Feasibility Assessment of Parametric Insurance for Volcanic Unrest and Volcanic Eruption

Component 2 Technical Report

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Executive Summary

Component 2 of the 'Feasibility Assessment of Parametric Insurance for Volcanic Unrest and Volcanic Eruption' project concentrates on investigating the feasibility of applying parametric principles to enable early financing flows during periods of volcanic unrest. Volcanoes are inherently complex and unrest episodes have high uncertainty surrounding them. Financing can usefully be deployed to enable more robust early warning to help reduce the uncertainty and to build awareness of potential outcomes in early phases of unrest and to facilitate live-saving evacuations when an eruption threatens.

We have identified and comprehensively explored a variety of indicators which could be used as the basis for parametric indices in the context of disaster risk financing. These indices must reasonably proxy development of volcanic unrest and the consequent need for financing to support and enable more effective and efficient actions to manage the crisis and protect lives. We have considered how these various indicators are generated, how well they proxy unrest, and how they might be used, alone or in combination, within a parametric insurance framework.

The outcomes of our feasibility assessment can be summarised as follows:

- Objective data-based indicators of hazard, the usual basis for parametric indices, are generally either not available or not suitable in the volcanic unrest case:
  - Ground-based volcano monitoring capacity varies hugely between, and within, the five focus countries (as it does globally). As such, using these data as an index across multiple volcanoes is challenging.
  - Where data do exist, it is typically only available for use by the Volcano Observatories and generally requires interpretation. Therefore, these data will not typically be suitable for use as or input to an externally verifiable independent index.
  - Other challenges include the short history of individual ground monitoring datasets, the common data gaps in those extended time series that might exist, and the difficulty in using pre-defined single or multiple data streams to proxy the development of unrest across multiple volcanoes.
  - Satellite-based monitoring data can, in theory, overcome some of these shortcomings, but the key monitoring data streams currently available are either not yet sufficiently mature, or are not sufficiently good unrest indicators (or both) to be ready to underpin a parametric index or indices.
- Available data combined with current scientific understanding are used by countries to set Volcano Alert Levels (VALs). Setting of VAL is the only indicator at any given volcano which both takes into account available data and is focussed specifically on tracking unrest.
- VAL systems vary between, and in some cases within, countries, but are most similar in the early stages of unrest (low level VAL). As such, they provide the most promising candidate for use as an index on which to base an early parametric trigger.
- At higher levels of volcanic unrest, VAL systems diverge substantially between, and within, countries, with some including recommendations for evacuation and others remaining more focussed on volcanic activity. As such, issuance of an official evacuation order to reduce risk to life

safety is the most promising candidate for use as the trigger for finance flows to support evacuation.

- We conclude that a dual-trigger structure, using early VAL movement as a first (and smaller) trigger and evacuation order as the second (main) trigger is the only currently viable option for a parametric insurance product focussed on supporting finance flows during volcano unrest.

Based on this conclusion, we outline a probabilistic risk assessment methodology which would be required to underpin insurance policy pricing, present a case study of the risk assessment for a potential policy for a focus country, and develop the necessary parametric insurance structure and supporting information to implement this parametric solution.

1 Introduction

This report details a feasibility assessment of a parametric insurance product for volcanic unrest, focussing in particular on five countries: Indonesia; Papua New Guinea; the Philippines; Tonga; and Vanuatu. Drawing on existing data and new analysis presented in the Component 1 Technical Report, and on new data collected during this project and presented in this report, we explore the feasibility of using various indicators[1] of volcanic unrest, in index form[2] and individually or in combination with one another, to underpin a parametric insurance product.

The indicators cover a range of possibilities, from declared Volcano Alert Level (VAL), a subjective but widely used categorisation of volcanic activity (including unrest), that, depending on jurisdiction, may be directly linked to preparedness activities including evacuations, through to a Volcanic Unrest Index (VUI)[3], conceived as an objective amalgam of available unrest indicators. We also explore how different indices could be applied at different stages of an evolving unrest situation, and how they can take account of actual decisions made by authorised sovereign agencies such as evacuation calls, allowing for multiple triggers[4] and a progressive pay-out mechanism.

Volcanic unrest involves many different phenomena, such as elevated seismicity, ground deformation, gas emissions and sometimes minor volcanic activity. Volcanoes pose several different kinds of hazards (perils), some of which are strongly influenced by external factors such as volcano topography and / or intense rainfall; these external factors may become important in preparedness and evacuation decisions. We highlight that for most of the volcanoes in the study region many of these parameters will be unmonitored or poorly monitored at the start of an unrest episode, and that in many cases no baseline information is available.

We note that under-monitoring of volcanoes is a global problem, as illustrated by the recent update of the United States Geological Survey national volcanic threat assessment[5], which considers as a criterion whether there is sufficient monitoring to detect unusual seismic activity, and which found that for tens of US volcanoes, the answer is no. An analysis of global monitoring capacity[6] indicates that the proportions of unmonitored and inadequately monitored volcanoes in developing countries is even greater.

Thus, although the most comprehensive, objective index to capture volcanic unrest would be multi-parametric, the amount of information on which to base that estimate, and the number of available parameters, will vary enormously between the best and worst monitored volcanoes. Hence, different indicators and indices may be more or less relevant to different regions depending on data availability.

A further issue is that volcanic eruptions can last for weeks, months and even years, making volcanic emergencies distinctly different to rapid onset and short duration natural hazards like earthquakes and

[1] Indicators are parameters or measures of the phenomenon under investigation, which may be subjective or objective.
[2] An index is the sorted numerical representation of the underlying indicator, or a derivative of that indicator, which can have from 2 (in which case it is referred to as binary) to an infinite number of units.
[3] Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E. & Johnston, D.M. (2015) Introducing the Volcanic Unrest Index (VUI): a tool to quantify and communicate the intensity of volcanic unrest. Bulletin of Volcanology 77:77.
[4] A trigger is the point or step on an index at which an action occurs. In the parametric insurance context, a trigger generally refers to the index level at which a pay-out occurs; an index can have one or multiple trigger levels, with the same or different pay-outs at each, depending on the insurance product structuring.
[5] Ewert, J.W., Diefenbach, A.K. & Ramsey, D.W. (2018) 2018 update to the U.S. Geological Survey national volcanic threat assessment. U.S. Geological Survey Scientific Investigations Report 2018–5140.
[6] Ortiz Guerrero, N., Brown, S.K., Delgado Granados, H. & Lombana Criollo, C. (2015) Global monitoring capacity: development of the Global Volcano Research and Monitoring Institutions Database and analysis of monitoring in Latin America. In: S.C. Loughlin, R.S.J. Sparks, S.K. Brown, S.F. Jenkins & C. Vye-Brown (eds) Global Volcanic Hazards and Risk, Cambridge: Cambridge University Press.

tropical cyclones. Dangerous situations may arise at any time within an eruptive sequence, and major evacuations can be called well into an ongoing eruption. If activity escalates then there may be staged or multiple evacuations. Thus, a parametric insurance product that only relies on information prior to the start of an eruption is unlikely to be successful in many cases. Our evaluation criteria will highlight such complexities.

We have followed the following broad design steps for the unrest product:

- Explore indicators and resulting index options;
- Identify the quantum and timing of financing needs during unrest episodes;
- Evaluate feasibility of various trigger options, and identify most feasible parametric structure(s);
- Test selected structure(s), including probabilistic analysis and historical case studies; and
- Frame the potential implementation of a parametric insurance policy in the focus countries.

Five further sections in this report cover each of the design steps listed above.

2 Volcano unrest indicators and potential parametric indices

Volcanoes are dynamic landforms within which a variety of physical and chemical process operate. Volcanic unrest therefore involves many different physio-chemical phenomena, and the signals sent out by these phenomena – and received by any active monitoring instrumentation – is itself highly complex.

Volcanic unrest presents many challenges. What is considered 'normal background behaviour' at one volcano can result in serious concern at another. Furthermore, volcanoes almost always provide ambiguous signals, and monitoring data streams can easily pick up non-volcanic signals, including but not limited to, regional earthquake activity, wind, lightning, and anthropogenic noise.

Over the past century, and particularly the past 40 years, volcano monitoring has become increasingly sophisticated and has saved at least many tens of thousands of lives[7] and probably many hundreds of thousands. Volcano monitoring is the proven and most effective way to forecast and understand the evolution of volcanic activity.

Some activity implicitly indicates activation of a volcanic system. Sustained ground deformation on the scale of metres per day is an obvious example. Interpreting data during unrest is best done with knowledge of the volcanic system, and even then, it is often challenging. Small eruptions can happen at well-monitored volcanoes with little or no useful warning. Furthermore, the scale, duration and intensity of a given unrest episode does not necessarily correlate with the probability or scale of the associated eruption, let alone its impacts.

Put bluntly, unlike all other major natural hazards systems and despite major steps forward in understanding of the physical and chemical processes driving eruptions, there is no overarching model or process that associates observed and measured unrest with the precise character of subsequent eruption style, hazards and impacts.

In this section, we:

- Provide background for quantitative ground and space-based monitoring indicators, with a detailed discussion of the global state-of-the-art capabilities for both provided in Annexe 1;
- Describe synthesising products including Volcano Alert Level (VAL) systems, with a detailed discussion of each focus country's VAL system provided in Annexe 2, and more rigorous multi-parameter products including Bayesian Event Trees and the Volcano Unrest Index[8];
- Discuss volcano response and evacuation considerations and actions;
- Provide an overview of the current capabilities in each focus country; and
- Summarise the results of our comprehensive analysis of candidate parametric insurance triggers, available in Annexe 3.

[7] Auker, M.R, Sparks, R.S.J., Siebert, L., Crosweller, H.S. & Ewert, J. (2013) A statistical analysis of the global historical volcanic fatalities record. Journal of Applied Volcanology, 2:1–24.
[8] Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E. & Johnston, D.M. (2015) Introducing the Volcanic Unrest Index (VUI): a tool to quantify and communicate the intensity of volcanic unrest. Bulletin of Volcanology, 77:77.

