Journal of Volcanology and Geothermal Research 178 (2008) 397–415

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Developing an Event Tree for probabilistic hazard and risk assessment at Vesuvius

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ARTICLE INFO

Available online 26 May 2008

Keywords:
Vesuvius
volcanic hazard
volcanic risk
probabilistic risk assessment
Event Tree

ABSTRACT

Probabilistic characterizations of possible future eruptive scenarios at Vesuvius volcano are elaborated and organized within a risk-based framework. In the EXPLORIS project, a wide variety of topics relating to this basic problem have been pursued: updates of historical data, reinterpretation of previous geological field data and the collection of new fieldwork results, the development of novel numerical modelling codes and of risk assessment techniques have all been completed. To achieve coherence, many diverse strands of evidence had to be unified within a formalised structure, and linked together by expert knowledge. For this purpose, a Vesuvius 'Event Tree' (ET) was created to summarise in a numerical-graphical form, at different levels of detail, all the relative likelihoods relating to the genesis and style of eruption, development and nature of volcanic hazards, and the probabilities of occurrence of different volcanic risks in the next eruption crisis. The Event Tree formulation provides a logical pathway connecting generic probabilistic hazard assessment to quantitative risk evaluation. In order to achieve a complete parameterization for this all-inclusive approach, exhaustive hazard and risk models were needed, quantified with comprehensive uncertainty distributions for all factors involved, rather than simple 'best-estimate' or nominal values. Thus, a structured expert elicitation procedure was implemented to complement more traditional data analysis and interpretative approaches. The structure of the Vesuvius Event Tree is presented, and some of the data analysis findings and elicitation outcomes that have provided initial indicative probability distributions to be associated with each of its branches are summarized. The Event Tree extends from initiating volcanic eruption events and hazards right through to human impact and infrastructure consequences, with the complete tree and its parameterisation forming a quantitative synoptic framework for comprehensive hazard evaluation and mapping of risk impacts. The organization of the Event Tree allows easy updating, as and when new information becomes available.

1. Introduction

In recent years the philosophy underpinning volcanic hazard and risk assessment has undergone a notable paradigm shift — a transformation from reliance on simple conceptualizations, that provide an elemental basis for selective deterministic evaluations, to the conviction that full-fledged probabilistic modelling is the most appropriate way to characterize the intrinsic uncertainties associated with volcanic hazards and risks (Woo, 1999; Newhall and Hoblitt, 2002; Sparks and Aspinall, 2004). As part of this shift, consideration has to be given in applied volcanology to important radical probabilistic concepts, such as "quantitative hazard assessment", "treatment of uncertainties", "short- and long-term hazard forecasting", and so on (e.g. Marzocchi et al., 2007).

For Vesuvius, hazard and risk assessments undertaken in the last decade or so were mostly based on the characterization of a single "Maximum Expected Event" (MEE), and this still represents the reference scenario for the current National Emergency Plan (DPC, 1995, 2001). Such an event largely corresponds in terms of expected effects to the hazardous phenomena that occurred during the last sub-Plinian eruption of Vesuvius, in 1631 AD. The definition of a single precautionary scenario, such as this, represented a first important step

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doi:10.1016/j.jvolgeores.2008.05.014

towards the quantification of the volcanic risk at Vesuvius. However, that definition was not based on a fully quantitative analysis of the whole system and its potential range of eruptive activity, and no probabilistic estimates were provided of the likelihood of occurrence of the hazard events being considered. Only recently, Marzocchi et al. (2004), following the Event Tree scheme suggested by Newhall and Hoblitt (2002) and using statistical analyses of records from Vesuvius and analogue volcanoes, sought to quantify the probability of occurrence of selected scenarios (based on Volcanic Explosivity Index, VEI, scale) and to define an initial quantitative version of a Vesuvius Event Tree with specific reference to pre-eruptive branches.

In this context, converting traditional collaborative research efforts into applicable implementations for civil protection, within a full probabilistic approach, entails significant new challenges for field volcanologists, modellers and analysts alike. Thus, the present work seeks to create a suitable generic framework for transcribing complex, and inexact, science into a probabilistic representation suitable for decision-support, and to generate related software for estimating the number (and severity) of casualties in a region at risk around a volcano and the extent and severity of building damage. At the heart of this framework is a quantitative risk model set in a logic-tree structure (Woo, 1999) — within which a wide range of event types, magnitudes and potential outcomes can be considered, each with an associated probability of occurrence.

For the Vesuvius Event Tree described here, a set of pertinent eruptive scenario definitions were decided by expert conferencing, and associated event probability distributions were obtained from formalized expert elicitations. In addition, work was undertaken to quantify hazard time-lines for the different eruption scenarios, using expert elicitation of Vesuvius specialists. This paper also summarises some of the work (Cioni et al., 2008-this issue; Guidoboni, 2008-this issue; Papale and Longo, 2008-this issue; Macedonio et al., 2008-this issue; Esposti Ongaro et al., 2008-this issue; Zuccaro et al., 2008-this issue) and the key inputs that went into designing, configuring and enumerating the Vesuvius ET, and describes the expert elicitation procedure that was the basis for quantifying event probabilities and other variable distributions. Then, some selected provisional outcomes are reported to illustrate the concepts in application. These are presented in terms of: eruption scenario recurrence rate probabilities, in which use is made of historical data for Vesuvius from different datasets and new fieldwork; Event Tree node probability distributions; and event- and hazard time-lines with associated probabilities, elicited for a range of different eruptive scenarios. Lastly, samples of hazard and risk mappings results, derived directly from the Event Tree formulation, are reproduced for illustration.

