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Case study

ST-HASSET for volcanic hazard assessment: A Python tool for evaluating the evolution of unrest indicators

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ABSTRACT

Short-term hazard assessment is an important part of the volcanic management cycle, above all at the onset of an episode of volcanic agitation (unrest). For this reason, one of the main tasks of modern volcanology is to use monitoring data to identify and analyse precursory signals and so determine where and when an eruption might occur. This work follows from Sobradelo and Martí [Short-term volcanic hazard assessment through Bayesian inference: retrospective application to the Pinatubo 1991 volcanic crisis. Journal of Volcanology and Geothermal Research 290, 111, 2015] who defined the principle for a new methodology for conducting short-term hazard assessment in unrest volcanoes. Using the same case study, the eruption on Pinatubo (15 June 1991), this work introduces a new free Python tool, ST-HASSET, for implementing Sobradelo and Martí (2015) methodology in the time evolution of unrest indicators in the volcanic short-term hazard assessment. Moreover, this tool is designed for complementing long-term hazard assessment with continuous monitoring data when the volcano goes into unrest. It is based on Bayesian inference and transforms different pre-eruptive monitoring parameters into a common probabilistic scale for comparison among unrest episodes from the same volcano or from similar ones. This allows identifying common pre-eruptive behaviours and patterns. ST-HASSET is especially designed to assist experts and decision makers as a crisis unfolds, and allows detecting sudden changes in the activity of a volcano. Therefore, it makes an important contribution to the analysis and interpretation of relevant data for understanding the evolution of volcanic unrest.

1. Introduction

Active volcanoes are thermodynamic systems in which complex sequences of non-linear processes occur. These processes encompass the generation of magma in the source region, its ascent to and differentiation at shallower levels, and finally, the eruption on the Earth's surface. How volcanoes actually prepare to erupt is still not fully understood in detail, even if the general physics that govern such process are already well formulated. For instance, it is widely accepted that volcanic eruptions occur when an over-pressurised batch of magma is able to open a path through the host rock and reach the surface. This movement of over-pressurised magma through the host rock will cause physical and chemical changes in the environment that may be detectable if ground base and/or remote monitoring systems are operating on the volcano. These changes will mainly consist of an increase in seismicity, surface deformation and changes in potential fields (gravity, magnetism, etc.) and in the gas composition of fumaroles and/or groundwater (e.g.: Kilburn, 2003; López et al., 2012; Phillipson et al., 2013; Jousset et al., 2013). Phillipson et al. (2013) define volcanic unrest as "the deviation from the background or baseline behaviour of a volcano towards a behaviour which is cause for concern in the short-term, because it might prelude an eruption". Thus, indicators or precursors are geophysical and geochemical signals that help identify any deviation from the background activity, and provide sufficiently long and robust time series that can be used with a variety of different methodologies to interpret the evolution of a system, and to determine whether or not an eruption is imminent (McNutt, 2000). Efforts to establish monitoring networks are increasingly being made in many areas to gather real-time information about the reawakening of volcanic systems. Most of the historically recorded volcanic eruptions are preceded by an unrest episode of greater or lesser intensity, which thus represents an important eruption precursor (Sandri et al., 2004). However, there are also examples of unrest that wanes after months or even years of restlessness without evolving into a volcanic eruption. Two of the most relevant cases are the volcanic calderas in Long Valley

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(Battaglia et al., 2003) and the Campi Flegrei (Dvorak and Berrino, 1991). Therefore, to be able to forecast a volcanic eruption or to anticipate whether or not a new episode of volcanic unrest will culminate in an eruption, it is essential to understand the causes of unrest indicators and how they may evolve. Moreover, the absolute values and trigger threshold (that is, the values that unleash the chain of events) of these indicators may differ significantly from one volcano to another. Thus, when monitoring information is available, we require a methodology for interpreting indicators if we are to accurately evaluate the volcanic hazard in the short-term.

In general, natural hazard assessment commonly implies two stages. The first one is the long-term analysis that looks at the past behaviour of the system and uses past data to identify possible future scenarios and, ideally, corresponding probabilities of occurrence. It is basically used for territorial planning and to define emergency plans. The second stage is the short-term analysis, a result of combining long-term hazard assessment with real-time monitoring data to update the status of the imminent hazard. In volcanology, we also use long- and short-term hazard analyses. The long-term hazard assessments is conducted using quantitative analysis of past volcanic activity (geological mapping, structural and petrologic studies) and a determination of the physical volcanological parameters of past eruptions, while the short-term incorporates current monitoring data in order to forecast where and when the eruption may take place and to define the most likely eruptive scenarios. It is also one of the stages in the volcanic management cycle that contributes to minimising risk (Fig. 1). A common procedure in both long- and short-term hazard assessment is to use an event tree structure based on a Bayesian approach (Newhall and Hoblitt, 2002; Aspinall, 2006; Marzocchi et al., 2004, 2010; Martí et al., 2008; Neri et al., 2008; Sobradelo and Martí, 2010, 2015). Essentially, this method aims to highlight all possible relevant outcomes of volcanic unrest at progressively greater degrees of detail, and to assess the implied hazard of each scenario by estimating its probability of occurrence within a future time interval. Each node of the event tree represents a step and contains a set of possible branches (the outcomes for that particular category). The nodes represent alternative steps from a general prior event, state or condition that progress through increasingly specific subsequent events to the final outcomes.

