Forecasting During Volcanic Crises

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Chapter Outline

Abstract

Forecasting during a volcanic crisis is vital to the preservation of life and mitigation of loss during eruption. Decisions on when, where and how to evacuate, where to send the evacuees, and when they can return, are all informed by forecasts of impending volcanic activity. We review input data and models that underlie short-term forecasts during an eruption crisis, software and tools applied, how forecasts are framed, ways to integrate data during a crisis, and several case studies of forecasting in action. The workflow during a crisis can be simplified by precalculation of possible hazard impacts using long-term forecasting techniques. Short-term forecasts should be evaluated after a crisis in order to improve methodology and utility of forecast information. As data availability increases, computational tools are developed, unrest patterns are identified, and underlying processes better understood, there will continue to be improvements in volcanic crisis forecasting and decision support tools.

Key words

Forecasts; Unrest; Hazards; Software; Analogs

GLOSSARY

Eruption Source Parameters (ESPs) – physical parameters that describe the initiation condition for numerical models. These include, for example, the volume, column height, grain size, lava volume, and effusion rate.
Forecast – a prospective probabilistic statement specifying the probability that one target event will occur in space-time subdomains.
Prediction – a deterministic statement on the future evolution of the unrest/eruption, commonly presented as a scenario, without a likelihood attached.
Volcanic Explosivity Index (VEI) – a logarithmic measure of the explosivity of an eruption that combines magnitude and intensity
Volcanic unrest (or crisis) – a situation in which at least one monitored parameter is outside 'normal' range (aka baseline activity). For a slowly evolving volcanic system, the definition of 'normal' range has to be regularly revised, and it has to be defined on a time frame that is of interest for the decision-makers.

1 INTRODUCTION

Volcanic eruptions pose considerable risk to both life and infrastructure. Siting of the latter should be addressed by means of a long-term probabilistic volcanic hazard analysis (Connor et al., EoV 2nd Ed, Chapter 51) as part of land-use planning, although resettlement may occur during lengthy crises (e.g., Sinabung, Ubinas, Fuego). In general, short-term volcanic crisis management (Jolly and De la Cruz-Reyna, EoV 2nd Ed, Chapter 68) is concerned with evacuation, rescue, and management of existing infrastructure. These actions are implemented by the responsible authorities in the light of scientific information, particularly hazard forecasts, which enable risk assessments (Aspinall and Blong, EoV 2nd Ed, Chapter 70) to be carried out at societal and individual levels. Hence eruption forecasts must be 'actionable', i.e., specific enough in time and quantified hazard(s) at specified locations, for emergency managers to take action. Table 1 lists some historical eruptions where crisis forecasting had significant successes or shortcomings.

Table 1. Some notable eruptions for crisis forecasting

Volcano	Year	VEI	Remarks
Guadeloupe	1976	2	72,000 evacuated, excessive for an eruption smaller than expected.
Mount St. Helens	1980	5	Onset poorly forecast, hazard magnitude too low, 57 dead.
Mount St. Helens	1980-6	0-1	Lava extrusion well forecast through seismicity and deformation.
Rabaul	1983-5	N/A	Non-eruptive unrest (forecasted eruption did not occur). Eruption later occurred in 1994.
Nevado del Ruiz	1985	3	Poor communication of and lack of action responding to lahar forecast, 23,000+ dead.
Pinatubo	1991	6	Multiparameter forecast at awakening volcano led to extensive evacuation. Major eruption 'precursor' to worst-case Plinian eruption.
Ontake	2014	3	Phreatic eruption, without eruption forecast, 57+ dead.
Calbuco	2015	4	Atypical awakening volcano, little precursory behavior, hence no quantitative forecast of sub-Plinian eruption.

Poor outcomes can occur when forecasts do not include low likelihood, unheralded, or unknown hazards. The best forecasts are flexible, inclusive, and responsive to changes in conditions or understanding. For systems with well-characterized or well-understood cyclic behaviour, there have been some great successes in forecasting the timing of eruption onset. However, patterns are only useful until the system changes. Forecasts of eruption magnitude, style and duration carry much larger uncertainties. The forecasting time window, the spatial resolution, and the specific hazard of interest must be defined by (or coordinated with) decision makers who know what they need for their mitigation actions.

Crisis forecasting is relevant to several of the United Nations 17 Sustainable Development Goals. Volcanic eruptions create fertile soils (SDG 2,8) but exploiting this resource puts people at risk which can only be mitigated (SDG 3,11) through forecasts and subsequent decisions. Forecasting can also preserve critical infrastructure (SDG 9) to be preserved through, for example, shutting down ash-prone systems.

1.1 Short-term forecasts

Short-term forecasts are typically based on monitoring data, eruptive history, and expert knowledge [1] using combinations of various methods (Figure 1). Forecasts are communicated through relative or absolute probabilities of specific events and/or using a volcano alert system (Gregg et al., EoV 2nd Ed, Chapter 67). In cases where mitigation actions are low-cost, observatories have often issued qualitative assessments along the lines that eruption has become more (or less) likely. This can then initiate consequential precautionary mitigation actions, bypassing a rational and quantitative decision-making. In order to evaluate the success or failure of such qualitative assessments, quantify the uncertainty therein, or to pass them to a decision-maker for quantitative risk-based decision-making, these qualitative assessments would need to be converted into probabilities, using methods as illustrated in Figure 1.

Here, we use the term ‘volcanic crisis’ to be synonymous with volcanic unrest, i.e., when a monitoring parameter is anomalous as compared to baseline (non-unrest) records. Volcanic crisis forecasting builds upon long term hazard assessment by incorporating new monitoring data and models of those data to communicate actionable information to authorities. Unrest is often also the trigger for augmentation of the monitoring network.

Forecasts are only useful to decision makers if they include information about quantities of interest such as whether an eruption will happen and how big it will be over a specified time interval. Different data are used to estimate probabilities of each of these parts of the forecast, where monitoring data provide more information about eruption onset (if/when an eruption will start) and eruption history and analogs provide more information about style of eruption and hazards produced (what/where of an eruption). A historical reporting bias has focused far more on eruptions than on unrest that does not lead to eruption, resulting in overestimates of the relative frequency of unrest that leads to eruption [2]. Furthermore, intrinsic natural variability in volcanic systems leads to unpredictability in pre-eruptive unrest patterns. Hence whether unrest leads to eruption can only be handled probabilistically. One means of doing so is through a probability tree [3], which can incorporate both observations and prior knowledge/judgments. However, in using a probability tree, a ‘look forward window’ needs to be pre-defined as a function of its practical usefulness, and hence the eruption onset precision is limited to the window length. An alternative approach to a probability tree is to focus on when, ignoring the if, through techniques such as the failure forecast method (e.g., [4]), which tracks acceleration in, e.g., the energy of V-T earthquakes.