2.1 Quantitative unrest indicators

Typically, volcanoes entering into or already in unrest will shows signs of some or all of the following:

- Elevated seismicity and changes to the characteristics of the seismicity;
- Ground deformation;
- Enhanced gas emissions and changes to the form and composition of emitted gases;
- Thermal changes which might be detected from space or on the ground;
- Groundwater and other related chemical changes;
- Observable landform and vegetations changes; and
- Minor volcanic activity.

International experience convincingly demonstrates that volcano monitoring is the best way to prepare for and reduce the consequences of volcanic eruptions. The recognition of unrest typically involves combining several of the above indicators into an integrated assessment.

This section provides an overview of the state-of-the-art in ground and space-based volcano monitoring globally. More detailed information is provided in Annexe 1. We place particular emphasis on the potential of monitoring systems which could provide indicators suitable for use in a data-driven index underpinning parametric mechanisms for risk financing (see Annexe 3).

2.1.1 Ground-based volcano monitoring

Visual methods

Visual observations are a critical part of volcano monitoring. There are several ways this is undertaken, including training local observers that provide regular or *ad hoc* reports to volcano observatories, site visits by observatory staff, and webcam imagery.

Geophysical methods

Geophysical techniques measure signals at the ground surface that are symptomatic of processes occurring at depth, and also can be used to monitor surface processes, including but not limited to pyroclastic density currents, landslides, and volcanic plumes. Traditionally, most geophysical techniques require permanently emplaced monitoring equipment, or at least frequent monitoring campaigns. The spatial and temporal coverage of monitoring equipment typically depends on the resources available to the monitoring organisation, though sometimes political boundaries or geographical features limit access to the area of interest.

Seismology

Seismic monitoring can indicate the intensity of volcanic activity or unrest. A single station can be used to estimate overall release of seismic energy (e.g. Real-time Seismic Amplitude Measurement (RSAM)[9]), and three or more stations can be used together to locate earthquakes. Overall, seismic

[9] Endo, E.T. & Murray, T. (1991) Real-time Seismic Amplitude Measurement (RSAM): a volcano monitoring and prediction tool. Bulletin of Volcanology, 53: 533–545.

monitoring is the most valuable, near real-time, volcanic monitoring technique; it is more widely used to monitor changes in volcanic activity than any other technique.

Geodesy

Geodesy is the second most commonly used geophysical monitoring technique, which detects changes in ground deformation that generally indicate changes in subsurface pressure. Traditionally, geodetic techniques were rarely used in real-time; electronic tiltmeters have been deployed during unrest episodes and can provide information on short-term changes if the signal to noise ratio is sufficiently high. Improvements in the global GPS system and associated calculation techniques over the past two decades now enable continuous, real-time GPS monitoring to be useful on temporal scales of hours to days.

Acoustic

Acoustic sensors measure atmospheric pressure fluctuations caused by transient, unstable fluid motions. Acoustic sensors are principally used to detect surface activity, such as volcanic eruptions, and are often paired with seismic monitoring networks.

Other geophysical methods

Other geophysical monitoring techniques include micro-gravity, magnetics and borehole strainmeters. These techniques are often deployed, and data collected, only intermittently and such deployments are usually intended for studying longer-term volcanic processes, on the scale of months to years. Borehole observatories, including the strainmeters, are very effective and sensitive but also very expensive so they have only been deployed on a small number of volcanoes.

Volcanic geochemical monitoring

Monitoring volcanic gases emitted at the surface provides information about processes at depth, such as the influx and emplacement of magma and changes in fluid pathways. Geochemical monitoring can detect subtle changes that may not be detected by geophysical techniques and is used to complement geophysical methods and visual observations. Few geochemical monitoring techniques are available in real-time, so the techniques usually aim at detecting changes occurring on long temporal scales.

Emission rate of volcanic gases

Gas emission rate is often measured using ground-based remote sensing techniques (e.g. DOAS, FlySpec and COSPEC spectrometry instruments), and is mostly concerned with the emission of sulphur dioxide (SO_2), because it is normally not present in the atmosphere so is easy to measure. Near-real time data acquisition is possible provided there are favourable wind conditions and ambient sunlight.

Chemical composition of volcanic gases

Determining the chemical composition of volcanic gases generally requires direct sampling and lab analysis, although technological developments are beginning to provide more real-time alternatives for some geochemical elements (e.g. multi-gas detection instruments).

Other geochemical methods

Other geochemical methods include water chemistry sampling where volcanic gases are discharged into lakes or hot springs (instead of open vents or fumaroles). In most cases, water sampling requires direct sampling and lab analysis.

2.1.2 Space-based volcano monitoring

Over the past couple of decades, space-borne techniques have increasingly been used to monitor volcanoes. These techniques usually consist of some form of imagery captured from space, whether in the visible or other spectra (e.g. IR, thermal, radar). During volcanic unrest, satellites may be used to monitor ground deformation, ground temperature, changes in ground vegetation, gas emissions and volcanic activity (such as lava dome growth) concealed by meteorological clouds.

Table 2.1 provides a summary of the key characteristics of space-based monitoring datasets.

	Satellite	Acquisition	Processing	Analysis
High-T Thermal	Terra / Aqua	Sub-daily	Automated 12-18 hrs (MODVOLC / MIROVA)	Automated alerts issued
Low-T Thermal	ASTER	~16 days	Google Earth Engine	Expertise required
Deformation	Sentinel-1	6 - 12 days	Automation in development (LiCSAR)	Expertise required to distinguish atmospheric artefacts and model deformation source
SO_2 (UV)	OMI	Sub-daily	Automated 1-2 days (Global Volcano Sulfur Monitoring Program)	Regional time series of SO_2 mass produced automatically
SO_2 (IR)	IASI	Sub-daily	Expertise required	Expertise required

Table 2.1 Summary of characteristics of satellite volcano monitoring data streams. Further details and references are provided in Annexe 1.

The greatest advantages of satellite remote sensing are surface coverage and the reliable nature of the data stream. The greatest challenges are poor temporal resolution (in many but not all cases) and, depending on the technique, a dependence on favourable atmospheric or ground conditions. Some aspects of data processing and interpretation also require highly specialist expertise which may not be readily available.

Ground deformation

Interferometric Satellite Radar (InSAR) is used to measure ground deformation with millimetre precision and repeat intervals of 6 to 24 days depending on geographic location. Baseline measurements back to the early 1990s are available. Significant expertise is required to process and analyse the data appropriately. The major limitations of satellite InSAR are a loss of coherence in vegetated areas, which increases with time between acquisitions, and slope and atmospheric artefacts at high relief edifices caused by stratification in tropospheric water vapour[10]. Both are especially prevalent in the tropical regions of Asia-Pacific.

Degassing

Satellite measurements of volcanic degassing focus primarily on SO_2 emissions, and measurements of volcanic SO_2 have been made routinely since 1978[11]. Satellite detections of other volcanic gas species have only been made occasionally and for recent eruptions. The interpretation of volcanic SO_2 observations from both satellite and ground-based methods is inherently ambiguous and needs to be made in the context of other monitoring information and the specific circumstances of the particular volcano. However, the detection of SO_2 emissions above any background at a dormant volcano is very likely evidence of the onset of unrest.

Thermal

Thermal anomalies associated with lava flows and fumaroles can be detected using Thermal Infrared (TIR) or Middle Infrared (MID) satellite sensors. Two distinct categories exist: (1) high temporal / low spatial resolution systems (e.g. MODIS with sub-daily repeats but 1 km resolution) and (2) high spatial / low temporal resolution systems (e.g. ASTER with 16-day repeats at the equator but 90 m resolution). For the former, the spatial resolution is too low to estimate the temperature of the anomaly or to identify low-temperature features associated with geothermal or hydrothermal systems. For the latter, detections are often caused by low-temperature thermal anomalies associated with fumaroles and low magnitude eruptions. Elevated thermal fluxes have been identified prior to some eruptions but the majority of detected thermal anomalies are co-eruptive.

Morphology

Volcanoes, particularly in tropical climates, can be covered by cloud so changes in gross morphology that might be regarded as suspicious or concerning, particularly in an active crater, may not be directly observed. Radar images can see through cloud and satellite-based radar imagery has provided critical evidence, on, for example, rapid dome growth, in some volcanic emergencies.

2.2 Synthesising products

2.2.1 Volcano Alert Level

Volcano Alert Level (VAL) systems are used by many volcano observatories around the world to quickly and simply communicate a pre-determined status update, outlook or message concerning a volcano[12,13]. VAL systems generally cover the entire eruptive cycle, including dormancy, unrest, and eruption. VAL systems are non-linear, typically have between 4 and 6 discrete levels, and can be numbered (e.g. VAL 1), named by colour (e.g. orange), or named by an action word (e.g. Watch). There are many different purposes to VAL systems including, but not limited to, communicating

[10] Ebmeier, S.K., Biggs, J., Mather, T.A. & Amelung, F. (2013) Applicability of InSAR to tropical volcanoes: insights from Central America. Geological Society London Special Publications, 380: 15–37.
[11] Carn, S.A., Clarisse, L. & Prata, A.J. (2016) Multi-decadal satellite measurements of global volcanic degassing. Journal of Volcanology and Geothermal Research, 311: 99-134.
[12] Potter, S.H., Jolly, G.E., Neall, V.E., Johnston, D.M. & Scott, B.J. (2014) Communicating the status of volcanic activity: revising New Zealand's volcanic alert level system. Journal of Applied Volcanology, 3:13.
[13] Fearnley, C. & Beaven, S. (2018) Volcano alert level systems: managing the challenges of effective volcanic crisis communication. Bulletin of Volcanology, 80:5.

volcano status, forecasting future activity, and instructing mitigative actions (e.g. evacuations, area access). VALs are usually designed – and assigned - by volcano observatories, but in some jurisdictions VALs are set by emergency managers or the government. VALs are communicated via official channels to government officials and other responding agencies. The media and the public are also typically notified simultaneously.

VALs are issued for both increasing and decreasing volcanic activity based on analysis of data from some or all of monitoring networks, direct observations and satellite sensors. They include information about the nature of the unrest or eruption, as well as about current or potential hazards and likely outcomes. Most VALs are country-specific and may be further subdivided by the repose time (frequently active / reawakening). Broadly, all contain several or all of the following points:

- Indicative phenomena (description of the precursory activity, including seismic, geodetic or gas changes);
- Volcano status (a one-line description of the overall activity);
- Recommended action (informing on exclusion zones and recommendations for evacuations);
- Time scale (potential time-frame before an eruption); and
- Number or colour scale (to communicate changing volcanic threat).

