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Event trees for eruption forecasting at Vesuvius volcano

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Abstract

A probabilistic approach is used to forecast a future eruption at Vesuvius volcano. Such approach, differently from a deterministic one, allows to account for spatial and temporal variability of eruptive style (effusive, explosive), event magnitude (VEI), and environmental impact (dispersion, runout) (Newhall and Hoblitt, 2002; Marzocchi et al., 2004; Neri et al., 2008). This variability is quantified by means of Event Trees and conditional probabilities (Newhall and Hoblitt, 2002). To better constrain uncertainty, different sources of information should be considered and integrated with each other: geological record, historical observations, monitoring activities, results from scenario modelling. The integration of the different data is important to provide a robust characterization of the state of Vesuvius over geological vs. historical times, also in light of its current state as inferred from monitoring data and conceptual models. Different techniques exist to carry out this integration. For Vesuvius, available studies are based on the application of the Bayesian Event Tree (BET) model (Marzocchi et al., 2008; Sandri et al., 2009; Selva et al., 2014), and on the development of an Event Tree informed by expert elicitations (Neri et al., 2008), making possible to set up probabilistic eruption forecasting models both at long- (years) and short-term (hours to days), based on the current vs. past states of the volcano.

1. Introduction

A probabilistic approach is used to forecast a future eruption at Vesuvius volcano. Such approach, differently from a deterministic one, allows to account for spatial and temporal variability of eruptive style (effusive, explosive), event magnitude (VEI), and environmental impact (dispersion, runout) (Newhall and Hoblitt, 2002; Marzocchi et al., 2004; Neri et al., 2008). This variability is quantified by means of Event Trees and conditional probabilities (Newhall and Hoblitt, 2002). To better constrain uncertainty, different sources of information should be considered and integrated with each other: geological record, historical observations, monitoring activities, results from scenario modelling. The integration of the different data is important to provide a robust characterization of the state of Vesuvius over geological vs. historical times, also in light of its current state as inferred from monitoring data and conceptual models. Different techniques exist to carry out this integration. For Vesuvius, available studies are based on the application of the Bayesian Event Tree (BET) model (Marzocchi et al., 2008; Sandri et al., 2009; Selva et al., 2014), and on the development of an Event Tree informed by expert elicitations (Neri et al., 2008), making possible to set up probabilistic eruption forecasting models both at long- (years) and short-term (hours to days), based on the current vs. past states of the volcano.

2. Formulation

The BET approach is adopted to integrate monitoring data, geological and historical data, and modeling of the hazardous phenomena. The approach quantifies conditional probabilities for each pre-determined volcano state, by considering such probabilities as a random variable to model epistemic uncertainty. In other words, conditional probabilities are described by a probability density function with associated aleatoric (intrinsic unpredictability issue) and epistemic (lack-of-knowledge issue) uncertainties. The approach practically goes through fitting probability distributions to the available data and models, including the monitoring ones, toward a long- to short-term eruption forecasting (Marzocchi et al., 2004, 2008, 2010). In general, forecasting an eruption in the long-term mostly requires information from past data and expert elicitations (Marzocchi et al., 2008; Neri et al., 2008).

On the other hand, forecasting a future eruption in the short-term will take advantage from the monitoring informations: in the case of Vesuvius, these are summarized in daily bulletins from the INGV Osservatorio Vesuviano (Marzocchi et al., 2008; Selva et al., 2014). In particular, for each selected parameter from the monitoring network, the corresponding observed value on a given day is compared with its threshold values, with the aim of assigning, in real time, a degree of anomaly that is then translated into the probabilities of a given volcano state.

Such procedure was tested during MESIMEX (Major Emergency SIMulation EXercise), which was a drill carried out in 2006 by the Campania Region Administration and the Italian Civil Protection, with the help of a pool of experts for the scientific aspects of the simulated eruptive scenario. A retrospective analysis of this application is given by Marzocchi et al (2008), while the extension to short-term tephra fall hazard is discussed in detail by Selva et al. (2014).

Forecasting an eruption in the long-term is discussed in detail by Neri et al. (2008), where elicitation of experts is used to formulate an Event Tree that integrates the different sources of information, through the lens of experts' knowledge about historical and geological data, as well as numerical modelling.