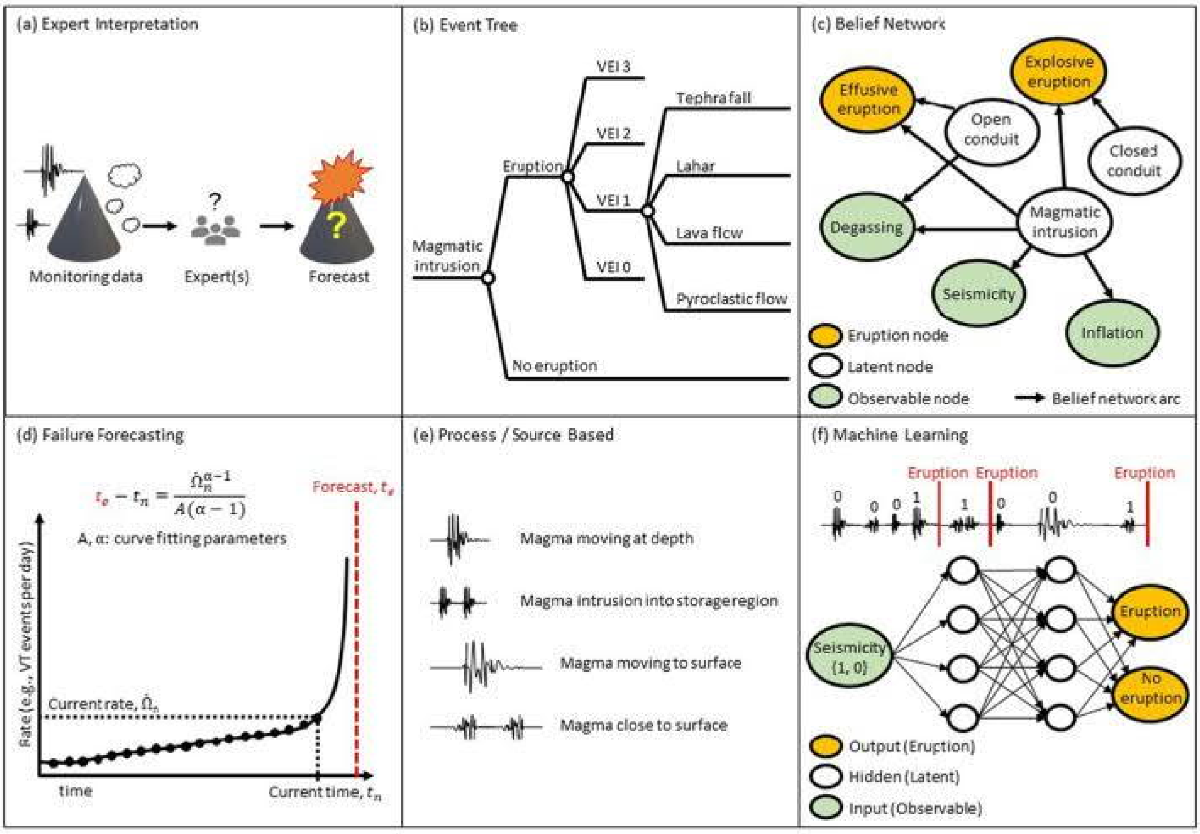

Figure 1. Six examples of short-term eruption forecasting methods that can be used in various combinations. Event trees (b) and belief networks (c) help frame forecasts and require combination of multiple sources of data, which can include expert judgement (a), model results (d and e) and machine learning approaches to pattern recognition (f). Reprinted from [1], Copyright 2021, with permission from Elsevier.

The second component of eruption crisis forecasting is the 'what' and 'where.' Volcanic eruptions can be complex entities, producing many different possible hazard phenomena, which can occur repeatedly in different sequences and combinations, and have varying intensities across multiple locations [5]. Reconstruction of eruptive histories requires deposit mapping, stratigraphic logging, and review of historical accounts of past eruptions. These data are combined with model runs over modern topography to create hazard maps (Part V, Chapter 2.2), which form the basis of emergency management plans. Once unrest is identified, further monitoring data may provide improved resolution on hazard zones or on eruptive scenarios. For example, in the Auckland Volcanic Field, it is anticipated that precursory seismicity will localize prior to vent formation [6]. Estimation of reservoir volumes (through deformation modelling, seismic tomography, or other methods) may provide an upper bound on eruptible magma volume.

Finally, there is the question of how long the eruption will last, or 'is it over yet'. Statistical models can be used to dynamically calculate a probability forecast for the remaining eruption length, and once the production of magma at the surface ceases, when it will resume. Calculations can also be made of the rate of magma production, and the state of the magma plumbing system, which usually considers as a random variable the time of the eruption onset, instead of the occurrence of the eruption in a given period of time.

1.2 Time scales and presentation

The aim of crisis forecasting is to be able to operate in real-time, providing information as required by the decision-makers in the most timely, clear manner possible. A change in behavior, either pre- or syn-eruption needs to be recognized as quickly as possible in order to update hazard forecasts to the new situation. To streamline this process, the spatial distribution of potential hazards (Part III) can be delineated, including those for pyroclastic density currents (PDCs), ballistics and lahars, and suitable probabilistic tools, such as event trees and Bayesian Belief Networks [7], can be set up ahead of time. At polygenetic volcanoes, hazard zones can be calculated or estimated on the known topography correlating with levels of eruption intensity, but in monogenetic volcanic fields, as the vent location and hence topography is unknown, the spatial distribution (usually a circle) of the dominant hazard can be substituted. Prior to a crisis, monitoring data baselines must also be established in order to be able to detect anomalies.

Unrest and eruption can last from seconds to decades. During unrest, the focus is on determining the need and timing of an evacuation and on community and infrastructure risk mitigation, which require expertise beyond volcanology. Evacuations (Part VI, Chapter 2.7) have costs due to transport and housing of the evacuees, interruption of economic activities, and from livelihood dislocation. The timing and operation of evacuations must be weighed against likely precursor run-up times and forecast spatial hazard maps, in order to ensure efficacy and safety during evacuation. The desire for additional data to improve forecasts and the need to have sufficient time to evacuate people operate against one another, and the authorities must weigh their alternative actions based on uncertain forecasts.

Volcanoes with little to no previously monitored unrest (e.g., Mount St. Helens 1980, Pinatubo 1991, Calbuco 2015) present different challenges to persistently active volcanoes (e.g., Mount St. Helens 1980-1986, Merapi, Stromboli), and phreatic eruptions (e.g., Ontake 2014, Whakaari 2019) may provide little if any warning. Calderas (e.g., Rabaul, Campi Flegrei, Santorini, Taupo) seem to be particularly prone to persistent unrest without eruption [8].