Annexe 2 provides detailed descriptions of the VAL systems in each of the five focus countries, newly compiled and elaborated for this project.

2.2.2 Other synthesising products

Volcanic Ash Advisories (VAA)

To mitigate the likelihood of aircraft-volcanic ash encounters, nine Volcanic Ash Advisory Centres (VAACs), set-up and coordinated by the International Civil Aviation Organisation, monitor volcanic ash and issue warnings. VAACs issue Volcanic Ash Advisories (VAAs) when there is ash in the atmosphere within their region. While VAACs maintain situational awareness about volcanic activity in their region, they are only concerned about ash-emitting volcanic activity. The focus countries for this project are covered by the Darwin (Indonesia, PNG, Philippines), Tokyo (Philippines), and Wellington (Vanuatu, Tonga) VAACs (Figure 2.1).

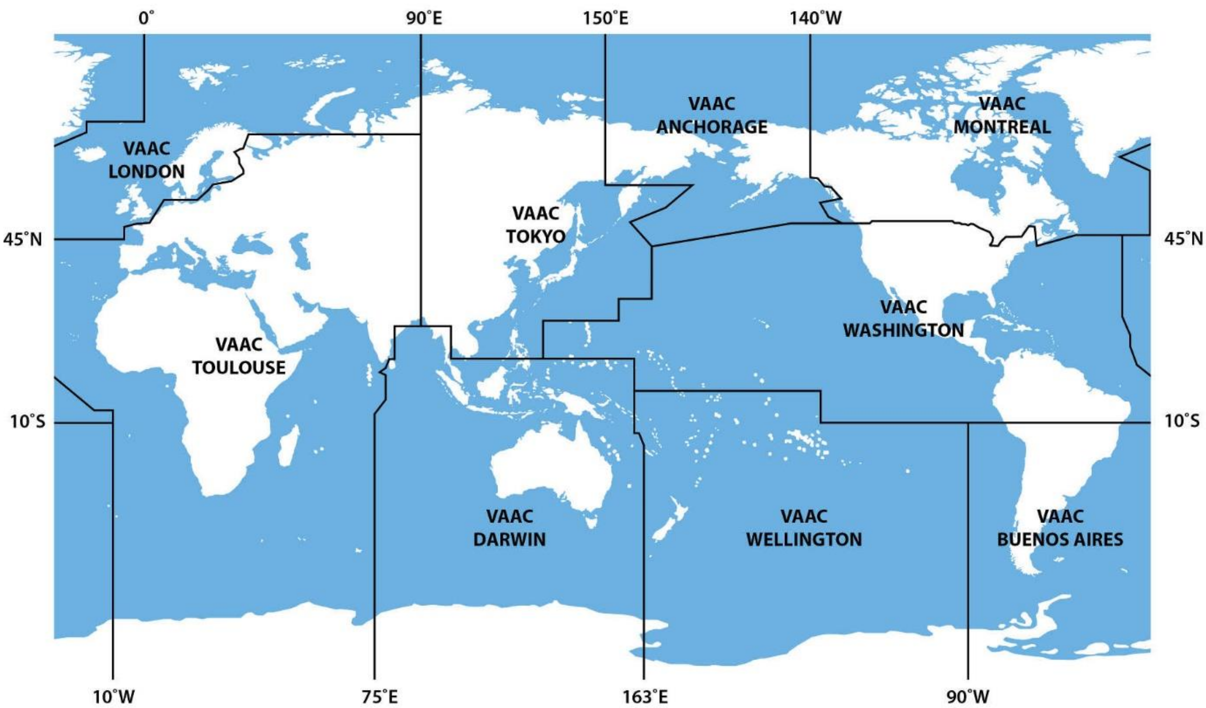

Figure 2.1 Areas of responsibility for Volcanic Ash Advisory Centres (image provided by New Zealand CAA).

Bayesian Event Trees

Bayesian Event Trees (BETs) provide a framework for quantifying possible volcanic unrest through eruption sequences (Figure 2.2)[14,15,16]. As a situation unfolds, the probabilities of various 'branches' are updated to estimate the current probability of various outcomes. BETs are used by several observatories around the world[17], and have been applied retrospectively to explore applications for crisis management[18].

[14] Newhall, C.G. & Hoblitt, R.P. (2002) Constructing event trees for volcanic crisis. Bulletin of Volcanology, 64:3-20.
[15] Marzocchi, W., Newhall, C. & Woo, G. (2012) The scientific management of volcanic crises. Journal of Volcanology and Geothermal Research, 247-248:181-189.
[16] Sobradelo, R., Bartolini, S. & Martí, J. (2014) HASSET: a probability event tree tool to evaluate future volcanic scenarios using Bayesian Inference. Presented as a plugin for QGIS. Bulletin of Volcanology, 76:770.
[17] Wright, H.M.N., Pallister, J.S., McCausland, W.A., Griswold, J.P., Andreastuti, S., Budianto, A., Primulyana, S., Gunawan, H., 2013 VDAP team & CVGHM event tree team (in press) Construction of probabilistic event trees for eruption forecasting at Sinabung volcano, Indonesia 2013–14. Journal of Volcanology and Geothermal Research.
[18] Sobradelo, R. & Martí, J. (2015) Short-term volcanic hazard assessment through Bayesian inference: retrospective application to the Pinatubo 1991 volcanic crisis. Journal of Volcanology and Geothermal Research, 290: 1-11.

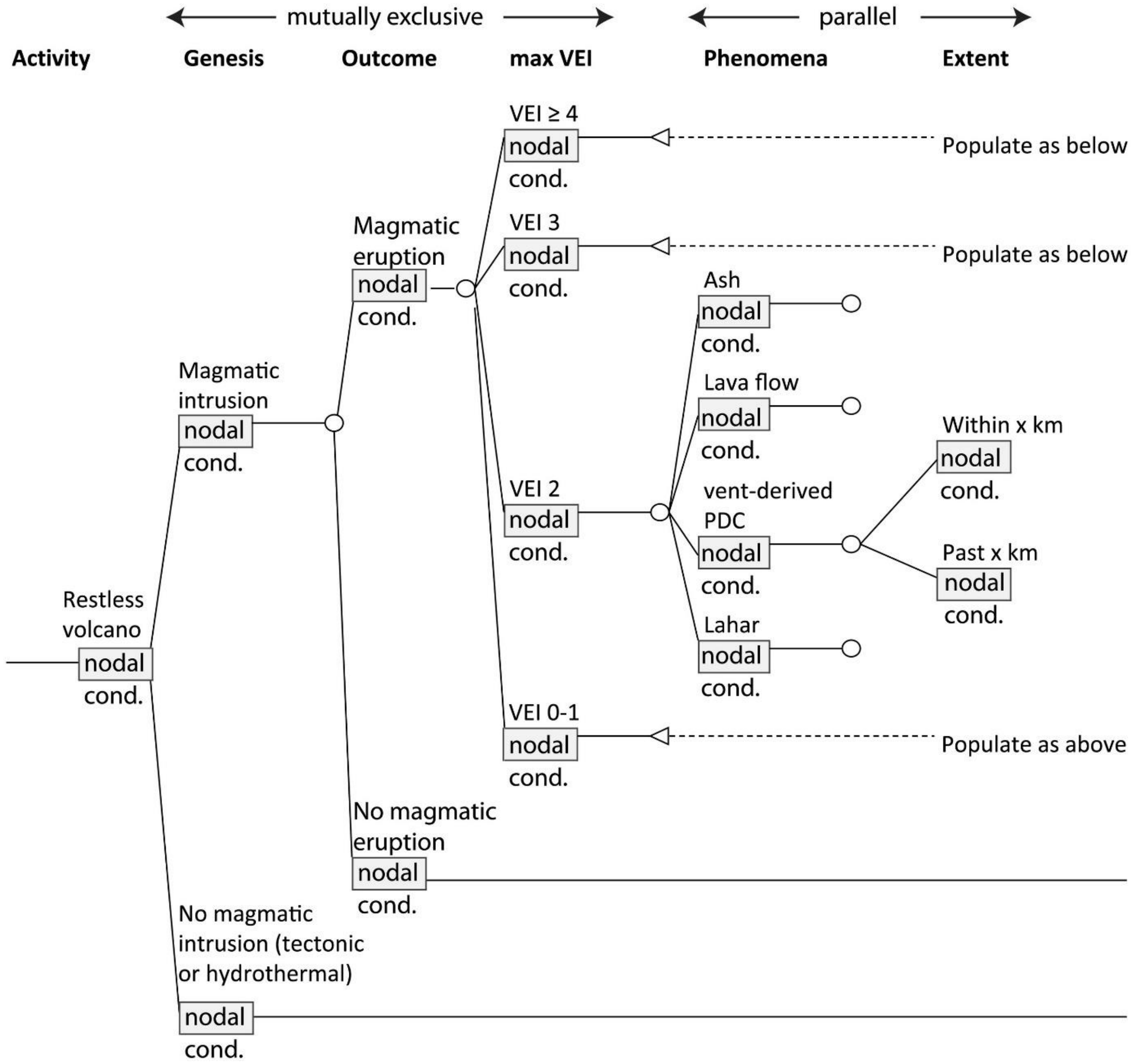

Figure 2.2 Generic example of a BET. In the case of mutually exclusive scenarios ('Genesis', 'Outcome', and 'max VEI'[19]), conditional probabilities must sum to 100%. Parallel limbs ('Phenomena' and 'Extent') can occur simultaneously so probabilities do not necessarily sum to 100%. Conditional probabilities are abbreviated as 'cond.', and nodal probabilities are listed within boxes denoted 'nodal'. (Figure from and caption after Wright *et al*., in press[20].)

[19] Volcanic Explosivity Index, see Section 2.2 of Component 1 Technical Report.

[20] Wright, H.M.N., Pallister, J.S., McCausland, W.A., Griswold, J.P., Andreastuti, S., Budianto, A., Primulyana, S., Gunawan, H., 2013 VDAP team & CVGHM event tree team (in press) Construction of probabilistic event trees for eruption forecasting at Sinabung volcano, Indonesia 2013–14. Journal of Volcanology and Geothermal Research.

