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

Stefania Bartolini a,*, Rosa Sobradelo b, Joan Martí a

a Group of Volcanology of Barcelona (GVB-SIMGEO), Institute of Earth Sciences Jaume Almera, ICTJA-CSIC, Lluis Sole i Sabaris s/n, 08028 Barcelona, Spain
b UCL Hazard Centre, Department of Earth Sciences, University College London, Gower Street, London, WC1E 6BT, UK

A R T I C L E   I N F O

Article history:
Received 23 November 2015
Received in revised form 6 May 2016
Accepted 9 May 2016
Available online 11 May 2016

Keywords:
HASSET
Short-term volcanic hazard assessment
Unrest
Monitoring data
Python

A B S T R A C T

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.

© 2016 Elsevier Ltd. All rights reserved.

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...
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 foresee 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...
geothermal), which may give different outcomes (magmatic eruption, phreatic explosion, sector failure or others) in a range of locations with different possible eruption magnitudes, products, scope, etc. (Sobradelo and Martí, 2010, 2015). Hence, to analyse the short-term, a systematic approach is required to complement previously acquired long-term hazard assessment with up-to-date monitoring data, and to estimate (or to recalculate in case of presence of a long-term assessment) the probability of occurrence of a particular volcanic event. The new methodology proposed by Sobradelo and Martí (2015) consists of applying the Bayesian event tree approach to the evaluation of different eruptive scenarios as part of a short-term hazard assessment; in this way, past information can be complemented by current monitoring data as a means of estimating the probability of occurrence of a volcanic event as the unrest period evolves. This probabilistic method uses Bayesian inference to estimate for each variable (the unrest indicator) the probability of experiencing a significant variation (increase or decrease) by the next monitoring report, given the current information and what has been observed up to the last report. This information can be interpreted on its own or combined into a set of ‘precursory signals’, which can then be linked to the evolution of a particular unrest episode and a corresponding eruptive potential (if there is one).

In order to facilitate the efficiency of Sobradelo and Martí (2015) methodology, we propose here a new tool (ST-HASSET, Short-Term Hazard ASSEsment Tool) that quantifies the short-term volcanic hazard in a simple and automatic way. In addition to estimating the probability of occurrence of each individual unrest indicator, ST-HASSET estimates the probability of occurrence of a particular eruptive scenario (as a combination of various unrest indicators) by going one step further and including information from past data (long-term hazard assessment). In this way, we can search across consecutive time intervals for significant changes in the values of the measured unrest indicators, and update probabilities whenever new data is available. This tool will be very useful for estimating the corresponding potential risk and for assessing the different mitigation actions needed for every possible eruptive scenario.

In order to demonstrate the application and advantages of the tool, we use the same example of the Pinatubo unrest as presented in Sobradelo and Martí (2015). The reason for this is to show the end-user how the mathematical formulation presented in Sobradelo and Martí (2015) via the Pinatubo example can be translated in a user-friendly tool. By applying the same example it is easier to identify which part of the probability model feeds each step of ST-HASSET, proving its reliability and accuracy. Another advantage of using the same example is to show how the display and presentation of the results from the mathematical model are largely improved with the user-friendly tool. We want the focus to remain on the usability and applicability of a new method for merging real-time monitoring information into a probabilistic scale, and present a tool that would allow the end-user to easily incorporate this new approach during an emergency situation. The next step would be to apply this methodology to a range of different case studies, retrospectively and in real-time, and learn about the behaviour and interaction of the various volcanic unrest indicators comparing the results.

2. ST-HASSET: short-term hazard assessment tool

ST-HASSET is based on a simple structure that uses a quantitative approach via Bayesian inference to assess the hazard of a particular scenario. This structure enables us to map individual unrest indicators onto a common probability scale. The approach estimates (for each unrest indicator) the probability that a significant variation between two consecutive stages or time intervals will occur during an unrest episode, which can be interpreted as the evolution towards the onset of a particular eruptive scenario. The short-term probability of occurrence for an eruptive scenario takes into account monitoring data, as well as any relevant past history of the volcano (long-term hazard assessment).