During an eruption, forecasts often concentrate on the evolution of ongoing hazards such as lava flows, dome growth, production of ash clouds and PDCs, and the possible triggering of lahars. In addition, new vents can open, and fresh eruptive phases can occur. Together, these changes are forecast using monitoring data from the syn-eruption period, by tracking eruption progress and changes in topography, and as augmented by eruptive data such as changes in magma composition (e.g., as at Kilauea and Fagradsfjall volcanoes).

Eruption forecasts are presented to partners and community members in a variety of ways. In some cases, forecasters may provide a ranked list of eruption scenarios, from most to least likely. In other cases, a full set of probabilities of hazardous events (as can be produced in an event tree) is presented. In far more cases, useful forecasts address the relative or absolute likelihood of a particular event or outcome. Forecasts can also contain spatial information, sometimes hazard maps showing the distribution of possible hazards from individual or multiple scenarios, or in some cases fully probabilistic zones based on numerous runs of physical model(s) across a wide range of model inputs. Communication of eruption forecasts is challenging, due to the complex multi-hazard nature of eruptions, the challenges inherent in communicating uncertain information, and the variation in ways that people interpret and respond to risk. Therefore, with the assistance of experts in communication, forecasters could consider the audience, the purpose, and the context of forecast communications before communicating results to stakeholders (cf. Part 6, Chapter 3.2 'Volcanic Crisis Management').

1.3 Risk and consequences

Eruption forecasting and volcanic hazard analysis are the basic information to evaluate the risk and consequences for each individual and for the society at large. A pedagogic definition of the risk reads

$$\text{Risk} = (\text{volcanic hazard}) \times (\text{exposed value}) \times (\text{vulnerability}).$$

This assessment requires additional competences that are usually beyond the common background of a volcanologist, such as, for example: i) engineering to estimate the physical vulnerability of edifices and infrastructures; ii) sociology and medicine to evaluate the human vulnerability and collective behaviors; iii) economics and politics to quantify the exposed value. A sound risk assessment is essential to plan rational decision-making processes, in particular for high-risk volcanoes where you may be asked to justify any mitigation actions in post-event audits. In a few, but important, cases, the volcanic risk can be easily estimated: for example, the individual risk to be killed by a pyroclastic flow is the same value of the volcanic hazard, i.e., the probability to have a pyroclastic flow in that site (the vulnerability is 1). In other cases, it is more complicated, because it involves long-term and indirect consequences of a volcanic eruption, such as the increased probability of lahars in the years following the eruption, or the pollution of the aquifer resources and of the ground.

One important aspect that is not considered in the risk calculation given by the equation above, and is not yet quantified, is resilience, which may be broadly defined as the capability of a society to return to most of the initial functionalities. Recovering from a large eruption can be challenging for complicated social systems like big cities, critical lifeline networks, or productive districts, which may commonly show a pervasive low resilience to these kinds of events; in these cases indirect consequences will easily overcome the direct loss. A careful analysis, made before crises, of the criticalities, possible losses and major disruptions can be useful to prepare in advance possible steps to reduce the risk and improve resilience, such as the de-energizing of electrical grids, or shutting off of water and sewage networks, which can be justified on the basis of syn-crisis forecasting and a rational cost-benefit analysis.

Under this general framework, the function of syn-crisis forecasts is to provide updated estimates of volcanic hazard, and in particular, estimate their uncertainty to get a more reliable assessment of risk and resilience.

2 DATA AND INFORMATION

Pallister et al. [9] summarize best practices in the work of volcano observatories, which includes forecasting. Among the recommendations are a minimal monitoring level at all active volcanoes, and the use of databases and numerical and statistical models.

2.1 Monitoring

Despite international templates and some regional protocols, there are not yet international standards on what a minimal volcano monitoring level is, or should be. Here we define minimal monitoring as the level of monitoring (in terms of numbers and type of monitoring stations) which is necessary to identify changes from the background level of a specific volcano or volcanic area. Indeed, the capability in anticipating the potential outcomes of a volcanic unrest directly depends on the sensitivity of the monitoring network in detecting the onset of the unrest itself. In most cases, a volcano monitoring system is intended as a multi-parametric network capable of measuring seismicity, ground deformation and volcanic gas emissions and of detecting surface changes.

Anomalous seismicity, deformation, gas fluxes (or composition), or surface features provide indirect evidence of perturbations to the magmatic system, which in some cases lead to eruption.

Monitoring of volcanoes and volcanic areas therefore requires a long-term database of parameters from which it is possible to identify a variation or a change. This task is more challenging if the volcano of interest has not experienced historical unrest or if monitoring data are non-existent. The more complete and extended in time the database is, the more robust are the interpretations. Furthermore, operation of an in-situ monitoring network is costly and demanding for the institutions in charge of the volcano surveillance, including instrumentation purchase and maintenance fees, and support for field operations costs. For this reason, volcano monitoring in many areas is still too sparse to reliably detect volcanic activity precursors. However, the era of satellite coverage and the availability of multiple kinds of satellite data with different spatial and temporal resolution has been extending the capability of detecting anomalies at remote volcanoes where in-situ monitoring is poor or very limited.

After detection of unrest, defined as anomalous monitoring signals, the monitoring network is commonly expanded in order to better constrain underlying processes and to assess and forecast its potential evolution. These additional sensors and instruments help estimate the location, depth, and extent of the magma body, changes in magma volume or gas content, and to develop and update potential scenarios and timeline.

2.2 Analogs

During volcanic unrest, forecasting further activity is aided by understanding previous activity at the restless volcano. When unrest conditions are unclear and past data are limited, global databases like Volcanoes of the World (volcano.si.edu) and WOVOdat (wovodat.org) can be used to identify similar cases. These *analog* cases are identified by comparing features such as morphology, tectonic settings, rock compositions, eruptive styles, eruption sizes, chronologies, and phenomena. Statistics from analog unrest sequences can then inform probabilistic forecasts. For example, a volcanologist might ask, "Where has unrest like this been seen before, what happened then, and what were the outcomes?" Identifying systematic unrest patterns is crucial during crisis response, to answer questions such as "Are there systematic differences in unrest signals between intrusions that erupt and those that don’t?", or “Is this unrest pattern at this type of volcano likely to produce an effusive or an explosive eruption?” Different analogs can be used for different questions at a single volcano. WOVOdat enables interactive retrieval and display of historical data, including synchronized time plots of parameter changes, and comparisons of unrest within or between analog volcanoes [2]. However, as no analog is identical to the volcano of interest, it is unwise to base forecasts solely on analogs. Instead, they provide a range of possible processes and activities to inform hypotheses, which can be tested with ongoing data during crisis response [2]. Comparative studies between analog volcanoes are particularly helpful in uncertainty estimation when historical data are insufficient or no instrumental records exist, and in quantifying potential low probability, high consequence events never recorded at the volcano of interest. Even forecasting at frequently erupting volcanoes can benefit from leveraging global data, since behaviors can change between eruptions.