3. Eruption forecasting and hazard quantification

In Fig. 1, a complete scheme of the event tree for Vesuvius, from unrest to risk levels, is shown as presented by Marzocchi et al. (2004). Each volcano node (columns) is subdivided in volcano states (rows), the whole scheme having the typical structure of an event tree.

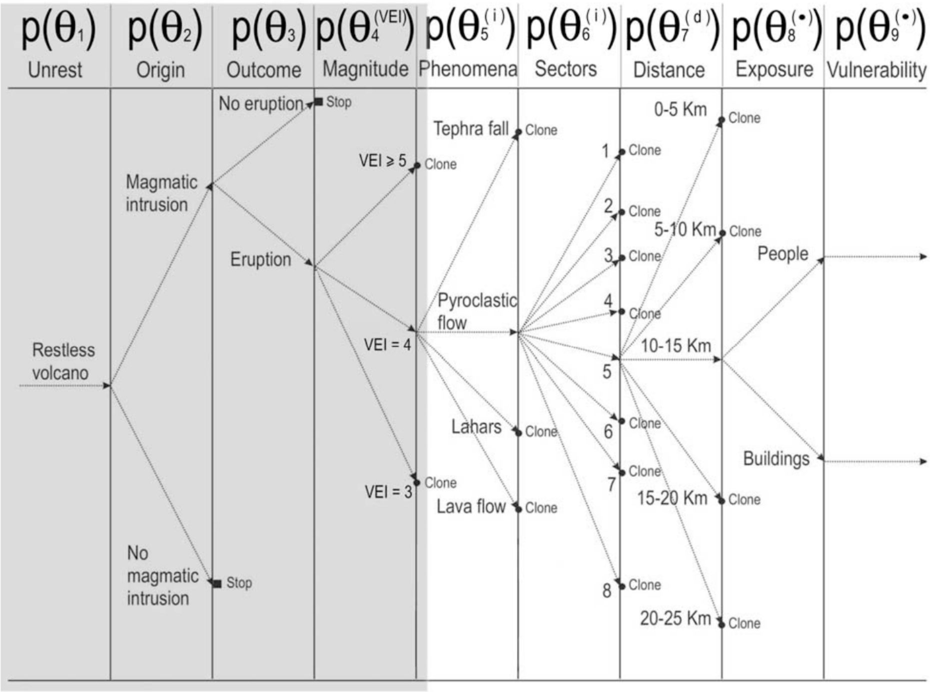

Fig. 1 – General sketch of the event tree for Vesuvius (after Marzocchi et al., 2004).

The probabilities at all nodes are set based on prior models and past data. During unrest episodes, the monitoring measures become more informative about these states. Even if the various volcano states cannot directly be measured neither identified with certainty, they can be forecast with the help of observable parameters from the monitoring network, which are related to seismic, geochemical, and ground deformation observations. In particular for the case of Vesuvius, from

Marzocchi et al (2008), the probability of the unrest level, $p(\theta_1)$, is based on the identification of anomalies of the monitoring parameters, defined as in Tab. 1. The probability of the different origin (magmatic or not) of the unrest, $p(\theta_2)$, is quantified with the anomalies of monitoring parameters as defined in Tab. 2. The probability of eruption, $p(\theta_3)$, is quantified with the anomalies of the monitoring parameters as in Tab. 3.

Parameter	Threshold interval
Monthly number of seismic events with $M_d \geq 1.9$	23 – 150 month^{-1}
Monthly largest duration magnitude of seismic events	3.4 – 4.3 month^{-1}
Monthly number of LF scriptsize events deeper than 1 km	1 – 3 month^{-1}
Presence of significant SO_2	yes/no
Daily CO_2 emission rate	5 – 30 kg m^{-2} day^{-1}
Strain rate	>0 day^{-1}
Temperature of the fumaroles in the crater	98 – 105 °C

Tab. 1 – Monitoring parameters and threshold intervals characterizing the passage from unrest to eruption origin for Vesuvius (after Marzocchi et al., 2008).