In the case of the long-term hazard assessment, the attention is focused on identifying all possible eruptive scenarios (and potential unrest episodes) that could occur in the future, and estimate the probability of occurrence of each and all of these possibilities. To achieve this, we use geological and historical records on past activity, existing models and expert knowledge of the volcanic system. One of available tools is HASSET (Hazard ASSessment Event Tree, Sobradelo et al., 2014) that uses the event tree structure to make estimations based on Bayesian Inference. The advantage of HASSET, when compared with existing similar tools (e.g. BET, Marzocchi et al., 2008), is that HASSET accounts for the possibility of (i) flank eruptions (as opposed to only central eruptions), (ii) geothermal or tectonic unrest (as opposed to only magmatic unrest), (iii) felsic or mafic lava composition (or the absence of composition data), as well as (iv) certain volcanic hazards, as possible outputs of an eruption, as well as (v) the location of the hazard. The main goal of HASSET is to focus discussion and draw attention to possible scenarios that would otherwise remain unnoticed or be underestimated. This tool has been successfully applied in different volcanic areas for long-term hazard assessment (see Becerril et al. (2014); Bartolini et al. (2014)). However, HASSET did not incorporate monitoring data, and the evaluation of the uncertainties surrounding unrest indicators (short-term hazard assessment) needs to be incorporated into long-term hazard assessment, especially during volcanic crises. To overcome the limitation of the previously designed tool, Sobradelo and Martí (2015) defined a new methodology, which merges and translates real-time monitoring measurements on unrest indicators into a common probabilistic scale, so that scientific experts from across different monitoring fields can come together to analyse, to interpret and to foreseen the future behaviour of the system by incorporating all the unrest indicators as a group.

When an active volcano enters in a phase of unrest, its evolution will depend on the causes of the unrest (magmatic, tectonic or

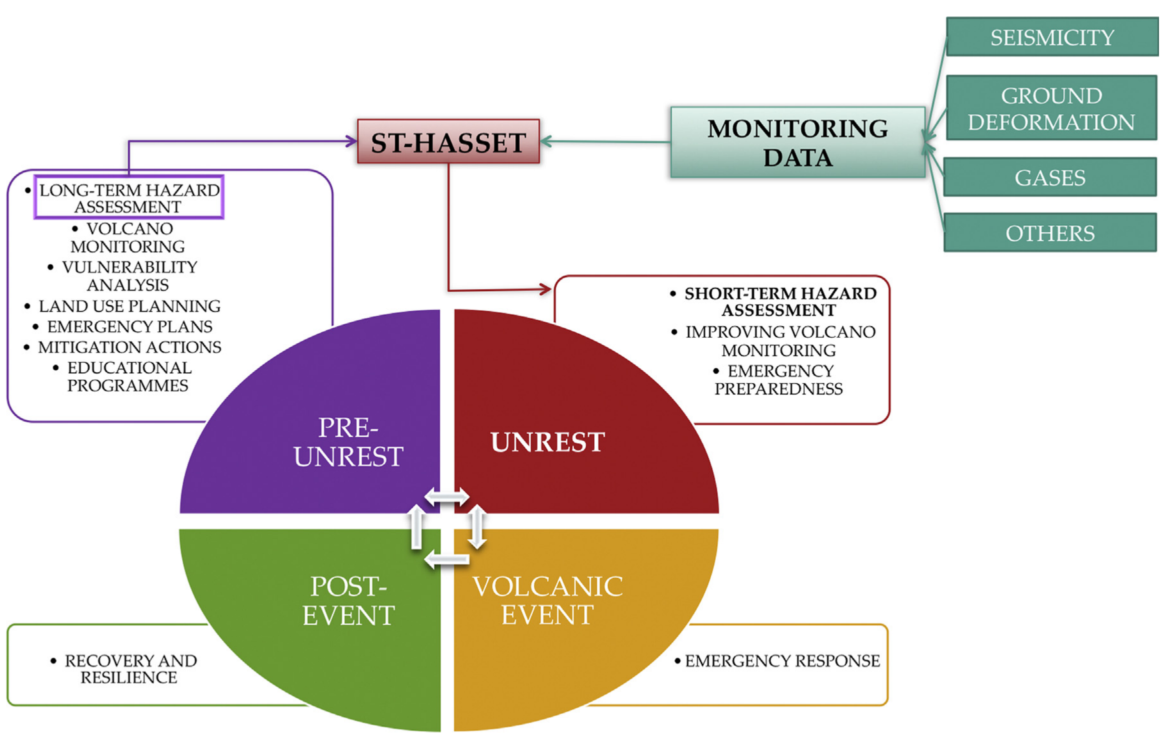

Fig. 1. Volcanic crisis management cycle.