2.3 Hazards: models and data

In addition to local data and analog information, scientists use a wide range of model results to contribute to forecasts. These models require careful consideration of input data, selection of which is largely informed by past activity at the volcano, by the geometry and morphology of the volcanic vent and surrounding topography (e.g., topography of crater rim, source region for possible mass flows), by current unrest/eruption conditions (e.g., degassing, lava flow crystallinity, tephra grain-size distribution), or by borrowing from analog volcanoes, as mentioned above.

The wide range of model types that inform forecasts is partly due to their application for the wide variety of forecast elements, extending from likelihood of eruption within a given time frame to likelihood that a given hazard phenomenon will impact a location of interest. Model types include statistical models, e.g., of eruption recurrence; deterministic models, e.g., failure forecast models; physical, empirical, numerical models, e.g., of hazard transport, or of magma ascent and eruption; and machine learning models, e.g., of pre-eruptive monitoring data. All of these models can contribute to short-term eruption forecasts, where integration of datasets will improve model outcomes. Epistemic uncertainty in hazards forecasting can be estimated through ensemble forecasts or logic trees, which operate by assigning weights to multiple input sets.

Importantly, improvements in forecasting occur with advances in our understanding of the underlying time- and spatial-varying processes; with creation of more complete monitoring catalogs, from which we can construct contingency tables to compare predicted vs. actual outcomes of past unrest; and with appropriate treatment of uncertainty.

3 PRE-UNREST CALCULATIONS

Forecasting volcanic unrest is a particularly challenging task due to the very limited number of monitoring data for past crises and to the pervasive presence of large uncertainties of different kinds. To increase crisis management preparedness, identify possible volcanic crisis evolution paths, quantify uncertainties, and define operational protocols, a number of actions (sometimes partially overlapping) could be undertaken in 'peace' time. They include expert elicitation sessions, development of event trees and scenario definition.

3.1 Expert elicitation

In all volcanic crises, expert opinion is required through selection of forecast methods, choice of models and their inputs, and definition of eruptive scenarios (see also section 3.3). Expert opinion is sometimes also used to identify monitoring anomalies that may precede a volcanic eruption. In some circumstances, structured elicitation and aggregation of individual experts' judgments (SEJ) can be used to improve forecast performance and minimize cognitive bias, to provide quantitative probabilities with uncertainty ranges, to decision-makers. While "expert judgement" could be asking a single expert for her/his best guess, "structured" refers to a formalized, documented protocol for obtaining and combining probabilistic judgments from a panel of experts [10].

Important things to consider in organizing an effective structured expert elicitation in volcanology are:

1. definition of the problem to be investigated and the questions to be posed, related to probabilities (stalled eruption, vent location, eruption style, etc.), physical quantities (eruption size, plume height, etc.) and/or monitoring anomalies that characterize different phases of unrest;
2. identification of the problem owner, analysts and the panel of experts. Careful selection of sufficient experts with diverse backgrounds. Definition of both the elicitation method (behavioral or mathematical) and of the aggregation procedure (equal-weight, performance-based or both);
3. design of clear target questions (if necessary with the help of event trees, see section 3.2), that are the questions of interest for the problem under consideration;

4. for performance-based elicitation (see, e.g., [10]), design of appropriate calibration questions (usually >10 as close as possible to target items), or any other alternative (and meaningful) calibration rule. Comparison with equal weight is recommended. For operational purposes, consider a pre-weighted standing panel, with periodic meetings even outside volcanic crises;
5. organization of an appropriate introduction with multiple presentations about the main topics of the problem, expert elicitation basics (including eventually cognitive de-biasing, basic statistics, basic principles of Bayesian updating) and questionnaire answering mode;
6. definition of tools (e.g., [11]) and vehicles for eliciting and integrating judgments (e.g., event trees, Bayesian belief networks, scenario simulations) to be used;
7. discussion among experts, in light of the elicitation boundary conditions, about the proposed questions to eliminate ambiguities and discuss outside views. Multiple elicitation rounds are recommended and are necessary to clarify misunderstanding of the question(s), and to update opinion as new data are added or as the crisis evolves;
8. exercises that simulate an eruption and verify the preparedness of the experts (useful to think about less likely scenarios – see the following case study);

HOW TO: PITON DE LA FOURNAISE, EXERCISE 2021 [12]

WHERE: Piton de la Fournaise volcano

WHO: 28 experts from different nationalities and backgrounds (from geologists to civil protection officers)

WHAT: exercise simulating a volcanic crisis with the opening of a new vent and an eruptive fissure in a populated area of the island, and development of an effusive eruption.

HOW: full online meeting (1 day) with multiple presentations, calibration with 16 seed questions, 12 target questions divided in four parts about probabilities of vent opening, expected length of eruptive fissure, expected lava arrival times at sensitive sites, maximum impact distance of ballistics and expected time of eruption continuation. For each phase, a fake bulletin was prepared in advance and distributed to the experts, imagining that each phase was separated by a time-lag of 6-24 hours. Results were analysed using different weighting schemes and were presented to the experts at the end of the meeting.

3.2 Event trees

The event tree [3] is a graphical tree representation of events of pragmatic interest, in which individual branches are alternative steps from a general prior event, state, or condition, through increasingly specific subsequent events (intermediate outcomes) to final outcomes. In this way, the scheme shows all relevant possible outcomes of volcanic unrest at progressively higher degrees of detail (Figure 2). In essence, the event tree breaks down a complex problem into a set of problems (nodes) that are easier to approach.

The probability of each outcome is obtained by combining the conditional probabilities at each node of the tree through classical probability theory. As regards the probability of eruptions, the combination of the probabilities at the various nodes is

$$\Pr(\text{eruption}) = \Pr(\text{unrest}) \times \Pr(\text{magma} \mid \text{unrest}) \times \Pr(\text{eruption} \mid \text{magma})$$

The probability at each node can be estimated using data, models and experts' judgment (see, e.g., [3]). Notably, the probability at each node can be also described by a distribution instead of a single probability to quantitatively describe the level of agreement among experts, and if this probability has been obtained by a large/small dataset and/or widely accepted/one rough model [13]. Figure 2 illustrates the scheme, continued from eruption forecasting to impact forecasting.