Parameter	Threshold interval
Presence of significant SO_2	yes/no
Strain rate	>0 day^{-1}
Average spectral frequency of earthquakes	2.5 – 3.5 Hz
Ratio between average and dispersion of earthquake depths	0.3 – 0.4
Temperature of the fumaroles in the crater	98 – 105 °C

Tab. 2 – Monitoring parameters and threshold intervals characterizing the passage from eruption origin to outcome for Vesuvius (after Marzocchi et al., 2008).

Parameter	Threshold interval
Presence of phreatic explosions	yes/no
Average spectral frequency of earthquakes	2.5 – 3.5 Hz
Ratio between average and dispersion of earthquake depths	0.3 – 0.4
Acceleration of seismic energy release	>0 J^2 day^{-2}
Acceleration of strain	>0 day^{-2}
Cumulative strain since beginning of unrest	10^{-5} – 10^{-4}
Change of the ratios HCl/SO_2 and/or HF/SO_2	yes/no
Sudden reversal of at least one of the above parameters	yes/no

Tab. 3 – Monitoring parameters and threshold intervals characterizing the passage from outcome to eruption magnitude for Vesuvius (after Marzocchi et al., 2008).

The subsequent node of the Event Tree treats the uncertainty on the eruption magnitude through the probability $p(\theta_4)$, which is set from analog volcanoes and past data, since monitoring is not considered informative about this. All the other nodes treat the generation and propagation of the different volcanic phenomena that may generate damages around the volcano. Marzocchi et al. (2008, 2010) introduced a further level to treat the uncertainty on the position of the vent (node 4 in Fig. 2). This probability is set through the localization of the observed monitoring anomalies. Starting from the phenomena node (node 5 in Fig. 1, and node 6 in Fig. 2), the probabilities are evaluated by means of geological data and results from numerical or empirical models, and are expressed in terms of exceedance probability, i.e. the probability to exceed a given intensity measure in the target area of the volcano (Neri et al., 2008; Selva et al., 2014; Tonini et al., 2015). The application of the full procedure for short-term eruption forecasting and volcanic hazard for Vesuvius is discussed in detail by Marzocchi et al. (2008) and Selva et al. (2014), in which the case study of the MESIMEX exercise is developed.

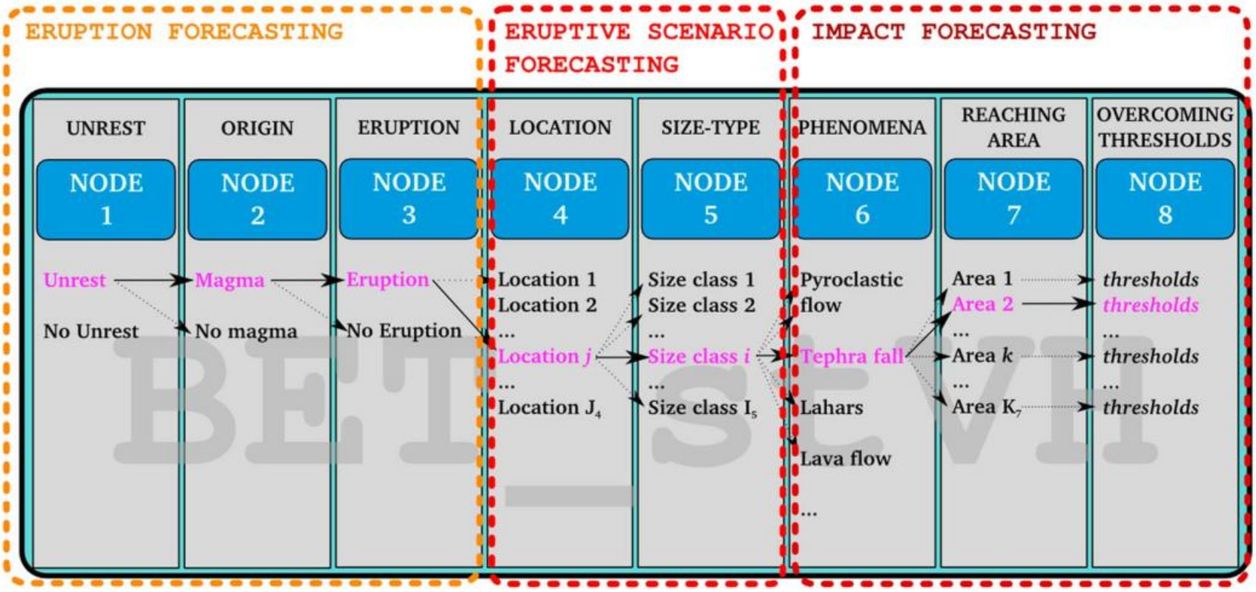

Fig. 2 – Event tree at the base of BET models for eruption forecasting and volcanic hazard (after Selva et al., 2014).