The innovation and the potential of this new tool are shown below through a brief description of the core of ST-HASSET. The section also explains the main features of this tool and a detailed presentation of the Graphical User-friendly Interface (GUI), built with QT Designer (http://www.qt.io), including a step-by-step guide for its use.

2.1. The core of ST-HASSET

ST-HASSET is a new probabilistic tool to merge and quantify the information from volcanic precursory signals, in order to detect possible patterns across various unrest indicators. It has been developed using Python programming language and implemented in QGIS (Quantum Geographic Information System, http://www.qgis.org/en/site/) software. However, it can also be installed in other platforms considering the broad compatibility of the Python language (such as VOLCANBOX, http://www.vetools.eu). This permits to integrate and use ST-HASSET in combination with previous tools developed to conduct volcanic hazard assessment (e.g.: QVAST, Bartolini et al., 2013; HASSET, Sobradelo et al., 2014). This tool will be available for free at http://www.gvb-csic.es.

ST-HASSET has been designed to be as simple as possible, guiding the user step-by-step (see Section 2.3. Overview of ST-HASSET) with the purpose of i) quantifying the uncertainty surrounding the monitoring variables through a Bayesian inference procedure and ii) estimating the probability that an unrest indicator will experience a significant variation in the next time interval compared to the previous one (for simplicity, we refer to the time interval as each length of time period between two consecutive reports or bulletins updating precursory data during a volcanic unrest episode). The theory and mathematical formulation of the Bayesian method applied here has been thoroughly explained in Sobradelo and Martí (2015). It considers two possible values (Yes, No) for the random variables (unrest indicators). The choice of method was to overcome the lack of data at some stages (specially in the initial stages) and to account for the aleatoric and epistemic uncertainties surrounding the probability estimates. In general, the Bayesian inference allows for every state of uncertainty to be modelled with a probability distribution, and for it to be updated as new evidence arrives. The flexibility of the tool allows for the scientific experts to interact and input their own hazard criteria based on their knowledge of the system.

The application of the tool can be divided into different stages: i) the selection of unrest indicators to be analysed, which have to be chosen by the experts; ii) the input data, which can be set in real-time as the unrest evolves, or retrospectively by looking at the monitoring data time series observed in a past unrest; iii) the evaluation of the probability of a possible outcome and of a specific scenario in case of an eruption; and iv) the interactive visualisation and saving of the results. A list of unrest indicators is already included in the tool but it can be extended by the expert (Fig. 2). For each indicators the expert has to provide a range of variation that she/he considers meaningful to confirm a change in the volcanic system. The input data can be divided in two categories: the absolute value of the observed unrest indicator, or the existence of a significant variation with respect to the previous report or bulletin (Y/N/na), given a specific time window (hourly, daily, monthly). If a measurement is not available in a certain time interval, whereas because it was not taken or it does not apply, we do not assume that a significant change has occurred, as we do not have evidence to say so. Instead, we take the probability since the
The length of the interval without a measurement should be reflected in the epistemic uncertainties, as the less information we have, the less we know about the evolution of the system. This allows to be flexible in the case that the monitoring data is not registered in the time window considered (such as data not processed or not available, failure in the instrument, ...). When the input data has been introduced, the output in ST-HASSET will be a "csv" (comma separated values) with the final probability values and the input value reported in the bulletin analysed. Moreover, ST-HASSET allows through its dynamic interface to view the probability results in a chart that can be saved as image.

2.2. Main features of ST-HASSET

As the main aim of ST-HASSET is to identify possible patterns in the evolution of a number of volcanic unrest indicators, its outputs are the probability of occurrence of (i) each individual unrest indicator, (ii) a particular eruptive scenario as a combination of a set of unrest indicators and (iii) eruptive scenarios incorporating past data. This capacity enables users to:

- merge and quantify information from precursory signals;
- quantify the uncertainty surrounding the monitoring variables and estimate the probability that an unrest indicator will have experienced a significant variation by the next time interval;
- observe the relative evolution of the precursory data;
- automatically update probabilities at each stage of a volcanic unrest episode as new data arrives;
- determine the overall tendency in the activity to increase or to decrease;
- assist in the analysis and interpretation of relevant data;
- compare the behaviour of similar parameters in different eruptions of the same volcano and thereby identify common patterns.