Volcanic Unrest Index

A Volcano Unrest Index (VUI) has been recently proposed to characterise objectively the severity of volcanic unrest (Figure 2.3)[21]. The five-level VUI is evaluated using a worksheet of observed phenomena, including local seismicity, local deformation, and geothermal systems and degassing. The VUI was developed for large caldera systems but could be applied to other volcanoes. Parameter thresholds and time interval must be designated in advance of VUI application and need to be tailored to the individual volcano. We note that VUI is presently used as an outreach and education tool, and not used operationally anywhere in the world that we are aware of.

Volcano: ___ Area used: ___ Date applied: ___ Real-time / Past episode Time window: ___		Volcanic Unrest Index (VUI) Worksheet					VUI = ___
		0 No unrest	**1** Negligible unrest	**2** Minor unrest	**3** Moderate unrest	**4** Heightened unrest	
Local Earthquakes	Duration of earthquake swarm (all EQ types)	No earthquake swarm	Short (≤ ___ time unit)	Short to moderate (___ ≤ ___ time unit)	Moderate to long (___ ≤ ___ time unit)	Long (> ___ time unit)	
	Location of earthquakes (all EQ types)	No locatable EQs or generally deep hypocentres (> ___ km)	Moderate depth (___ ≤ ___ km), or shallow depth (≤ ___ km) and distant from likely vent (___ ≤ ___ km)			Shallow (≤ ___ km) and close to vent (≤ ___ km), or unlocatable tremor	
	Maximum rate of volcano-tectonic (VT) earthquakes	No VTs or low rate (0 ≤ ___) of low magnitude (≤M ___) EQs per time unit	Moderate rate (___ ≤ ___) of low magnitude (≤M ___), or low rate (1 ≤ ___) of high magnitude (>M ___) EQs per time unit)	High rate (> ___) of low magnitude (≤M ___), or moderate rate (___ ≤ ___) of high magnitude (>M ___) EQs per time unit)	High rate (> ___) of high magnitude (>M ___) EQs per time unit)	Rapid acceleration in rate, may include sudden decrease in rate	Use only the highest of these 2 scores
	Tremor, low-frequency and hybrid earthquakes	None		Weak tremor (≤ ___ units) or low rate of LF or hybrid EQs (1 ≤ ___ per time unit)	Moderate tremor (___ ≤ ___ units) or high rate of LF or hybrid EQs (> ___ per time unit)	Strong tremor (> ___ units)	
Local Deformation	Maximum rate of local deformation	No deformation	Low rate of deformation (≤ ___ units ___ per time unit)	Moderate rate of deformation (___ ≤ ___ units per time unit)	High rate of deformation (> ___ units ___ per time unit)	Rapid acceleration in rate of deformation, or sudden decrease in rate	
	Location of deformation source (e.g., through modelling)	No deformation	Slowly deflating source or local tectonic fault movement	Deep inflating source (> ___ km)	Inflating source at a moderate depth (___ ≤ ___ km)	Shallow (≤ ___ km) inflating source or migration towards the surface	
	Groundwater levels and spring flows	Levels and spring flows reflect that of surrounding areas	Low levels and spring flows. May include wells or spring-fed ponds drying, or streams ceasing to flow		High levels or spring flows. May include hot or cold water spouting (not geysers), or high stream-flow/lahars without corresponding rainfall or lake contribution		
Geothermal systems and degassing	Surface temperature, heatflow, and manifestations	Ambient temperatures, no above-ambient heatflow, no active surface manifestations	Above ambient temperature, heatflow or activity at surface manifestations	Heatflow or temperatures near or at boiling conditions, or moderate activity at surface manifestations	Geothermal system hotter than boiling conditions, may include hydrothermal eruptions	High heatflow, temperatures or activity, may include phreatic eruptions	
	Gas flux	Low levels of gas flux (≤ ___ t/day of CO_2 and ≤ ___ t/day of acid gases)	Moderate levels of gas flux (___ ≤ ___ t/day of CO_2 or ___ ≤ ___ t/day of acid gases) Effects may include gas-induced vegetation kill or effect on animal life			High levels or acceleration of gas flux (> ___ t/day of CO_2 or > ___ t/day of acid gases), or a sudden decrease	
	Gas and fluid composition	Meteorological signature	Hydrothermal signature	Mixed to magmatic signature	Magmatic signature		

Figure 2.3 VUI worksheet proposed by Potter *et al*., 2015[22].

[21] Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E. & Johnston, D.M. (2014) Introducing the Volcanic Unrest Index (VUI): a tool to quantify and communicate the intensity of volcanic unrest. Bulletin of Volcanology, 77:77.
[22] Potter, S.H., Scott, B.J., Jolly, G.E., Neall, V.E. & Johnston, D.M. (2014) Introducing the Volcanic Unrest Index (VUI): a tool to quantify and communicate the intensity of volcanic unrest. Bulletin of Volcanology, 77:77.

Rate of Change Indicators

There are similarities in how volcanoes behave and how eruptions unfold; however, volcanoes are extremely complex and individual systems. While in some cases, logical groupings of volcanoes may be reasonable (e.g. volcanoes with no monitoring located in a specific country), any objective parametric index aiming to capture the evolution of unrest must be able to capture idiosyncrasies of different volcanoes. For an objective index to be applicable to all volcanoes, it is crucial it does not rely on absolute values. A promising alternative approach is rate of change, recently explored in retrospect for the 1991 Pinatubo eruption. Here, using a Bayesian approach, Sobradelo and Martí (2015)[23] built a table to follow the evolution in time of select unrest indicators. Next, using different combinations of unrest indicators, the probability of five different scenarios could be evaluated as the situation progressed (Figure 2.4). The novelty of this exploratory approach is that it allowed the compilation of the increase or decrease in unrest signals into a common measure (rate of change) to detect inflection points.

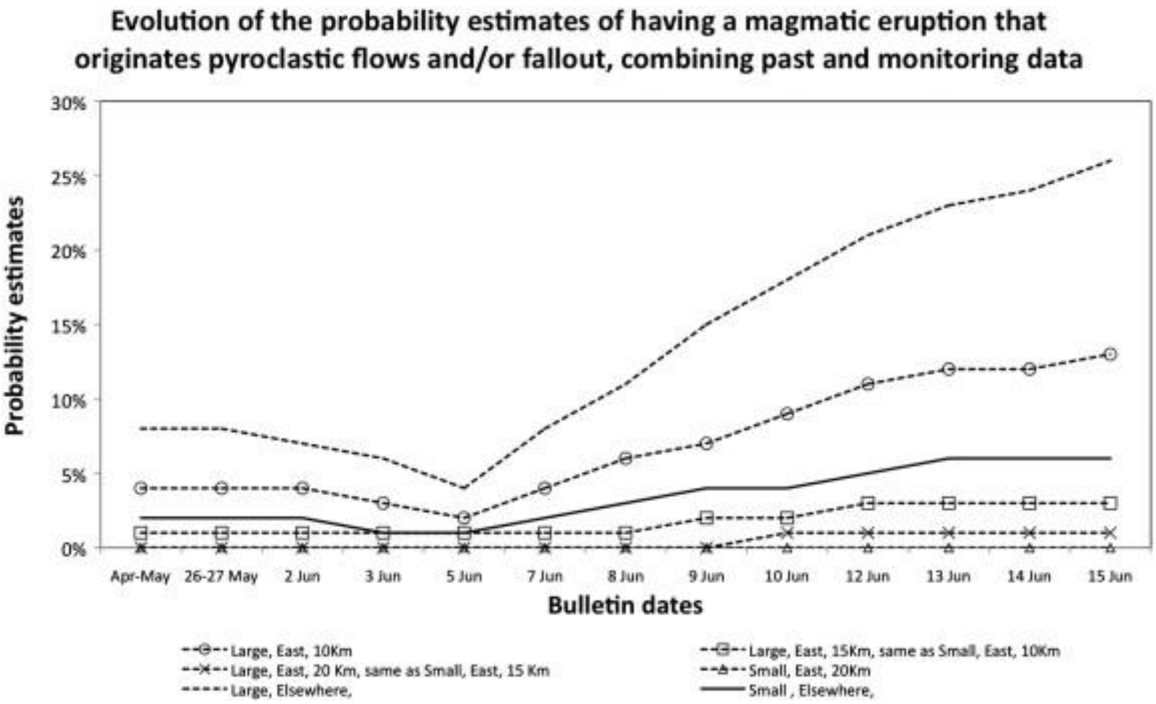

Figure 2.4 Retrospective analysis of the evolution of the probability of a magmatic eruption in the lead up to the 1991 Pinatubo eruption for various scenarios, merging past information on size, location and extent with monitoring data on overall seismicity increase, gas increase, deformation and fresh magma. (Figure from and caption after Sobradelo and Martí, 2015[24]).

[23] Sobradelo, R. & Martí, J. (2015) Short-term volcanic hazard assessment through Bayesian inference: retrospective application to the Pinatubo 1991 volcanic crisis. Journal of Volcanology and Geothermal Research, 290: 1-11.
[24] Sobradelo, R. & Martí, J. (2015) Short-term volcanic hazard assessment through Bayesian inference: retrospective application to the Pinatubo 1991 volcanic crisis. Journal of Volcanology and Geothermal Research, 290: 1-11.

2.3 Volcano unrest response and evacuation considerations

Volcano unrest response

How unrest is detected and what happens next depends on the local monitoring context, volcano observatory resources, and perceived situational urgency. Table 2.2 provides generalisations on volcano observatory actions relevant to the focus countries based on consortium partner experience and feedback received during country visits and a workshop on 19 October 2018 following the Understanding Risk Financing Pacific conference in Port Vila, Vanuatu, with representatives from Rabaul Volcano Observatory (PNG), the Vanuatu Meteorology and Geohazards Department, and the Tonga Geosciences Service.