Hazard quantification may also be based on expert elicitation experiments. The application of this technique for Vesuvius, particularly for the long-term hazard assessment, is discussed in detail by Neri et al. (2008). In Fig. 3, the Event Tree developed by Neri et al. (2008) is reported. Elicitation integrates the whole eruption forecasting, in particular by updating historical data, reinterpreting previous geological field data and collecting new ones, and implementing ad hoc simulations from numerical models to further refine the different volcano stages and styles, and associated hazardous phenomena.

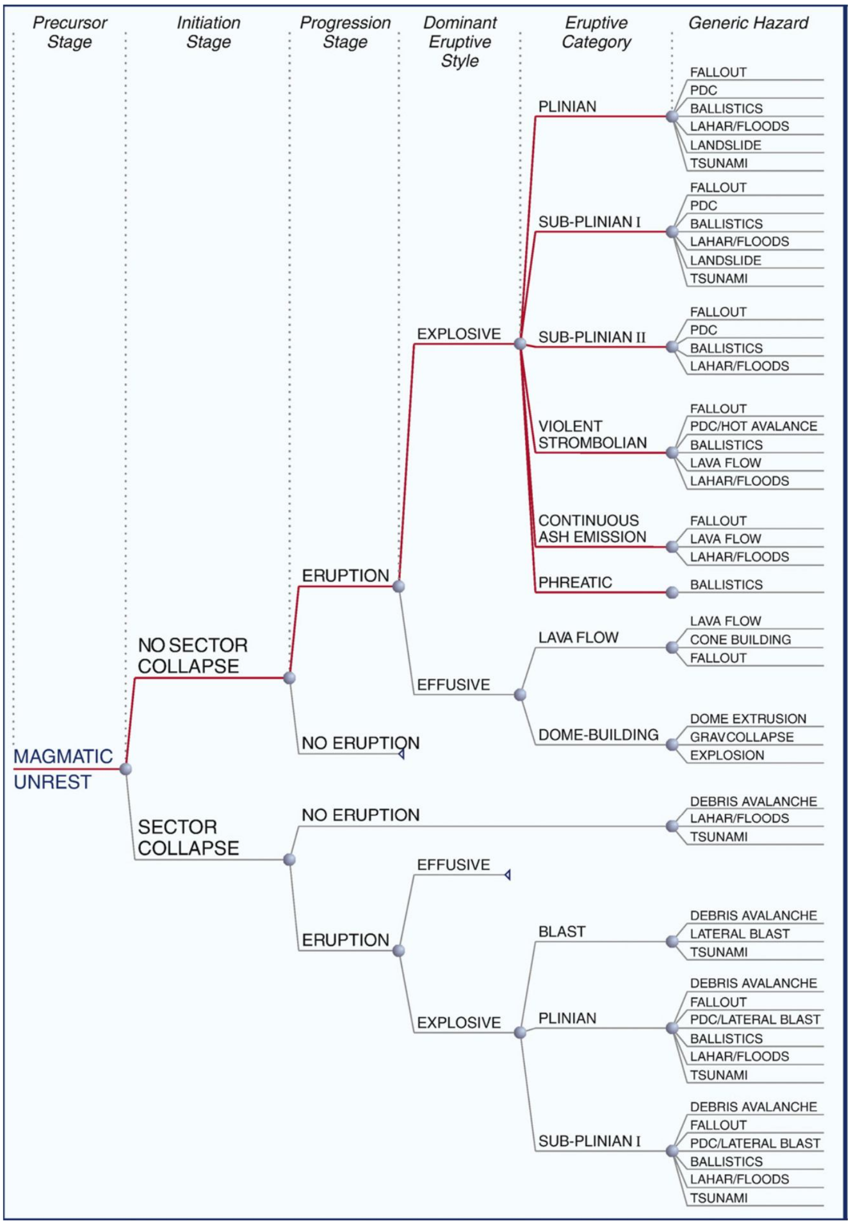

Fig. 3 – Event tree for Vesuvius through expert elicitation procedure (after Neri et al., 2008).