By adopting this approach, monitoring information can be transformed quickly and rigorously into a common probabilistic scale for comparative purposes, which will be useful for assisting decision makers and experts during an on-going volcanic crisis. By simply looking at the relative changes in the system that occur as the monitoring signals evolve, we can compare unrest episodes from different volcanoes or even from the same volcano, with different starting points and different patterns of behaviour.

All these features make ST-HASSET a powerful tool for interpreting and analysing relevant data, and a good complement for existing approaches to volcanic crises management.

2.3. Overview of ST-HASSET

This tool was built to enable users to move in a step-by-step fashion through a user-friendly graphical interface, and to visualise results in graphical form. The first window of ST-HASSET (Fig. 2, Unrest indicators tab) allows defining all the indicators to be taken into account by the expert in the unrest episode. The list of monitoring variables used in ST-HASSET is taken from the most representative monitoring indicators and interpretations used to forecast potential eruptive activity (Sparks, 2003; Sandri et al., 2006).
**Fig. 3.** ST-HASSET: Previous unrest data tab.

**Fig. 4.** ST-HASSET: Unrest data tab.
Fig. 5. ST-HASSET: P unrest indicators tab.

Fig. 6. ST-HASSET: P eruptive scenario tab.
Fig. 7. ST-HASSET: Long-term + Short-term tab.
values) and bulletins, which must be introduced into the programme. As ST-HASSET analyses different stages of the unrest with respect to the users to add previous analyses of unrest evolution if available. ST-HASSET enters the corresponding variable as YES (**Y**), NO (**N**) or **na** (not available). In the window (Fig. 3, Previous unrest data tab) enables users to add previous analyses of unrest evolution if available. ST-HASSET analyses different stages of the unrest with respect to the previous analysis already exists, it should be uploaded into this first window, so that ST-HASSET considers it when computing the probability estimates. Once the file is selected, the table with the unrest indicators is updated with the probability values associated to each precursor, as shown in Fig. 3.

The second step (Fig. 4, Unrest data tab) is to input the new monitoring data related to the significant variation (**Y**/**N**/**na**) of each unrest indicator. These parameters are grouped into four categories – seismicity, gases, ground deformation and others – that classify the changes perceived by people living close to the volcano, even before any local monitoring network is set up. If the unrest indicator has varied significantly with respect to previous reports, the user enters the corresponding variable as YES, **NO** or **na** (not available). It is also possible to enter the measure of the variable observed (the absolute value) if available. Here, users have to enter the volcano’s name, the year, month and day, and the time of the observed data, all of which is very useful for ensuring the correct storage of the probabilities (Save the .csv probabilities result).

Once all the data from the updated bulletin has been entered and the computation performed with the “Evaluate probabilities” button, users can visualise results, compare indicators and scenarios. In fact, the tab “P unrest indicators” (Fig. 5), which uses the input information from the observations of the unrest indicators, allows users to visualise the probabilities estimated at each stage and the corresponding variance. Users can select the indicator(s) to observe how the probability evolves over time for each unrest indicator. Moreover, the “P eruptive scenario” tab (Fig. 6) enables users to combine different volcanic unrest indicators to assess the short-term probability of a possible eruptive scenario. For example, suppose that the specific characteristics of a volcanic system imply that the occurrence of a volcanic eruption is closely related to the following unrest indicators happening simultaneously: an increase in seismicity and in the accumulated energy release rate, a Real-time Seismic Amplitude Measurement (RSAM) acceleration, increase of shallow seismicity, Volcano-Tectonic (VT) and Long-Period (LP) events and tremors. Then, users can evaluate the probability of this scenario by selecting these indicators. The “Evaluate scenario” button computes the probability and shows graphically how, by using different combinations of unrest indicators, the total probability of an eruption varies. The challenge is to determine which combination of unrest indicators best describes the particular volcanic system.