<table>
<tr><th>Monitoring status</th><th>Unrest detection</th><th>Volcano observatory actions</th></tr>
<tr><td>All volcanoes</td><td>See below</td><td>▪ Visual inspection and if possible, campaign survey
▪ Request satellite examination for past weeks, months, years
▪ Discuss with international colleagues if unrest severe enough or if there is great uncertainty</td></tr>
<tr><td>Volcanoes with no instrumental monitoring</td><td>Local report or remote sensing anomaly</td><td>As above, and:
▪ If possible, install a seismometer(s)
▪ If possible, acquire gas data</td></tr>
<tr><td>Volcanoes with limited monitored (international standards)</td><td>Notice something odd on a seismometer, local report and / or remote sensing anomaly</td><td rowspan="2">As above, and:
▪ If possible, install more seismometers
▪ If possible, install more instruments</td></tr>
<tr><td>Volcanoes that are well-monitored (international standards)</td><td>Detect unrest instrumentally</td></tr>
</table>

Table 2.2 How volcano observatories detect and respond to volcanic unrest as a function of existing and available monitoring capabilities.

Evacuation considerations

In the Pacific, there are two very different types of evacuations: evacuations of entire island(s), where individuals are unlikely to be able to self-evacuate and considerable resources are required (boats, planes), and evacuations where residents move via land to a safer place.

For land-based evacuations, often there are not major costs with the physical evacuation itself; the cost will be in providing shelter, food, water, possible health care, possible animal 'housing', and similar for displaced populations. Indonesia has been able to evacuate tens of thousands of people in a few hours. The cost is less the physical act of removing people from danger, but rather evacuee support.

For island evacuations, considerable resources and a sizeable lead time are often required. The longer the lead time, the less certainty there is concerning eruption occurrence / timing / size. In the case of evacuations to mitigate acute life-safety risk, evacuation decisions often need to be made in the face of great uncertainty. In the case of an evacuation when an eruption has started and is continuing to threaten lives (a rescue operation), there is very little time. In circumstances when evacuation is due to habitability (e.g., August 2018 evacuation of Ambae, Vanuatu), there is usually more time. However, the cost of organising and running boats, planes, etc. is quite high, in addition to the costs associated with land-based evacuations.

In all cases, often many more people are evacuated than are at high risk because of the precautionary principle and the large uncertainties in the assessment of hazard footprints of an impending eruption. There are also different types of evacuations, some that are effectively exclusions zones, and other relating to land-use (e.g., daytime entry permitted). Residents and tourists do not want to be evacuated unnecessarily, although self-evacuations do occur when individuals feel threatened. There can be self-evacuations outside the official evacuation zone if individuals, families, and communities feel the threat is higher than the official response suggests. Evacuations that are perceived unnecessary are very unpopular and can lead to erosion of trust in scientists and authorities amongst the population, with consequences for future events.

We note that evacuations driven by habitability concerns are explored in work under Component 3, as such evacuations are driven by the impacts of volcanic activity itself, rather than unrest.

2.4 Current capabilities in focus countries

Here we focus on volcano observatory activity in the five focus countries, considering monitoring and volcano alert levels separately.

2.4.1 State of volcano monitoring in focus countries

In the following section, we provide a short narrative summary of the status of ground-based monitoring systems as operated by the volcano observatory in each of the five focus countries, a summary table of which can be found in Table 2.3. We also comment on human resources and the real-time availability of data.

Country	Monitored / Holocene Volcanoes	Real time data?	Publicly available data?	Real-time instrument types	Local observers?
Indonesia	69/127	✓	✗	Seismometers cGPS Tiltmeters SO_2 flux Temperature sensors and IR cam Webcams Debris flow / lahars EWS (Merapi)	✓
Papua New Guinea	6/49	✓	✗	Seismometers SO_2 flux (1 volcano) cGPS (1 volcano)	✓
Philippines	10/42	✓	Some, not real time[25]	Seismometers cGPS Tiltmeters SO_2 flux CO_2 concentration in borehole (1 volcano?) CO_2 dissolved in water (1 volcano?) Multigas (1 volcano?) Webcams	✓
Tonga	0/20	✗	✗	Regional seismometers	✗
Vanuatu	6/14	✓	✗	Seismometers Webcams	✗

Table 2.3 Summary of volcano monitoring in focus countries.

Indonesia

Indonesia has 127 volcanoes in the country, 77 of which have erupted since 1600 CE (classified as A-Type volcanoes). 69 on-land volcanoes out of these 77 are monitored by the Centre for Volcanology and Geological Hazard Mitigation (CVGHM), the official volcano monitoring agency. CVGHM comprises of 3 sections covering the whole country: West Indonesia, Merapi Volcano, and East Indonesia. While these three sections started as independent monitoring networks, data across all sections is now being consolidated and made accessible through a single database.

[25] https://wovodat.phivolcs.dost.gov.ph

Visual observations

Visual observations are made through a mix of webcams (real time) and reports from local observers at each of the observatories. Observers report both regularly and on-demand if anomalous activity is detected or reported.

Geophysical methods

CVGHM uses a range of geophysical techniques, ranging from seismometers (300 across the entire network) to detect, classify and locate earthquakes to ground deformation monitoring equipment (GPS, tiltmeters). Seismic data are the main dataset providing real-time monitoring information. The level of instrumentation varies between volcanoes from high (e.g., multidisciplinary network at Merapi) to minimal (single to no seismometer at poorly instrumented volcanoes).

Volcanic gas methods

CVGHM monitors gas emission rate and composition at Merapi and Agung volcanoes.

Data availability

CVGHM data are not publicly available.

Human resources

As befits the country with the largest number of active volcanoes in the world, CVGHM is well-staffed, with more than 100 permanent staff and more than 200 lay visual observers.

<u>Papua New Guinea</u>

Papua New Guinea has 49 volcanoes, 6 of which are instrumentally monitored. There are plans (unknown timeline) for instrumental monitoring of a further two. Rabaul Volcano Observatory (RVO) is the fulcrum of the observatory and monitoring system; Rabaul volcano is well-monitored, and the observatory staff have a high level of expertise.

Visual observations

RVO does not have webcams around volcanoes but has part-time local observers at six volcanoes. Local observers are trained by RVO staff and provide reports daily or on request.

Geophysical methods

Seismology is the main geophysical technique used by RVO to monitor PNG volcanoes. It is mostly used to detect, classify and locate earthquakes. Rabaul volcano is by far the most instrumented volcano in the country. RVO has a response pool of 12 seismometers (9 are currently functional) available for deployment when needed.

Volcanic gas methods

RVO routinely monitors gas emission rates at Rabaul volcano.

Data availability

RVO data is not publicly available.

Human resources

There is one volcano observatory in the country, comprising of 16 staff (evenly split between scientists and technicians). Additionally, part-time local observers are employed to report daily or on-demand observations (and ash samples) for at least 6 volcanoes. Some local observers are on the RVO payroll, while others are on the provincial government payroll. RVO does not have control over the observers' tasks and priorities in the latter case.

Philippines

The Philippine Institute of Volcanology and Seismology (PHIVOLCS) runs 7 volcano monitoring networks, each with a manned local observatory (Taal, Mayon, Bulusan, Kanlaon, Hibok-Hibok, Pinatubo, General Santos). The most comprehensively monitored volcano is probably Taal.

Visual observations

Visual observations are made through a mix of webcams (real time, 13 in entire network) and reports from local observers at each of the observatories. Observers report both regularly (twice daily), and on-demand if anomalous activity is detected or reported.

Geophysical methods

PHIVOLCS uses a range of geophysical instruments, ranging from seismometers (54 across the entire network) to detect, classify and locate earthquakes, ground deformation monitoring equipment (30 GPS, 12 tiltmeters, levelling lines), electromagnetic stations (7 across the entire network) and some gravity stations. Seismic data are the main dataset providing real-time monitoring information. The level of instrumentation varies between volcanoes from high (e.g., multidisciplinary instrumental network at Taal) to minimal (single to no seismometer at little instrumented volcanoes).

Volcanic gas methods

PHIVOLCS continuously monitors SO_2 and CO_2 emission rates at Taal volcano.

Data availability

PHIVOLCS data are not publicly available in real or near-real time. Select monitoring data streams are uploaded semi-regularly (typically once every 6 to 12 months) to WOVOdat[26].

Human resources

PHIVOLCS is well-staffed, with around 200 permanent staff. Not all of the staff are focussed on volcanology.

[26] https://wovodat.phivolcs.dost.gov.ph

Tonga

The Kingdom of Tonga has 49 volcanoes, none of which are instrumentally or routinely monitored. If a volcano is known to be activity erupting, it is monitored primarily through visual observations. To date, pre-eruption unrest has not been detected in Tonga. Eruptions are confirmed with visual evidence, such as by satellite, by a photograph, or a report from a trusted source. Once an eruption is confirmed, Tonga Geological Services (TGS) issues a media release.

Visual observations

Tonga does not have webcams around volcanoes, nor does it have official local observers that report to TGS. However, local residents call TGS when they are concerned, for example following a widely felt earthquake on a volcanic island.

Geophysical methods

Tonga effectively does not undertake seismic monitoring of volcanoes nor does it undertake other geophysical monitoring of volcanoes.

Tonga has a national seismic network consisting of 5 stations (Tongatapu, Vava'u, Ha'apai, Niuatoputapu, Niuafo'oa) that is 15 years old and run down. Several instruments are not operating, including the instrument on Niuafo'oa (a volcano with historic eruption, with >500 nearby residents on island). The network is vulnerable to cyclone impacts. There is a plan (unknown timeframe) to upgrade and refurbish the existing seismic stations. Although there is interest, available finances preclude the addition of seismometers on volcanoes.

Volcanic gas methods

Tonga does not undertake any instrumental or *ad hoc* monitoring of volcanic gases, nor does it have the expertise or resources to do so.

Data availability

TGS data are not publicly available.

Human resources

The entirety of TGS consists of 26 staff, only some of which are in the hazards team. TGS fulfils the role of a geohazard observatory, including volcanoes. In addition to natural hazards, TGS is responsible for resources (especially water), mining, seabed / EEZ / marine boundaries, costal management, and plays a role in water, sanitation, and hygiene.

Vanuatu

Vanuatu has 14 volcanoes, 6 of which are instrumentally monitored. All 6 instrumentally volcanoes are on volcanic islands.