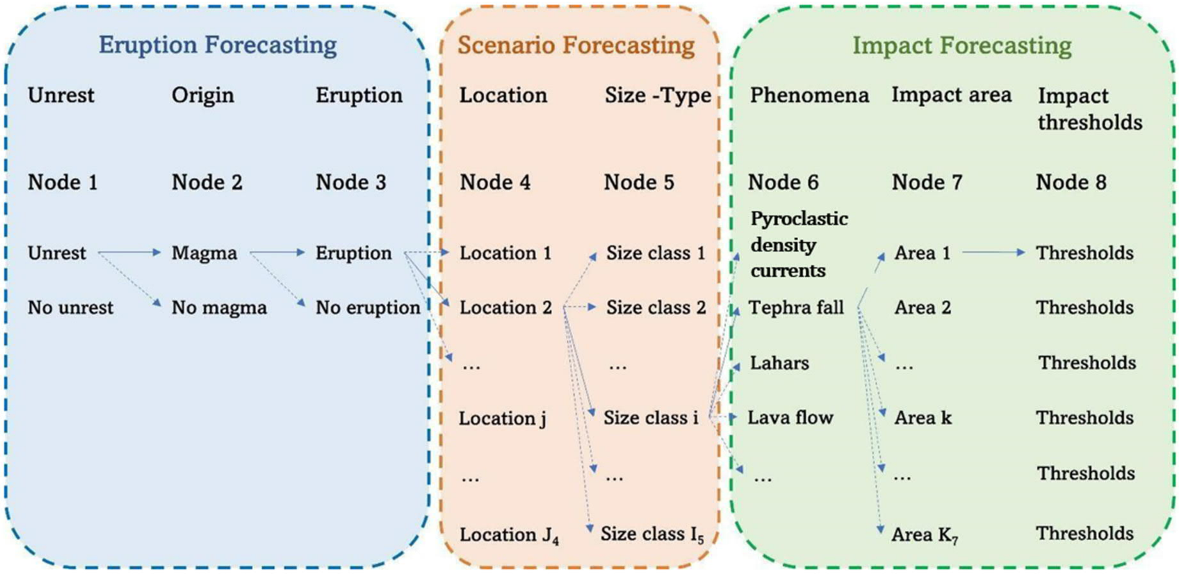

Figure 2. The event tree scheme: the first three nodes represent eruption onset forecasting, the fourth and fifth define the scenarios, and the rest of the nodes quantify the impact of the eruption.

3.3 Scenarios

Monitoring data are most useful in forecasting the onset of an eruption. This is because more is understood about the process of eruption and its relation to physically measurable precursors, and also to the fact that the onset time is a simple scalar. However, forecasts need to include hazards, which are of multiple types, all with their own intensities, timings and spatial dimensions. Because of the relative lack of known links between hazard generation and monitoring, a commonly used approach is to construct scenarios (Part VI, Chapter 2.6) based on the geologic past and analog volcanoes.

A scenario is a single realization of how an eruption and its hazards might play out over time and space. Single scenarios are too prescriptive to be of value in a crisis forecasting situation, contributing mainly to training and in pre-crisis evaluation of possible risks and mitigation actions. Importantly, low likelihood, high impact scenarios commonly rely on the use of analogs based on their low frequency in volcanic cycles (e.g., sector collapse, lateral blast, far-travelled PDC, or ultra-Plinian eruption).

Although eruptions are processes of almost infinite variability, multiple scenarios that discretize the space possibilities can be useful as a means of communication between scientists and emergency managers. They are also particularly adapted to certain forecasting techniques. Multiple scenario approaches include the product of multiple branches in an event tree ([3]; see Section 3.2), or more detailed constructions based on quasi-temporal sequences of multiple hazards [5]. Time, if included, is generally in the form of a single window or a deterministic set of timings. Detail is concentrated on what hazards occur and where.

The spatial aspect at polygenetic volcanoes should include the flow of lava and PDCs, tephra dispersal and deposition, the area impacted by ballistics and gas, new vent formation, edifice collapse, and lahar initiation and propagation. In this case, scenarios could be divided into severity classes, and probabilities assigned to them for presentation to decision makers for potential evacuation decisions. Scenarios have also been devised for distributed volcanic fields, such as the Auckland Volcanic Field [6]. These include pre-eruption seismicity but are otherwise difficult to use for crisis forecasting as the extensive hazard modelling is vent-location dependent. Calderas (e.g., Campi Flegrei) are generally treated as volcanic fields in this regard.

4 SYN-UNREST FORECASTING

The classic example of crisis forecasting is that during an unrest episode. The foremost question is whether (or when) the eruption will occur, and then what will happen; depending on the societal risk tolerance, risk-management typically, and subjectively, assumes either a likely, or close to a worst-case, scenario if an eruption occurs.

4.1 Eruption onset

Forecasting eruption onset is often an essential ingredient for a successful evacuation of endangered people living around the volcano. To date, this goal is achieved through different approaches, which all rely on the observation of anomalies in one or more monitoring parameters that depend on the type of volcano and the design of the monitoring network. These parameters can include those derived from seismology, geodesy, geochemistry, or other volcano observations. Examples include strong and asymmetrical ground deformation, acceleration of seismic or deformation rates, presence of seismic tremor or very long period seismic events, detection of magmatic gas.

Most of the approaches provide a *forecast*, i.e., the probability of eruption onset in a given forecasting time window *T* (e.g., all kinds of Event Tree and Bayesian Belief Networks). Some other models – such as the Failure Forecast Method (FFM) (e.g., [4]) that relies on the observation of the acceleration of seismicity and/or ground deformation – provides a *prediction*, which is a deterministic statement on the occurrence of an eruption at a time given by a window or probability distribution. Sometimes, the latter can be also expressed as a forecast of the eruption onset time, instead of a binary prediction. All models, based on probabilistic or deterministic approaches, acknowledge the existence of uncertainties of different kinds and the practical impossibility to predict exactly the eruption onset in a time frame that is useful to safely evacuate citizens under threat. However, providing a *forecast* or a *prediction* of the eruption onset may have a great impact on the decision-making process and on the role and responsibilities of volcanologists. Whereas a forecast leaves the responsibility of selecting a probability threshold (e.g., evacuate/not evacuate) to the decision makers, when delivering a prediction volcanologists act, *de facto*, as decision-makers, because predictions and decision-making are rooted in the same boolean logic.

A large, but unknown, proportion of volcanic unrest does not lead to eruption, and is the subject of much research (e.g. [8]). Forecasts are expected to be more reliable when the unrest/eruption cycle demonstrates a degree of repetition. However, even the most well-behaved system changes behavior at some point. Systems with rapid runup, or metastable systems such as open conduit volcanoes or calderas where the eruption trigger could be subtle, are particular challenges to forecast.

4.2 Eruption source parameters (ESPs)

Forecasting the character of eruptions may be equally important for risk management, as understanding potential phenomena during ongoing unrest and how it evolves over time is essential for risk management decisions, which rely on understanding the potential impacts and extent of hazards that may be produced. Commonly, this part of a forecast is primarily informed by knowledge of the eruptive history of the studied volcano and its mapped deposits. For volcanoes with sparse geologic knowledge, eruptive parameters may be inferred based on analogy with morphologically or compositionally similar volcanoes. Historical records of eruption styles, intensity, mass eruption rates, erupted volumes, durations, intervals, and unrest chronology establish a forecasting baseline.