The passage between precursor, initiation and progression stages, and the confluence to dominant eruptive styles and categories, then to associated hazards of the Event Tree (Fig. 3) is usually done by parameterizing probabilities in the EXCALIBUR (Cooke, 1991) framework for the quantification of collective scientific uncertainty. For Vesuvius, a variant to such scheme was adopted, which is called ‘‘constrained optimization weighting’’ (Aspinall, 2006). It consisted of a calibration exercise by means of ten volcanological questions specific for Vesuvius, to set up numerical scores for the experts, where each score represented the empirical performance to making uncertainty evaluations against known parameters. In this way, conditional probabilities from the elicitation results are expressed as 5th, 50th and 95th percentiles. As an example, in Fig. 4 it is reported the exceedance probability relative to different eruption categories of the Event Tree, built on eruptions catalogues for Vesuvius (Neri et al., 2008 and references therein).

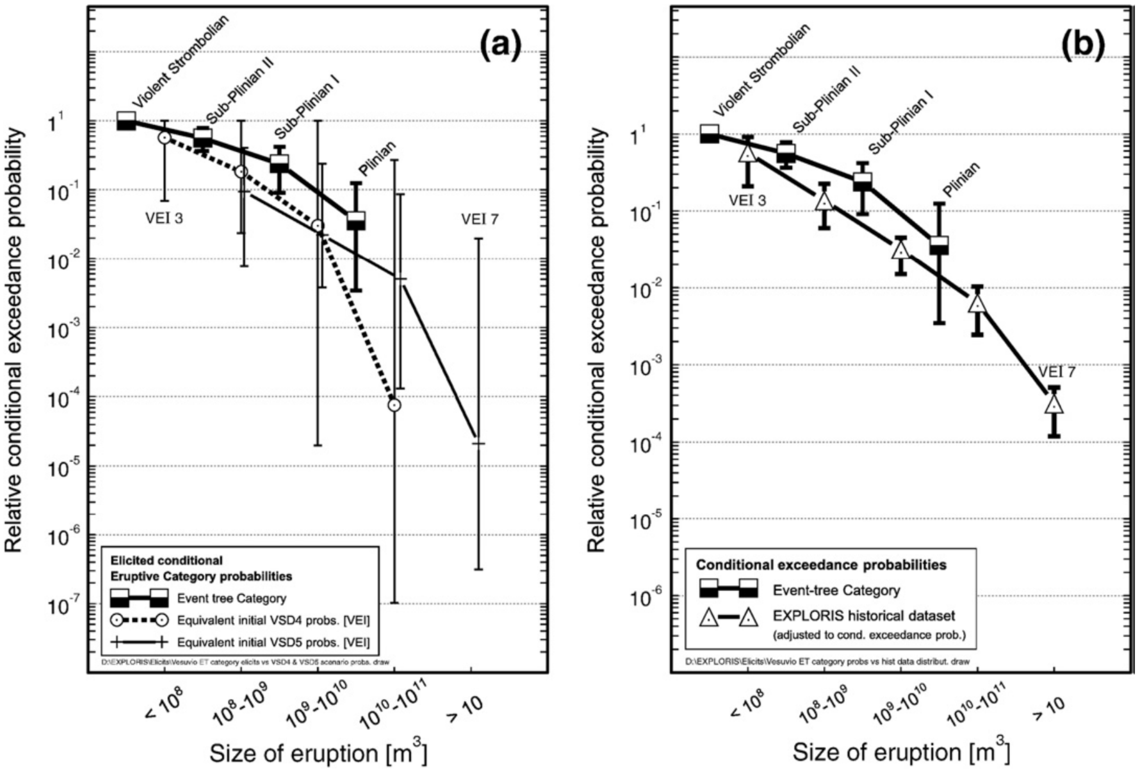

Fig. 4 – Exceedance probability relative to different eruption categories of the Event Tree for Vesuvius (after Neri et al., 2008).

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