Visual observations

Four volcanoes have webcams (Ambae, Ambrym, Lopevi, and Yasur), although maintenance at some volcanoes can be challenging due to access or environmental conditions. There are some local observers who can provide reports on request. In recent events, the Vanuatu Meteorology and Geohazards Department (VMGD) has been contacted via Facebook by the local population providing reports and sharing photos.

Geophysical methods

All the monitored volcanoes have at least one seismometer telemetered in real time to Port Vila. No volcano has three or more. The seismic data streams are reviewed nearly daily to count the number and type of earthquakes, although the vast majority of earthquake locations are unavailable due to low network density.

Volcanic gas methods

Vanuatu does not undertake any instrumental or *ad hoc* monitoring of volcanic gases, nor does it have the expertise or resources to do so. Foreign-based scientists occasionally undertake campaign gas surveys, but the results are rarely if ever shared with VMGD in a timely matter.

Data availability

Webcam data are available in near-real time on the WMGD website, and screenshots of seismic data are often (but not reliably) available. However, quantitative data are not publicly available.

Human resources

At VMGD there are 6 staff charged with volcano monitoring (evenly split between scientists and technicians). VMGD is also responsible for analysis of earthquakes and tsunami that might affect the country. The field technical team, which maintains the monitoring instruments, are also responsible for equipment that collects meteorological data.

International technical assistance

As indicated in Table 2.2, discussion with, and indeed, assistance from international agencies and colleagues is often an important component of volcano observatory unrest response. Discussions are sometimes informal, with colleagues or agencies with whom the volcano observatory has long-lasting relationships. In cases of rapidly escalating activity, particularly at a volcano with a poor eruptive or instrumental monitoring record, however, volcano observers in the focus countries often make formal requests via their governments for support. This is generally done by agreement between the two Ministry of Foreign Affairs equivalents. Table 2.4 indicates the international partners most often called upon by each focus country during a crisis.

Country	International partner typically called upon	Support often provided	Recent example
Indonesia	United States: Volcano Disaster Assistance Program	Remote technical support, in-country technical expertise, seismometer(s) and other instrumental monitoring	Singabung, 2010; Agung, 2017
Papua New Guinea	Australia: Geosciences Australia	Remote technical support and in-country support for maintaining and upgrading instrumental monitoring equipment, and some volcanic ash modelling	Kadovar, 2018
Philippines	United States: Volcano Disaster Assistance Program	Remote technical support, in-country technical expertise, seismometer(s) and other instrumental monitoring	Pinatubo, 1991
Tonga	New Zealand: GNS Science	Remote technical support, in-country technical expertise	Hunga Ha'apai, 2015
Vanuatu	New Zealand: GNS Science	Remote technical support, in-country technical expertise	Ambae, 2017/18

Table 2.4 Summary of international partners volcano observatories in focus countries often call upon for formal assistance.

<u>Ground data from regional or global networks</u>

WOVOdat is a comprehensive global database on volcanic unrest, currently hosted at the Earth Observatory of Singapore[27]. However, this database does not contain real or near-real time data; rather, the database “is intended for reference during volcanic crises, comparative studies, basic research on pre-eruption processes, teaching, and outreach”. All five focus countries have contributed to WOVOdat, in some cases solely through the inclusion of unrest or eruption confirmation notices.

Global monitoring of the nuclear test ban treaty, by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) relies on, amongst other detection systems, a global network which currently comprises 44 primary and 108 auxiliary certified seismic stations. The CTBTO does not report on earthquakes in real time but most of the stations do report to other agencies in real time so contribute to the global earthquake monitoring network.

The United States Geological Survey, through its Preliminary Determination of Epicenters (PDE) service, provides near-real time automatic, and then manually-reviewed, hypocentre locations for global earthquakes above magnitude 5.0. The historical catalogue back to 1976 is considered complete at this magnitude, and many smaller magnitude earthquakes are detected and reported even in the most remote parts of the world. Earthquakes directly related to volcano unrest and eruption are of lower magnitude than this; however, large tectonic earthquakes in certain regions can trigger volcanic unrest[28].

[27] Newhall, C.G., Costa, F., Ratdomopurbo, A., Venezky, D.Y., Widiwijayanti, C., Nang Thin Zar Win. Tan, K. & Fajiculay, E. (2017) WOVOdat – An online, growing library of worldwide volcanic unrest. Journal of Volcanology and Geothermal Research, 345:184-199.
[28] Linde, A.T., Sachs, I.S. (1998) Triggering of volcanic eruptions. Nature 395, 888-890.

2.4.2 Volcano Alert Levels in focus countries

Table 2.5 provides a summary of the Volcano Alert Level (VAL) systems in the focus countries; Tonga does not currently have a VAL system and is hence not included. Annexe 2 provides detailed descriptions of the VAL systems in each of the five focus countries, newly compiled and elaborated for this project.

Country	# VAL systems	Issuing agency	Focus	Evacuation order link	Level description
Indonesia	One system for all volcanoes	CVGHM	Actions for population	Yes CVGHM recommends evacuation. Decision made by local authorities.	▪ Normal ▪ Advisory ▪ Watch ▪ Warning
Papua New Guinea	Bespoke for individual volcanoes Broad similarity for open vent volcanoes. Broad similarity for closed vent volcanoes	National Disaster Centre, advised by RVO via the Department of Mineral Policy and Geohazards Management	Size of potential eruption	Yes RVO recommends evacuation. Decision made by local / national authorities.	1 to 4: Escalating (volcano specific)
Philippines	Six VAL systems, bespoke for the six monitored volcanoes	PHIVOLCS	Volcano unrest	Yes Evacuation focuses on settlements. Local Govt Units decide in advance on access to evacuated zones for various activities	▪ 0: Background ▪ 1-4: Escalating unrest / small eruptions (volcano specific) ▪ 5: Hazardous eruption
Vanuatu	One system for all volcanoes	VMGD	Volcano status	No	▪ 0: Normal ▪ 1: Signs of volcanic unrest ▪ 2: Major unrest ▪ 3: Minor eruption ▪ 4: Moderate eruption ▪ 5: Very large eruption

Table 2.5 Overview of VAL systems in focus countries. Tonga does not have a VAL system.

2.5 Candidate unrest indicators for use in parametric insurance

Annexe 3 provides a detailed description, analysis, and feasibility analysis of candidate indicators which could form the basis of parametric indices and triggers for a volcanic unrest product. The candidate indicators were discussed during a workshop on 19 October 2018 following the Understanding Risk Financing Pacific conference in Port Vila, Vanuatu, in partnership with representatives from Papua New Guinea, Tonga and Vanuatu.

We consider two situations where release of funds quickly will have a significant positive impact on response efforts at the onset of and during periods of volcanic unrest, and therefore may make appropriate use-cases for parametric insurance:

- Financial support for enhanced preparedness, which may include, but is not limited to, volcano observatory support and community engagement / preparation; and
- Financial support for evacuations.

In the next two sections we will consider each potential use-case.

2.5.1 Enhanced preparedness

Table 2.6 lists candidate indicators and summarises the results of the feasibility assessment as the basis of indices and triggers for the enhanced preparedness case. For details refer to Annexe 3.

Our analysis indicates that VALs are the best available (in four of the five focus countries) candidate indicator, which is also immediately an index, for a product to release funds in the early stages of volcanic unrest to support enhanced preparedness.

VALs track the evolution of volcano unrest as they capture, either explicitly or implicitly, the evolution of volcanic risk. Although inherently subjective, the setting of VAL by a sovereign authority is based on the integrative assessment of all available data, including real-time ground and, potentially, remotely-sensed monitoring, direct (unquantifiable) observations and other relevant factors.

The sovereign authority making VAL decisions is responsible for ensuring the safety and security of the population and the minimising of impact of volcanic hazards; therefore, there is an inherent connection between an upward change in VAL and increased burden on the sovereign (which, for the purposes of this project, would be the insured party). The very action of increasing the VAL will, in many cases, cause certain actions to be taken, with those actions designed to better-protect the at-risk population and each (or most) bearing a cost to the sovereign. Put differently, it can be reasonably assumed that VAL is a good proxy for sovereign ‘exposure’ to financial ‘loss’ (in this case, additional cost), so it therefore has potential as a parametric index.

Candidate indicator	Feasibility assessment summary
Direct visual observation of unusual activity on the ground	■ Critical data for volcano observatories ■ Not objective / independent
Increase from background to unrest Volcano Alert Level (VAL)	■ VAL systems vary from country-to-country (Annexe 2) ■ Varying levels of objectivity / independence
Volcano Ash Advisory from regional responsible Volcanic Ash Advisory Centre (VAAC)	■ Not suitable as focus is ash in airspace ■ Outside VAAC mandate to monitor unrest and non-ash volcanic hazards
Increase in locatable volcano-tectonic earthquakes	■ Good indicator for well monitored volcanoes ■ Public real-time data not available in focus countries ■ Limited or no seismic monitoring of many volcanoes in focus counties
Increase in seismic energy (RSAM)	■ Helpful indicator for volcanoes with seismic monitoring ■ Public real-time data not available in focus countries ■ Limited or no seismic monitoring of many volcanoes in focus counties
Ground-based detection of increased gas emissions	■ Can be a good indicator for well monitored volcanoes ■ Public real-time data not available in focus countries ■ Limited or no gas monitoring of large majority of volcanoes in focus counties. Gas emissions are not a useful signal at all volcanoes
EO detection of increased gas emissions	■ Can miss the early stages of unrest due to latency, resolution and atmospheric effects (e.g. cloud cover) ■ Signal processing challenges can lead to misinterpretation of data, and anthropogenic sources in some areas can complicate signal interpretation ■ Not suitable for submarine volcanoes ■ Potential data sovereignty and related ethical issues if use of 'external' data (both raw and interpreted) is not appropriately authorised[29]
EO detection of thermal anomaly	
EO detection of deformation	
Eruption of volcanic ash	■ Suitable for volcanoes that are perpetually erupting, which excludes a large majority of volcanoes
Increase of spatial extent of eruptive hazards	

Table 2.6 Summary of candidate indicator feasibility assessment for the enhanced preparedness case. Green shading: method is suitable for a vast majority of volcanoes. Amber shading: the method may be suitable for select volcanoes but with considerable caveats. Red shading: the method is not suitable.

[29] IAVCEI Subcommittee for Crisis Protocols (1999) Professional conduct of scientists during volcanic crises. Bulletin of Volcanology 60: 323-334.