2. An Event Tree for Vesuvius

Devising the structure of the Event Tree for Vesuvius involved extensive discussions amongst numerous specialists. In due course, an overall framework was agreed which was deemed to capture the full range of possibilities that could be envisaged for the next eruptive episode at the volcano. Due to its relative complexity the Vesuvius Event Tree is best viewed part-by-part (see Fig. 1). The main activity-related element is a generic onset section which comprises three main ‘stages’, starting with an unrest state node, moving through a phase when antecedent sector collapse might be provoked (or not), on to the juncture, critical for decision makers, at which either a subsequent eruption occurs, or fails to occur. The terminology used here diverges from that of Newhall and Hoblitt (2002) and Marzocchi et al. (2004) to reflect the specifics of the current Vesuvius situation: thus, the key initial pre-eruption stages here are captioned *Precursor Stage*, *Initiation Stage*, and *Progression Stage*, but the scope of the present study does not deal specifically with detailed issues of short-term volcanological anomalies and the interpretation of monitoring observations (for that see, e.g., Marzocchi et al., 2004, 2008) rather, the aim is to provide an overall quantitative synoptic framework for comprehensive hazard evaluation and mapping of risk impacts, given the need for forward-looking resilient planning support for the next eruption of Vesuvius, current conditions at the volcano and the state of contemporary scientific knowledge.

If an eruption does ensue, all the main potential possibilities for its character are represented in the next set of branches on the Event Tree – located on Fig. 1 in the column headed *Dominant Eruptive Style* – the alternatives denoting that the episode could have either a main “explosive” eruption style or an “effusive” eruption style. This portion of the main Event Tree continues with further branching, under *Eruptive Category*, which provides partitioning by approximate type of *explosive* activity (i.e. Plinian; Sub-Plinian, and so on, as discussed later on), such as has occurred in the past at Vesuvius, or into “dome-building” or “lava flow” types for the class of eruptions described as *effusive*. It should also be noted that these categories partially reflect also the magnitude and intensity of related activity, although unequivocal relationships cannot be achieved in these terms alone (Cioni et al., 2008-this issue). Associated with these Eruptive Categories are the relevant *Generic Hazards* that might arise in each case.

For the upper portion of the ET, under the title *Eruptive Category,* a coherent set of mutually exclusive volcanological scenarios was defined that represent the potential different eruption behaviours (Cioni et al., 2008-this issue). Six main alternatives were recognized: Plinian (intensity $10^7 \rightarrow 10^8$ kg/s, magnitude $1 \rightarrow 10$ km^3), Sub-Plinian I (intensity 1–8×10^7 kg/s, magnitude $0.1 \rightarrow 1$ km^3), Sub-Plinian II (intensity $10^6 \rightarrow 10^7$ kg/s, magnitude $0.01 \rightarrow 0.1$ km^3), Violent Strombolian (intensity $10^5 \rightarrow 10^6$ kg/s, magnitude $0.001 \rightarrow 0.1$ km^3), Continuous Ash Emission (maximum intensity 10^5 kg/s, magnitude ~ 0.001 km^3) and Phreatic (intensity unknown, magnitude ~ 0.001 km^3). Each eruptive category is generally characterized by a complex sequence of phases, presenting as different styles of activity or phenomena, thus making the VEI scale parameter an incomplete way to characterize individual scenarios (Cioni et al., 2008-this issue). As examples, the Pomici di Base, the Mercato, the Avellino and the AD 79 Pompeii eruptions belong to the Plinian category, the Greenish Pumice, AD 472 and 1631 belong to the Sub-Plinian I category, the AP1, AP2, and AD 512 eruptions to the category Sub-Plinian II, and the 1906 and 1944 eruptions to the Violent Strombolian category (Baxter et al., 2008-this issue; Cioni et al., 2008-this issue). The so-called Continuous Ash Emission eruption type could be associated with long-lived activity at Vesuvius – perhaps lasting months or years – such as is recorded in the deposits of some eruptions of the periods between the Avellino and Pompeii eruptions, and the two Sub-Plinian I events of AD 472 and 1631. In contrast, no stratigraphic record exists of past events characterised by purely phreatic activity. However, the possibility that similar events have occurred in the past at Somma–Vesuvius cannot be precluded; the well-known case of Guadeloupe 1976 is taken to epitomise this category.

A few words of explanation are necessary concerning the categories Sub-Plinian I and Sub-Plinian II. In discussion, as fully described in Cioni et al. (2008-this issue), it was clarified that whereas the dynamics of Plinian and Sub-Plinian I eruptions are very similar (in both cases there is a quasi-steady fallout phase for prolonged time periods followed by a pyroclastic flow phase) and classification differences relate primarily to magnitude of eruption, the dynamics of Sub-Plinian II eruptions are quite distinct and mainly characterized by a series of pulsations of the convective column with no, or only very weak, pyroclastic flow phases. Therefore, Sub-Plinian I and Sub-Plinian II eruptions are identified as separate categories. In addition to the innate differences in magnitude and intensity of these different categories, each can be roughly associated with its own distinct frequency of occurrence (or, average recurrence interval), established on the basis of statistical analysis of the full Vesuvius eruptive record (Cioni et al., 2008-this issue), combined with expert judgement, as more fully discussed in the following sections.

Similarly, the lower portion of the Event Tree focuses on the different eruptive scenarios in the case of a prior *sector collapse* of the volcano. Such a possibility, although quite remote, cannot be ruled