Important considerations include: what styles of eruptions may occur at this volcano and what phenomena may be produced at the initial phase of eruption, including tephra, PDCs, lava domes/flows, ballistics, lahars, landslides/avalanches. Additional information is also useful for eruption style forecasts.

Continuous monitoring of seismic, ground deformation, and gas emissions, supplemented by visual observations from unoccupied aerial vehicles (UAVs) and satellites, can detect evolving activities like magma migration, dike propagation, fissuring, fracturing, crater rim and slope instability, all of which are critical for understanding potential hazards. Monitoring data can also inform eruption scenarios, forecasts or predictions, as with indicators of pressurization (e.g., rapid edifice deformation) as a proxy for eruption intensity, slope instability (e.g., crack formation) as may precede slope failure, or migration of a magma body (e.g, migration of seismicity) as may inform vent location/geometry. Environmental factors, such as rainfall that can trigger lahars and hydrothermal activity that may influence flank stability, also play a significant role.

5. SYN-ERUPTION FORECASTING

Eruptions can continue for days up to decades. In this case, continual forecasting is valuable in risk-management, such as in Iceland 2023/4 (https://en.vedur.is/volcanoes/fagradalsfjall-eruption/). Questions of particular interest are "is it over?" (so people can return), "where is the lava going (to erupt) next?", or "will the type of activity change?" (particularly to a more dangerous style). Often key monitoring stations can be compromised by the eruption; where additional sensors are brought in, an adjustment in forecasting methods may be necessary.

5.1 Change in style/end of eruption

After eruption begins, the focus shifts from forecasting the onset and initial magnitude of eruption to forecasting the evolution of the ongoing eruption. Many hazards are grouped into styles of eruptions as commonly produced at volcanoes of different types (Part III, Chapter 2.1), for example dome collapse assumes the presence of a dome, lava flows the extrusion of lava, etc. It has been shown [14] that more than half of all eruptions are multi-phase. Changes in style (Part III, Chapter 2.5) can be probabilistically forecast, dynamically in time using semi-Markov chains conditioning on the previous and/or current styles and their durations. This can be extended to the end of the eruption, which is commonly formally defined as '90 days surface quiet'.

Physics-based models can also be used to forecast dome extrusion duration through flux and stability estimates, or initial lava extrusion rate through geodetic measurements and dike inflow estimates (Part VI, Chapter 3.1). Complementary datasets - seismic, geodetic, geochemical - may be jointly interpreted to build up a conceptual model of the magma chamber and its feeding system and hence potential eruptive scenarios. It may be possible to forecast variation in explosive intensity by correlating geodetic measurements and pressure changes in the volcanic system with volcanic plume height [15].

5.2 Hazards in progress

During volcanic eruptions it is important to track the progression of hazard both in space and time, to provide up-to-date information to decision-makers. Field/in-situ measurements and real-time numerical modelling are complementary and linked approaches that can be necessary in this context.

Field measurements are useful for updating scenario information and its evolution (see also Section 5.1) but also provide quantitative data related to eruptive source parameters. Source parameter updates that are crucial for modelling efforts include volcanic plume elevation, mass flow rate, topography changes, or the location of newly opened vents (see Part 6, chapter 3.1). Satellite, radar, aircraft and (UAVs) are extremely useful instruments that enable rapid and in most cases precise quantification of the above-mentioned parameters, particularly for lava flow tracking.

On the other hand, the large availability of numerical models that simulate volcanic phenomena is of great importance in providing quantitative hazard assessment and identifying potentially affected areas. This could be achieved both with a deterministic (e.g., for a single scenario quick evaluation) or with a probabilistic approach: the latter (which provides more complete estimations) allows volcanologists to sample the input parameter space and therefore to obtain up-to-date probabilistic hazard maps (see also Section 5.4).

For example, lava flow hazard assessment was conducted and repeatedly updated during the 2021 Fagradalsfjall eruption in Iceland [16]. In this specific case, a pre-eruptive digital elevation model (DEM) and syn-eruptive data (aerial/satellite images) were used to calculate bulk eruption volumes and time-averaged discharge rates). These data were in turn used as input parameters for a stochastic model, whose outputs were used to discuss with stakeholders both short-term (hours to days) and long-term (months to years) hazard scenarios. Another example of syn-eruptive evaluation is related to tephra dispersal hazard assessment, as shown for example by Pardini et al. [17] for Mount Etna volcano. In this case, during the 2021 lava fountains episodes at Mount Etna, a coupled plume-tephra dispersal model was initialized with information about the eruption timeline and column height from Volcano Observatory Notice for Aviation notifications to produce probabilistic hazard maps of tephra fallout and atmospheric dispersal.

Finally, the hazard from lahars can be both coupled to and decoupled from eruptions. Lahars are generated through melting of ice and/or snow, by remobilization of volcanic material by means of rainfall [7], by liquefaction of a landslide block, by interaction of hot rock with wet soil, or by breaching of a crater lake.

5.3 Secondary hazards

After an eruption has begun, volcanologists and decision-makers are challenged by forecasting changes in eruption style and/or changes in eruptive phenomena that produce new hazards or secondary/cascading hazards (Part III, Chapter 5). This situation is common because changes in volcanic-related flow path, edifice topography, slope stability, and meteorologic conditions might change the hazard scenarios at a given volcano.

Lahars and debris flows are common secondary hazards that occur both during and after eruptions, dependent upon the availability of water (glaciers, summit lakes, rainfall) and sufficient unconsolidated volcanic debris. Ash resuspension by wind might be responsible for health and respiratory problems, especially if tephra fall affects highly urbanized areas. Volcano flank/dome instabilities and collapse could also be the source of PDCs and/or long-runout debris avalanches not directly linked to the eruption itself (i.e., rainfall triggered collapses). Volcanogenic tsunamis are potentially highly destructive secondary hazards that could be generated both from lateral collapses on volcanic islands or submarine eruptions. Fire ignition from volcanic activity is a potential and often underestimated hazard that is linked to a variety of triggering primary volcanic hazards (ballistic projectiles, PDC, lava flow, tephra fall) and eventually enhanced by atmospheric conditions.

Since a pre-crisis evaluation of secondary hazards does not always consider all of the above-mentioned hazards, ad-hoc forecasts/simulations may be conducted for specific areas based on updated volcanic, topographic, and/or meteorologic conditions.

5.4 Hazard maps

Short-term or crisis hazard maps can be created during a volcanic crisis to show the potential distribution of hazards produced in a particular eruption scenario (e.g., the most likely, or a low probability-high impact scenario that forms the basis of emergency planning) at specified dates/times. Crisis maps can provide a spatial representation of an eruption forecast and can focus on the volcano-scale or on one quadrant or sector of the volcano only. These maps incorporate information about the current state of unrest and can include one or multiple different types of hazards, such as maps that showed potential vent-opening locations in the Reykjanes peninsula, Iceland, based on updated locations of seismicity, deformation, and ground cracking (https://en.vedur.is/volcanoes/fagradalsfjall-eruption/hazard-map/).