A VAL index has previously been used in the design of a commercial parametric insurance product. Sompo, a major insurer in Japan, designed and marketed a parametric volcanic eruption product to cover business interruption for local businesses, which pays out based on the Japan Meteorological Agency announcing a VAL of 3, which indicates a high likelihood of eruption, for Mt. Fuji. While markedly different in its aims from the sovereign product being explored in this project, the precedent is useful in helping to evaluate the viability of using VAL as a parametric index.

2.5.2 Evacuation support

Table 2.7 lists candidate indicators and summarises the results of the feasibility assessment for the evacuation support use-case. For details refer to Annexe 3.

Candidate trigger	Feasibility assessment summary
State of Emergency declaration	■ Would need to be specifically called for a volcano
Official evacuation called	■ Suitable when considerable resources are required to evacuate the population (e.g. evacuations of entire islands)
Self-evacuation occurred	■ Not a reliable trigger ■ Self-evacuation can sometimes be unwarranted
Official evacuation has occurred	■ Suitable when resources required to care for evacuated population
Fatality outside evacuated zone	■ Not a reliable trigger ■ Moral and ethical issues
Volcano Alert Level increase	■ In three of the four focus countries with VAL systems, evacuation orders are linked to VAL
Volcano Unrest Index (VUI) increase	■ Primarily in research and development stages ■ For BET, potential data sovereignty and related ethical issues if not appropriately authorised[30]
Volcano observatory forecast	■ Primarily in research and development stages ■ For BET, potential data sovereignty and related ethical issues if not appropriately authorised[30]
Bayesian Event Tree (BET) forecast	■ Primarily in research and development stages ■ For BET, potential data sovereignty and related ethical issues if not appropriately authorised[30]

Table 2.7 Summary of candidate trigger feasibility assessment for the evacuation support case. Green shading: method is suitable for a vast majority of volcanoes. Amber shading: the method may be suitable for select volcanoes but with considerable caveats. Red shading: the method is not suitable.

The decision to evacuate a population deemed at risk from an eruption which may follow the period of unrest – or indeed from the products of the unrest itself – is hugely consequential. In many cases, one of the changes in VAL will be linked directly to evacuation (this is the case in three of the four focus

[30] IAVCEI Subcommittee for Crisis Protocols (1999) Professional conduct of scientists during volcanic crises. Bulletin of Volcanology, 60: 323-334.

countries which have VAL systems), but in any case, we believe the evacuation decision is a key step which must be precisely captured by an 'index' which is designed to trigger financing to offset evacuation costs.

Given this context, we identify here the call for an evacuation by the mandated sovereign entity as an index in and of itself (though it is obviously just a binary index; either the evacuation has been called, or it hasn't). This index effectively behaves as an exact proxy for evacuation costs; if there is no evacuation call then there are no costs related to evacuation which can reasonably be the responsibility of the state, whereas if there is an evacuation called then costs will be incurred (though there will be different costs for different scales of evacuation, for different evacuation requirements (e.g. off-island rather than land based), and potentially for multiple evacuations).

The decision to evacuate is not made lightly, as there are great political and credibility consequences with an unpopular evacuation order. Also, it is unlikely that any pay-out will fully cover the true costs of evacuation. Thus, we conclude that the moral hazard[31] of calling an evacuation primarily motivated by triggering a pay-out is not a major concern. Terms of any insurance contract can also be made that mitigate against this, as further discussed in later sections of this report.

2.5.3 Pre-VAL increase trigger

At a workshop on 19 October 2018 following the Understanding Risk Financing Pacific conference in Port Vila, Vanuatu, with representatives from the World Bank, VIP consortium partners and from Papua New Guinea, Tonga, and Vanuatu, the volcano observatory representatives reflected that modest yet often unallocated resources are needed in the very early stages of unrest to ascertain if the volcano has, in effect, gone into unrest (Table 2.1). These resources could include transportation (e.g., plane, helicopter, boat) for observatory staff to conduct an aerial survey of or to visit the volcano. This modest support is required before the observatory raises the VAL to indicate that unrest is underway.

At the workshop the concept of a pre-VAL trigger was discussed which would allow a volcano observatory to get resources such that it could quickly collect the information required to confirm volcanic unrest. The candidate indicator most in line with this requirement would be a local report of unusual activity. This indicator was evaluated to be too subjective to be feasible (Table 2.6). However, a promising solution might be an internal fund that is a condition of the parametric product for observatories to use to confirm the presence or not of reported volcanic unrest.

2.6 Conclusions

In this section, we have provided background on ground- and space-based volcano monitoring indicates, described synthesising products including Volcano Alert Level systems, and described generic volcano observatory response and governmental evacuation considerations. We have then provided an overview of current capabilities in each focus country and presented the results of our comprehensive analysis of candidate indicators to underpin parametric insurance indices and triggers, an analysis which is presented in full in Annexe 3.

[31] In this report we have used both 'moral hazard' and 'conflict of interest' to describe this situation.

Our findings point to two candidate indices:

- VAL change to an unrest state to support enhanced preparedness; and
- Evacuation call to support evacuation.

Additionally, we note that focus countries also identified a need for funding support to undertake ground-truthing of early unrest observations, before a VAL is moved from background to the first level indicating unrest. While we do not consider such funding as being a viable part of insurance coverage per se, government's commitment to such funding could be made a condition of purchase of the insurance product and/or such funding could be integrated into the operational costs of an insurance programme (in the same way that calculation agent costs are embedded in a parametric insurance programme's operational costs).

Finally, we note that these findings are for the present time and for the five focus countries; we provide some recommendations in the final section of this report regarding how the future pathway towards enabling more quantitative indicators to become viable as parametric indices can be best supported.

3 Resources required to respond to volcanic unrest

This section describes the resources required to respond to various stages of a volcanic unrest. Here we present a qualitative assessment, based on our discussions with volcano observatories in the focus countries and the consortium members' experience with eruption response. Some quantification is used in later sections of this report.

3.1 Pre-VAL increase resourcing

Pre-VAL increase resourcing allows volcano observatories to confirm volcanic unrest (Section 2.5.3 and Table 2.1). This is unlikely to be suitable as the subject of a parametric trigger, as what prompts an observatory to investigate the existence or not of unrest is largely subjective.

Requirements may include:

- Aerial survey
- Field visit
- EO data collection

As these are modest costs, they might be allocated from an internal fund that is set up as a condition of the parametric product for the sole use by observatories to confirm the presence or not of reported volcanic unrest. Alternatively, such costs, for pre-defined purposes, might be wrapped into the 'index calculation' costs of the product itself (e.g. there is some equivalence to the running of a catastrophe model to calculate a parametric loss).

3.2 Enhanced preparedness

A pay-out triggered once a VAL is increased to an unrest level would support volcano observatory efforts to reduce scientific uncertainty around likely future short-term volcanic activity and support community preparedness activities to enhance the prospects of efficient evacuation if required and in-situ safety and security if not.

Resources may be deployed to support the following:

- Observatory activities:
    - Repeat aerial and field surveys
    - Installation of webcams
    - Installation of one or more seismometers
    - Installation of one or more gas sensors
    - Campaign surveys of volcanic gas or deformation or other monitoring method
    - Laboratory analyses
    - Acquisition of EO and other remotely sensed data

    - Geologic and analytical studies of past eruptive deposits
    - Geochronological dating of past eruptions (e.g. radiocarbon age determinations)
    - Additional computer hardware
    - Additional temporary human resources, including consultation with international partners
- Community preparedness activities:
    - Preparation / review / updating of evacuation plan
    - Preparation of shelters
    - Public socialisation campaigns to raise awareness concerning volcanic activity, volcanic hazards, and what to do if an evacuation is called. Activities might include:
        - Public meetings
        - Discussions with community leaders and key community groups
        - Provision of information through traditional media (TV, Radio, Newspapers, leaflets)
        - Social media and web resources including public information films
    - Socialisation of personal protection measures (e.g. moving to high ground when lahars threaten, covering rainwater tanks during ashfall events, other public health measures)
    - Coordination of response actors, including the government, communities and NGOs

3.3 Evacuation support

It is anticipated the main trigger and largest pay-out will be made to finance evacuation support. The quantum of payment must consider:

- The size of the population at risk, which has a demonstrated relationship to evacuation size. The Population Exposure Index (PEI)[32] is a logical choice (see Component 1 Technical Report); and
- Additional payment component for evacuations of entire islands to account for higher transportation costs.

The main additional costs incurred by a government when evacuating a population include:

- Costs of evacuation itself, mainly transportation; and
- Welfare support for the displaced population, including basic needs such as food, shelter and healthcare, but also provision of the means to continue with livelihoods, education and other economic activities.

Long-term support for a displaced population during a prolonged eruption sequence is not considered as part of the potential use of a pay-out under the unrest product.

[32] Brown, S.K., Auker, S.K., Sparks, R.S.J. (2015) Populations around Holocene volcanoes and development of a Population Exposure Index. *In:* Loughlin, S.C., Sparks, R.S.J., Brown, S.K., Jenkins, S.F., Vye-Brown, C. (Eds.) Global Volcanic Hazards and Risk. Cambridge University Press, Cambridge.

4 Unrest product design

Based on our identification of potential indicators to underpin a parametric index for volcanic unrest, and the evaluation of those indicators and indices in terms of the practicalities of using each, alone or in combination, for a sovereign-level parametric insurance product, we present in this section the blueprint for what we propose is an implementable parametric insurance product based on a hybrid index of VAL and evacuation call.

4.1 Description of proposed structure

Table 4.1 summarises the key characteristics of the proposed unrest product structure.