When the short-term results are obtained, users can combine them with the long-term results by simply importing these last from HASSET tool (Sobradelo et al., 2014) to ST-HASSET using the specific button (Import scenarios .csv), or by entering the scenarios manually. The way in which these data are combined is the expected value of a particular scenario as a function of the expected value and variances of the variables that measure the uncertainty associated with monitoring data, weighted by the uncertainty associated with past events. Finally, the results obtained can be combined with past data (Fig. 7, Long-term+Short-term tab). In fact, the previous analysis estimates the probability of the occurrence of a particular scenario in the short-term based only on

### Table 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall seismicity increase</td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Seismicity increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>RSAM acceleration</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Accum. energy released rate increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
</tr>
<tr>
<td>Vertical migration of seismicity</td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
</tr>
<tr>
<td>Deep seismicity</td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Shallow seismicity</td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>VT events</td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>LP events</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Tremor events</td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Hybrid events</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Overall gas increase</td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Gas flux increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>H₂O increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>CO₂ increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>SO₂ increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Others</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Fluids temperature increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Overall ground deformation increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Strain increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Inflation rate increase</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Vertical migration</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Ag/Al anomaly</td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Other changes</td>
<td><strong>Y</strong></td>
<td><strong>na</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Fractures</td>
<td><strong>Y</strong></td>
<td><strong>na</strong></td>
<td><strong>Y</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
<td><strong>na</strong></td>
</tr>
<tr>
<td>Phreatic explosions</td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
</tr>
<tr>
<td>Fresh magma</td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>N</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
<td><strong>Y</strong></td>
</tr>
</tbody>
</table>
monitoring data. In addition to the monitoring data, it is also important to study the past behaviour of the volcano since this may be crucial in defining the potential outcome of the unrest period. By incorporating past behaviour into the monitoring data, we are computing the probability of the occurrence of a particular scenario in the short-term, but this time based on monitoring and past data.

Fig. 8. The results of the Pinatubo (Philippines) case study: (a) evolution of individual probabilities for unrest indicators as the unrest episode unfolds; (b) evolution of the probability of a magmatic eruption based on different combinations of unrest indicators; (c) evolution of the probability of a magmatic eruption that originates pyroclastic flows and/or fallout, generated by merging past information on size, location and extent with monitoring data on overall seismicity and gas increase, deformation and fresh magma.
So that the evolution of the short-term probability of a particular eruptive scenario may shift slightly now that we have incorporated additional information on the past behaviour of the volcano.

3. Applying ST-HASSET

We illustrate here the use of ST-HASSET by applying it to the same case study (unrest period prior to the Pinatubo eruption in 1991) that was used by Sobradelo and Martí (2015) to illustrate how the theory and the mathematical model for short-term hazard assessment can be easily applied.

The evolution of the unrest that preceded the 1991 eruption (Punongbayan and Newhall, 1996; Punongbayan et al., 1996) is shown in Table 1. Unrest was marked mainly by a significant increase in seismicity, ground deformation and gas emissions. Seismicity was characterised by the presence of VT, LP, tremor and hybrid events, located in two distinct source regions, one near the summit of the volcano at depths of 0–3 km and another approximately 5 km to the northwest at depths of 26 km (Cornelius and Voight, 1996; Harlow et al., 1996). Ground deformation including a significant inflation of the upper part of the volcano occurred on 4 and 7 June (Ewert et al., 1996), coinciding with an increase in shallow seismicity and a decrease in SO2 emissions (Daag et al., 1996). Together, these data were interpreted as indications that magma was ascending from the chamber to the surface.