Crisis hazard maps reflect the topography of the modern volcanic terrain, which may differ from that shown in long-term or background hazard maps, and they commonly incorporate the results of physical, empirical, or numerical models. For example, short-term tephra dispersal hazard maps present the results of scenario-based tephra models using current meteorological conditions. Short-term lava flow hazard maps are updated based on current lava flow front location(s) and potential flow paths and/or travel times from those location(s). These maps are commonly intended for crisis management purposes and may be revised multiple times as conditions change, as new models are run, or as understanding is improved. In some cases, these maps depict exclusion zones that are linked to alert level changes (e.g., in Indonesia). In other cases, crisis hazard maps are used to manage road closure decisions, flight traffic warnings, or selection of evacuation shelter locations.

6 EVALUATION OF FORECASTS

Just as cockpit recorders are present in commercial aircraft to provide lessons for the future, forecasts made during volcanic crises should be evaluated to see how they could be improved. The complexity of volcanic processes, poor knowledge, and the limited datasets mean that statistical tests, along the lines of the Collaboratory for the Study of Earthquake Predictability set-up in seismology (https://cseptesting.org/) are very challenging. Hence the forecasting process is intimately entwined with research and with retrospective analysis of past crises that are examined to improve forecasting models. At the level of hazards, much of the forecast is volcano-specific, often within a methodological wrapper such as event trees, meaning that models can be ‘tuned’ at both generic and volcano-specific levels. These tools provide (total, or conditional) probabilistic assessment, which mostly derive from experts’ judgments (pre-eruptive processes), or from the chaoticity of nonlinear processes (e.g., ash fall dispersion).

6.1 Hindcasting

We make a distinction between forecasting and prediction models. The former contain sufficient information to evaluate post-facto. Critically, a probability must be present, describing the time, location, style, intensity etc. These are often subdivided into finite windows in each dimension (event trees are an exemplar). Other models, such as the failure forecast method, provide forecasts as a probability distribution on the eruption onset time, with consequently poor statistical performance if the onset is greatly delayed. Predictions without likelihoods attached cannot be evaluated statistically.

Forecasting and prediction models are usually tuned looking at past eruptions retrospectively, using different predictors (a process known as ‘hindcasting’) in a search for the optimum formulation. The forecast/prediction is made as if in a ‘live’ situation, at (ir)regular intervals using only past data, generating a set of forecasts/predictions over the course of the unrest period. In case of predictions, the error is then a measure of the uncertainty inherent in the method, and how it varies with volcano, input series and amount of data. In the case of forecasts, the performance can be statistically scored against that of a suitable reference (non-informative) baseline model. The factor that cannot be controlled for in this process is the onset itself. Only prospective forecasts/predictions can account for the fact that the volcano may not erupt.

6.2 After action reports

After a crisis is over, there is great value in retrospective evaluation of the entire forecast process. Such efforts may result in improvements to forecast methodology, changes in expert elicitation processes, incorporation of new data streams or models, or modification of forecast communication approaches, for example. Given the probabilistic nature of forecasts, occurrence of a low likelihood event does not imply failure of a forecast. Instead, we expect that low likelihood events will occur much less frequently than high likelihood events, but the number of global forecasts is far too low to provide a statistical analysis of this type. Instead, a variety of evaluation methods exist to document what went well and what could be improved (e.g., “How could losses have been averted?”) as part of an after-action review of volcanic crisis management.

Counterfactual analysis, or consideration of what could have happened if the eruption had been either more or less hazardous or had not happened at all, can be a useful exercise to better understand cause and effect relationships between interventions and outcomes. Alternatively, quantitative evaluation of forecast skill can be measured using a forecast scoring system, such as the Brier score, originally developed for evaluation of weather forecasts, but since applied to a wide array of multi-category forecasts. Scoring systems are most useful when comparing accuracy between forecasters or when tracking forecasting success through time. Wadge and Aspinall [18] used such a system to demonstrate that forecasters at Soufriere Hills were most successful when the volcano was in a period of repose or when the volcano experienced near steady-state behavior.

7 SOFTWARE AND DATA REQUIREMENTS

Bayesian event tree analysis is a common technique used during volcanic crises to forecast eruption scenarios and their corresponding hazards. A generic event tree, as described by Newhall and Pallister [3], extends from the onset of unrest to potential risks of death, with relative and cumulative probabilities estimated and propagated at each node. These estimates rely on key parameters such as real-time and past monitoring data, eruption history, and recurring hazards. In some applications, expert elicitation is also adopted for the estimates of probabilities and associated uncertainties [10]. Several software tools have been developed for this purpose, including:

- Bayesian Event Tree for Eruption Forecasting (BET_EF), developed by Marzocchi et al. [13], and since expanded on, focuses on short-term eruption forecasting for magmatic unrest. It integrates real-time and historical data with probabilistic models, continuously updating as new monitoring data becomes available. The software (https://theghub.org/resources/betvh/about) computes short- to long-term eruption probabilities with graphical support, useful for crisis management and land-use planning. BET_EF combines theoretical models, a priori beliefs, and monitoring measures to manage uncertainties.

- Short-Term Hazard Assessment Event Tree (ST-HASSET), part of VOLCANOBOX (http://volcanobox.wordpress.com/) is a similar concept, using Bayesian inference to assess future eruptive scenarios based on past eruption records and potential hazards, such as pyroclastic flows and tephra fallout. It updates hazard assessment with new data and offers accuracy intervals to account for uncertainty.

- BET_UNREST (https://gitlab.rm.ingv.it/roberto.tonini/pybetunrest), incorporates both magmatic and non-magmatic unrest in short-term forecasting. It relies on real-time monitoring data and historical records to distinguish between magmatic and non-magmatic causes of unrest. It computes and visualizes probability density functions at all event tree nodes.

The above software all require input monitoring data thresholds which must be obtained by expert elicitation/judgement.

- Event tree using multiple data sets [3], provides a built-in Microsoft Excel-based template (https://theghub.org/resources/3690) that helps construct event trees tailored to specific volcanoes by integrating direct expert elicitation of probabilities informed by monitoring data and historical records. This tool allows customization, offering an approach that accommodates inclusion of wide-ranging volcanic scenarios. By using different data sets at each node, it defines plausible probabilities and indicates uncertainty. The template can be modified to build tailored event trees for any volcano.

- Another framing tool/integration system is a Bayesian belief network (e.g., [7]). Belief Networks connect monitoring observations to unobservable processes, commonly using conceptual or process-based models that incorporate interpretations of the physical and chemical attributes of the magmatic system in addition to an interpretation of the many processes capable of triggering eruptions (e.g., loading/unloading, magma or fluid recharge, second boiling). As with all of the above tools, belief networks can incorporate multiple data sources, including expert judgement, model results, and machine learning algorithms that analyse large datasets to identify patterns and predict behaviour [19].

