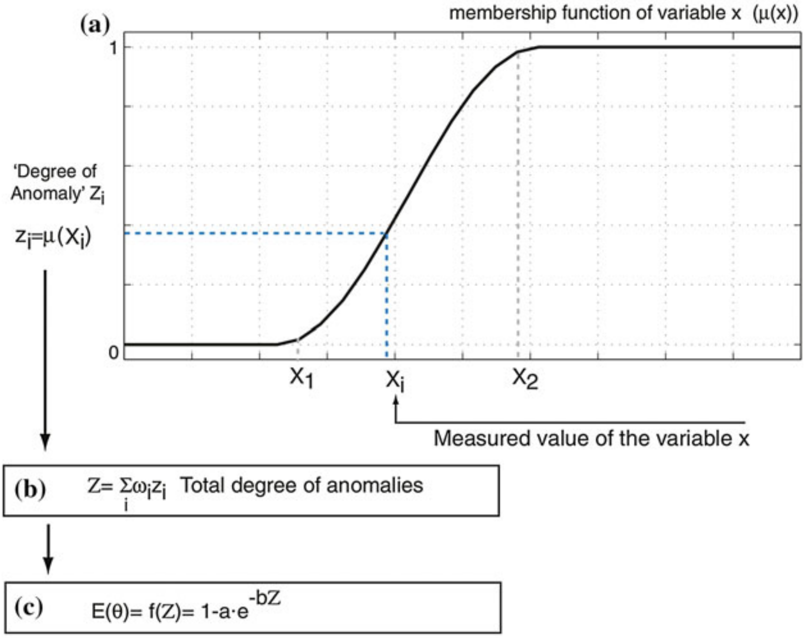


Fig. 4 Average values (*top left*) obtained by BET_UNREST during the three phases of Dominica exercise for $P(MU)$, $P(HU)$, $P(MEr)$ and $P(HEr)$. Asterisk points are the alternative average values for $P(MU)$ *and* $P(MEr)$ without considering HCl as detectable. On the *right column* the same probabilities are shown together with their confidence interval between 10th and 90th percentiles. On *bottom left*, a snapshot of PyBetUnrest tool shows the spatial probability of vent opening during Phase 1, localising the most probable position of the phreatic eruption

information from PyBetUnrest, there were two maps of the spatial probability of vent opening: one for the case of magmatic eruption, and one for hydrothermal eruption (Fig. 4). We believe this could be particularly useful, for example in a volcanic system like Dominica, where there are numerous areas showing hydrothermal activity, thus increasing the uncertainty on the position of a possible phreatic event.

The parameter "detectable SO_2, HCl, HF" created confusion and opened up a scientific discussion. For the sake of transparency, we provide the mean values of $P(MU)$ and $P(MEr)$ including, or not, the HCl anomaly (Table 8). Beyond the scientific implications of this issue, this concern reflected the sensitivity of BET_UNREST to the interpretation of some parameters. When relatively few monitoring parameters are provided, the weight of a single anomaly can be high: this is somehow a measure of the epistemic uncertainty.

4 Discussion and Implications for Unrest Tracking

This chapter presents the need for an updated BET model and tool that is able to account for the non-magmatic nature of some volcanic unrest episodes, which can often go under-estimated, if not totally neglected. The new model (BET_UNREST) and tool (PyBetUnrest) allow the tracking of unrest phases at volcanic systems and enables short-term volcanic forecasts. It has been fully developed within the VUELCO project, during which time it has been applied to some of the project's target volcanoes. In general, when we are able to distinguish magma-on-the-move (Rouwet et al. 2014) from the monitoring observations the new model basically "collapses" to BET_EF (or, better, the assessment of the probabilities related to magmatic outcomes provided by the two models coincide).

On the other hand, if we are not able to identify a magmatic “active role” in the unrest (from the available monitoring observations), BET_UNREST is still able to provide the probabilities of hazardous events that accompany non-magmatic volcanic unrest, rather than neglecting them. As discussed in Rouwet et al. (2014), a very difficult case is presented by phreatomagmatic eruptions that, sometimes, can occur without any precursors indicating magma movement. This is surely an important limit to overcome which requires further efforts to detect subtle changes in the very short-term (hours to minutes) by improving monitoring techniques.

The chapter illustrates the development and implementation of BET_UNREST model and PyBetUnrest tool through three different applications:

(i) the pure retrospective analysis at Popocatépetl volcano, where there is no compelling need for a hydrothermal branch due to the current magmatic nature of the unrest episodes. Popocatépetl has remained in unrest from December 1994 to present and, for this application, BET_UNREST and PyBetUnrest were run using the UNAM Data Base for the learning period 1997–2012, with a retrospective application aiming to forecast major eruptions (column heights greater than 8 km) for the April–June 2013 volcanic activity.

(ii) the application based on a simulation exercise at Cotopaxi. Here we tested the BET_UNREST retrospectively, but, this time, using the invented data provided during the VUELCO simulation exercise, in addition to data based on the real past history of the volcano.

(iii) the almost real-time simulation exercise organised by the VUELCO project in Dominica (May 2015). The volcanic system of Dominica presents a “prototype” setting for BET_UNREST due to its hydrothermal character. Phreatic/phreatomagmatic activity occurred during the simulation, coinciding with high associated probabilities from BET_UNREST (the average values $P(HU) = 0.73$ and $P(HEr) = 0.32$). We also positively tested the feasibility of providing different maps of the spatial probability of vent opening in case of magmatic or phreatic eruption.

As mentioned in previous sections, we implemented the BET_UNREST model into PyBetUnrest software tool using a graphical user interface aiming to provide a fast, open and user-friendly tool, which extends the usage of BET_UNREST to volcanologists with different expertise. The PyBetUnrest tool reached a mature and usable version during the Dominica simulation and its first stable release has been uploaded to Vhub cyber-infrastructure.

With these exercises we strongly believe we have brought BET a step closer to a full and proper implementation during a crisis situation. The PyBetUnrest tool eventually worked as expected, but it is important to take advantage of the lessons learned during these applications and pursue more tests that will improve its design and prove its usefulness in real-case scenarios.

As a final comment, we would like to remark that, as with any other event tree model (e.g. BET models by Marzocchi et al. 2004, 2008, 2010; HASSET model by Sobradelo et al. 2013), one can always apply and “populate” the BET_UNREST model in any “volcanic” circumstance. The uncertainty on the results provided by BET_UNREST, and consequently their practical use, will however be strongly dependent on the available information and data used to set up the models rules. If only a few pieces of evidence are available, the models results will be characterised by a large uncertainty, and thus might be not very helpful for decision-makers. As more and more knowledge is gathered, BET_UNREST output probabilities will become more attractive from a practical point of view, since their uncertainty will be increasingly small. This is an intrinsic feature of the Bayesian inferential procedure at the basis of the model.

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