Using the information of the evolution of the unrest (Table 1) and applying ST-HASSET, we can obtain graphical and numerical results (Fig. 8) for the eruption on Mount Pinatubo. In particular, it is clear that the individual analysis of the unrest indicators and of the various combinations of these indicators could potentially define a volcanic scenario. In the first case (Fig. 8a), the evolution of unrest indicators such as seismicity, gas flux, strain and fresh magma, and their increase/decrease during the unrest period, are patent. This allows us to identify trends and/or patterns in the indicators that evolve simultaneously over consecutive data bulletins. Subsequently, the probabilistic results of ST-HASSET for each indicator can be combined to obtain (Fig. 8b) the probability of occurrence of a particular eruptive scenario in the short-term (assuming that for any particular outcome, variation in specific indicators such as the overall increase in seismicity, gas and ground deformation will occur). Fig. 8c depicts a combination of a preliminary long-term hazard assessment conducted using past data on products, and the location of past volcanic events, which enables us to assess the possible outcome and products of a future eruption on Mount Pinatubo (Punongbayan et al., 1996; Newhall and Hoblitt, 2002). The probabilistic results of ST-HASSET take into account the overall changes in seismicity, gas and deformation, as well as the presence of fresh magma.

4. Final remarks

We have presented a new tool that implements in a systematic and easy way the methodology for conducting short-term volcanic hazard assessment defined by Sobradelo and Martí (2015). This new tool facilitates the task of calculating probabilities of possible eruptive scenarios and the potential time scale during the course of a volcanic crisis (Fig. 9). In this sense, it complements already existing tools and methods, such as HASSET (Sobradelo et al., 2014), developed to perform volcanic hazard assessment. In volcanology, the importance of conducting short-term hazard assessment is due to the need of interpreting real-time monitoring data and of subsequently updating the status of the volcanic hazard. Therefore, short-term analysis should ideally be based or built on a previous long-term hazard assessment. Leaving out of the analysis information on past episodes could make the short-term assessment inaccurate, and underestimate potential eruptive scenarios that could be relevant, such as the location (flank/central), size, extent of the eruption and even the type of unrest (geothermal, magmatic, seismic, other). For that reason, it is important to consider the short-term analysis in the context of the crisis management cycle (see Fig. 1) in which the long-term represents a previous step. This should be considered for preparedness plans, to improve resilience and mitigate vulnerability and exposure.

Therefore, ST-HASSET complements and expands on previously designed hazard assessment tools. In combination, they represent a systematic way to conduct long- and short-term hazard assessment. In particular, we refer to the following probabilistic...
methodologies and tools for interpreting volcanic data and assessing long-term volcanic hazard: QVAST tool (Bartolini et al., 2013) to define the spatial probability of vent opening; HASSET (Sobrado et al., 2014) to define all possible unrest and eruptive scenarios and estimate their probability of occurrence within a time interval; VORIS 2.01 (Felpeto et al., 2007) to evaluate the potential extent of the main volcanic hazards expected to occur in a volcanic area. Hence, ST-HASSET represents the following step in an unrest phase, which is to estimate the probability of an imminent eruption given the real-time monitoring information and all the previous hazard (spatial and temporal) assessment.

This new tool allows an interactive visualisation for comparing the behaviour of similar parameters from different eruptions of the same volcano, or for contrasting volcanoes of similar characteristics, that can identify common patterns quickly and easily. A graphical user-friendly interface aids data input and the visualisation of results. Hence, ST-HASSET provides a rapid and standardised way of transferring precursory information onto a common probabilistic scale for comparing and/or detecting sudden changes or shifts in a volcano’s activity that may require immediate action.

Acknowledgements

This research was funded by the European Commission (FP7 Theme: ENV.2011.1.3-1; Grant 282759: VUELCO and EC ECHO Grant SI2.695524: VeTOOLS). The authors are grateful to two anonymous reviewers for their insightful comments and review of the manuscript, which have helped us to greatly improve this work. We also thank the Editor Candan Gökoğeç for handling this paper. The English text was edited by Michael Lockwood.

References