These tools require comprehensive data sets, including analog cases, which are essential for robust short-term eruption forecasts to improve accuracy and manage uncertainty. Historical data provide baseline scenarios that refine forecasts as new data emerge. Combining expert knowledge with probabilistic models and advanced machine learning techniques ensures dynamic, responsive forecasts. Expert judgement, while subjective, offers insights that purely data-driven models may lack, and recent tools have been developed for simplifying and standardizing its usage in volcanological applications [11]. Comprehensive and multifaceted forecasting approaches improve the ability to forecast and respond to volcanic crises effectively.

8 CASE STUDY: MOUNT AGUNG 2017

In 2017, Mount Agung in Indonesia experienced volcanic unrest that led to eruptions beginning 21 November. Scientists from the Centre for Volcanology and Geological Hazard Mitigation and the Volcano Disaster Assistance Program used probabilistic event trees to elaborate possible unrest outcomes and to facilitate forecasting discussions. Event probabilities were updated via repeated anonymous expert elicitations prior to eruption onset, at which time the tree was modified and then updated three times after the eruption began. Here, we highlight some of the ways in which data were integrated to produce useful forecasts targeted to answer risk-related questions.

Aseismic deformation in February to March 2017 was detected on the Global Navigation Satellite System (GNSS) network, followed by a second period of deformation that was accompanied by volcano-tectonic (VT) seismicity in August to September 2017. Rates of VT seismicity increased dramatically toward a peak on 22 September and reaching M4.2 on 26 September and were accompanied by shallowing deformation northwest of the Mount Agung edifice. These changes were accompanied by minor heat flow increase and steam emissions. VT hypocenters began to migrate toward the summit by late October and on 12 November, low frequency (LF) and tremor seismicity appeared. Distal seismicity continued at a lower rate but included a M4.9 on November 8. On 20 November, a CO_2 anomaly was detected, just 9 hours before the first eruption.

Prior to eruption, probabilities of eruption onset (referenced to a 2-week forecast window) were influenced strongly by increasing rates of VT seismicity, its correlation in time with deformation (detected on the GNSS network), and then by appearance of LF and tremor seismicity. High uncertainties in forecasts were attributed to latency in data transfer or interpretation (e.g., GNSS data retrieval and InSAR interferogram creation), clouds and rain inhibiting DOAS SO_2 measurements, hazards in observing the crater directly, and lack of ability to measure CO_2 via multigas until Nov. 21. Uncertainty only increased through time, largely due to the absence of eruption for 2 months after the peak rate of change of seismicity (in latest September) and the lack of significant shallow and proximal seismicity in October and November. These characteristics prompted scientists to infer slowing rates of ascent and to decrease eruption likelihood (Table 2, accounting for possibility of no eruption).

Table 2. Forecast progression, 20 September to 15 November 2017

Date	Probability of eruption in 2 weeks	What happened?	Utility of forecast
20-Sep	0.50 ± 0.10	No eruption	Alert level decisions, field operations planning
23-Sep	0.70 ± 0.10	No eruption	
2-Oct	0.60 ± 0.10	No eruption	
17-Oct	0.50 ± 0.20	No eruption	
15-Nov	0.40 ± 0.20	Eruption started 21-Nov	

Table 3. Forecast Volcanic Explosivity Index (VEI), to 12 March 2018

Date	Probability of max VEI (2 weeks)			Observed max VEI	Utility of forecast
	VEI ≤ 2	VEI = 3	VEI ≥ 4		
15-Nov*	0.65	0.20	0.10	3	Hazard/evacuation zone maps, field operations planning
11-Dec	0.55	0.28	0.17	2	
24-Jan	0.75	0.20	0.05	1	
12-Mar	0.90	0.09	0.01	1	

*Forecast of eruption size was the same for preceding event trees before eruption onset

Useful forecasts require not only a forecast of when an eruption will start, but also what it will produce and how far it will travel. Eruptive parameter forecasts (Table 3) combined global basaltic andesite to andesite VEI distributions with a recent study of Mount Agung's highly explosive Holocene eruptive history, which identified high ash columns, abundant lava flows, lava flow-front collapse and column collapse PDCs, and many lahars. Further, scientists considered the 2-week time frame of forecasts (useful for making decisions about alert level, which was linked to evacuation decisions) and compared global data that showed that highest explosivity event in an eruption commonly occurs closest to eruption initiation, with local data from Mount Agung's history, which show that paroxysms have occurred weeks to months after eruption initiation in past eruptions. Finally, eruption forecasts were closely linked to crisis hazard maps and sector-based hazard and evacuation zonation based on the modeling of pyroclastic density currents, lahars, and ash dispersal. Potential ballistic hazard zones were also considered using data from the 1963 Mount Agung eruption and analog volcanoes. Together, these forecasts helped support important decisions about volcanic alert level changes, crisis hazard map zonation, instrumentation and field operations plans, and activation of emergency management protocols.

9 FUTURE RESEARCH

Quantitative eruption and volcanic hazard forecasting is a scientific field still in its infancy. We suggest some major objectives that could be prioritized in the field of eruption forecasting and volcanic hazard. The first is related to the development and improvement of data integration through systematic and homogeneous collections of monitoring and eruptive data. This is currently the main goal of important database initiatives (e.g., WOVOdat; [2]), but it and other community efforts require broad support. Such homogeneous databases are essential to finding possible common pre-eruptive behaviors, at least for some families of analog volcanoes. Moreover, richer and more homogeneous volcanic datasets will permit convincing and solid empirical tests of forecasts, the evaluation of their reliability and the comparison of the forecasting skills of different models. The testability of forecasts could become a primary goal, if we want to keep volcanology in a scientific domain.

To improve modelling, quantitative pre-eruptive models would be needed that are rooted in physical and/or stochastic processes and that can be easily adapted or adopted by a wide family of volcanoes. This could be based on better understanding of how monitoring signals relate to the pre-eruptive processes [20]. Regardless of the kind of modeling, probabilistic forecasts could best support an informed decision making for risk mitigation. Meanwhile, in the absence of such models, expert judgement is still going to play a major role in filling the modeling gap and providing probabilistic forecasts with uncertainty quantification. Experiences in this field accumulated in the past decades already allow volcanologists to set up structured expert elicitations oriented to minimize cognitive biases. This is an evolving methodology that could be further strengthened, and that will likely remain one of the best ways to build probabilistic forecasts for many volcanoes.

Finally, any successful improvements on this field and on planning sound risk reduction strategies ineluctably would benefit from better handling and more profound understanding and communication of the probabilistic concepts underlying forecasts, including uncertainty.

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