Unrest Product Summary	
Brief Index Description	Product utilises the official Volcano Alert Level (VAL) and an official Evacuation Call as dual indices, with a sub-trigger (small fraction of the full limit to be triggered) at the move from a background VAL to the next higher VAL and a main trigger at an official Evacuation Call.
Policy Purpose	Pays out once or more during increasing volcanic unrest to support additional costs related to that increasing unrest, including but not limited to: ▪ Enhanced volcano monitoring and community preparedness / awareness-building for the sub-trigger pay-out; and ▪ Evacuation costs and, potentially, benefits for evacuated individuals for the main trigger pay-out.
National Coverage	While individual volcanoes should be named in the policy schedule, all volcanoes will be covered in a single aggregate policy.
Index as Proxy for 'Loss' (in this case, additional costs)	In the case of VAL, there is an inherent connection between an upward change in VAL and increased burden on the coverage buyer (sovereign). The very action of increasing the VAL will, in most cases, cause certain actions to be taken, with those actions designed to better-protect the at-risk population and each (or most) bearing a cost to the sovereign. There is also an inherent connection between an Evacuation Call and an increased burden on the coverage buyer.
Use of Pay-out	Early smaller pay-outs might be used to enhance the monitoring network or to undertake preparedness measures (e.g. public awareness of evacuation procedures, installation or maintenance of warning systems, preparation of shelters). Later, larger pay-outs could offset the costs incurred in executing an evacuation and / or provide basic needs or cash to evacuees. In both cases, early access to funding is highly advantageous, so multiplying the benefits of parametric triggering of financial flow.

Main Advantages	■ Both indices implicitly involve the integrative assessment of scientific evidence and data ■ Both indices are simple, and both are tied to specific actions which incur a cost ■ Low-cost index monitoring and pay-out calculation process ■ Pay-outs can be made very quickly – validation of triggers will be quick ■ No local infrastructure or technical data required, eliminating issues of reporting failure etc
Key Challenges	■ Lack of history of VAL issuance ■ VAL is at least somewhat subjective (even though substantially based on objective data), so is difficult to assign with probability of occurrence without high uncertainty ■ While VAL is typically informed by quantitative scientific information, it can also be partially informed by qualitative information and by non-scientific issues, with the roles of scientists and authorities sometimes being ambiguous or blurred ■ Potential moral hazard / conflict of interest for sovereigns as buyer and with ultimate control over the Reporting Agency for both indices

Table 4.1 Summary characteristics of the proposed unrest product.

4.1.1 Early trigger based on VAL

As has been described earlier in this report, VAL systems vary between countries and, sometimes, within countries, they evolve through time, and they can have somewhat different purposes. VAL movements in the more developed phases of unrest (i.e. movements in the upper part of VAL systems) can be highly consequential, and are therefore more likely to include non-scientific elements feeding into the setting of the VAL. These factors introduce challenges in using VAL as an index to underpin parametric insurance.

However, the first movement of VAL, from a background level to the first level above that, is either much less, or not at all subject to these challenge factors, and is therefore regarded as a segment of the index that can be widely and simply deployed to create an early and reliable trigger to allow financial flows at the earliest point at which renewed – or new – unrest is recognised.

In our analysis, and based substantially on discussions with volcano observatory staff in the five focus countries, the move from 0 to 1 (Vanuatu, Philippines – where 0 is sometimes replaced by 'No Alert'), 1 to 2 (PNG) or 'Normal level' to 'Waspada / Advisory level' (Indonesia) is free from non-scientific inputs but is not undertaken without verification of unrest signs (whether they are subjective or objective). This move from background / normal levels of (in)activity to some level of abnormality is not undertaken lightly either; it imposes substantial additional burden on the volcano observatory responsible, which in turn is guided by the ethical guidelines and standards of scientific integrity laid out by its peer group across the international community.

As examples of international standards, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) has issued protocols on the conduct of scientists during volcanic crises[33] and guidelines on the roles and responsibilities of scientist involved in hazard evaluation, risk mitigation and crisis response[34]. While these protocols and guidelines are not legally or formally binding[35], they provide a resource to assess actions by VOs.

We note here that Tonga does not have a VAL system so would need to put in place some formal mechanism which allowed the official level of activity at any volcano to be communicated if the early trigger were to be included in coverage (and it need not be). This could begin with a simple system which might just include two levels, background and 'signs of unrest', or could comprise a full VAL system based on international standards.

We also note that, despite having different VAL systems for each of its monitored volcanoes, the Philippines system is consistent in the recognition of the move from 'No Alert' to 'Abnormal' (0 to 1) across all the systems, and it is a reasonable assumption that a volcano which showed signs of unrest would adopt one of the existing VAL systems so that that unrest could be officially recognised (particularly if it was motivated to do so under the terms of a parametric insurance policy).

A listing of the current status of all covered volcanoes would be required as part of the insurance policy documentation, and any that were not at background activity levels would be excluded from coverage for the early trigger.

We have not considered here the case of volcanoes which are at some level of unrest on a continuous basis and for which an upward movement in VAL could create similar needs and be made under similar informational circumstances to the movement from no unrest at 'normal' volcanoes. Such cases could be included in an unrest parametric policy as long as all the particular circumstances are clearly laid out in the policy schedule and the additional risk of this eventuality is included in the analytics.

In the formulation of the policy that we present in Section 5, we have limited the total number of early triggers at any given volcano to one, so that downward movement of VAL to background and then back up again would not trigger any pay-out. Although not impossible to include such eventualities in a coverage, we believe it would be complicated and the value-added might be rather limited.

4.1.2 Evacuation Call as main trigger

As previously described, the main need for funding during an unrest episode at any given volcano is if – and when – an 'evacuation order' is issued. While the legal form and power of an evacuation call, and the responsible entity, varies across the countries of focus (and globally), in each case the evacuation call is sufficiently well documented to be captured definitively in an insurance contract, and is therefore suitable as a parametric trigger[36].

We note that the evacuation call trigger could occur at the same time as the early, VAL-based trigger in the case where an unmonitored volcano with a proximal population moves immediately from

[33] Newhall, C., Aramaki, S., Barberi, F., Blong, R., Calvache, M., Cheminee, J.L., Punongbayan, R., Siebe, C., Simkin, T., Sparks R.S.J. & Tjetjep, W. (1999) IAVCEI Subcommittee for Crisis protocols: professional conduct of scientists during volcanic crises. Bulletin of Volcanology, 60, 323-334.
[34] https://www.iavceivolcano.org/iavcei-products/iavcei-guidelines/12-iavcei-guidelines-on-the-roles-and-responsibilities-of-scientists-involved-in-volcanic-hazard-evaluation-risk-mitigation-and-crisis-response.html
[35] One might consider requiring VOs to be 'bound' to such protocols in some way, as a pre-requisite to coverage being available.
[36] Hereinafter, we refer to an official evacuation order, whatever legal form it has, as an Evacuation Call.

background activity to sufficient unrest to warrant evacuation. In such a case, it would be logical for only the larger pay-out, triggered by the evacuation call, to be valid (as there would be no normal use-case for the early pay-out funds.)

Another ‘special case’ would be a second evacuation of the same population within a single policy period and whether this would trigger another payment. In formulating the insurance policy, the definition of an ‘unrest event’ might be used, and the stipulation made that only one evacuation of the same population is covered in any one unrest event. However, finding a suitable definition of the end of an unrest period is very difficult when it would need to cover multiple different volcano types etc, so instead, in the policy formulation presented here, only one evacuation pay-out is allowed per volcano per year, which removes the need to define the end of an ‘event’.

The question of moral hazard, or conflict of interest, arises, however, given that the evacuation call is always issued by a sovereign-mandated agency, ultimately responsible to the insured party in the case of sovereign parametric insurance. While even the potential for such conflict is generally avoided in parametric insurance contracts, there is no other viable option in this case (as discussed earlier in this report), so the question becomes whether or not the conflict will affect decision-making in the view of the ultimate risk taker (the ‘insurer’). The particular conditions as they relate to this conflict of interest issue, both in each individual focus country and more generally, are further described in Section 4.3.

While it would be impossible to completely eliminate the potential for an evacuation call to be made by a sovereign entity solely to trigger an insurance pay-out under the parametric policy described in the blueprint, some mechanisms can be used to make such an occurrence self-defeating and therefore sufficiently unlikely as to not impact on the ability of insurers to underwrite the risk at a fair technical price. These include:

- Limiting the total quantum of any pay-out, so that it was only ever a modest proportion of the total additional costs that such an evacuation would ultimately incur for the sovereign;
- Scaling any pay-out such that it can account for partial evacuations (so that one cannot trigger a big pay-out by evacuating a very limited number of people); and
- Including a requirement that an evacuation actually takes place (which would be required anyway to make the contract into insurance, which requires proof of ‘loss’).

4.1.3 Scaling pay-out amounts

One of the key features of parametric insurance is that it is very flexible in terms of the amount covered by the insurance contract. With traditional indemnity insurance, the insurance covers the replacement value (usually) of whatever it is that is being insured; the full value is paid out for a total loss, otherwise the amount required to repair the insured object to its original state is paid. With parametric insurance, specific assets are generally not identified, and damage to those assets not measured directly nor paid out against specifically.

Parametric insurance contracts often cover only a small portion of the total value of all the assets that could be damaged or destroyed by a particular event or of the costs that would be incurred as a result of or in advance of an event (for forecast-based insurance). Therefore, while it is important to understand the quantum of the ultimate need, it is not critical to structuring a coverage which can provide value to the insured and can be underwritten efficiently by the insurer.

In fact, absolute scaling of a parametric insurance coverage often occurs very late in the design process and, in the sovereign government / development space, is often dictated by the availability of premium. Put differently, the question is often how much coverage a fixed premium amount can buy rather than what a coverage of a particular size and structure costs.

Here, we outline an overall framework for quantifying the need and distributing that need between multiple individual volcanoes in a given country, and between the ‘early’ pay-out and the main pay-out. In Section 5, we outline how this framework can be used to structure an actual risk transfer product.

Early pay-out

Given the envisaged purpose for the early pay-out, described in Section 3, we estimate that the quantum for this pay-out is likely to be in the tens of thousands of US Dollars and that it might vary somewhat between volcanoes in a particular country dependent on the population at risk but recognising that deployment of monitoring equipment is likely to stay constant given that most of the cost will be in the hardware itself.

Across the five focus countries the quantum of need will vary, and in the policy formulation, we have allowed for the choice to be made between:

- The assumption of a constant link between the early pay-out needs and the main pay-out needs - so that at a given volcano in any country, the early pay-out will be a fixed proportion (selected by the client) of the maximum amount of the main pay-out.
- The assumption of a fixed amount at any volcano, the amount being selected by the client.

Main pay-out

As previously discussed, the quantum of the main pay-out should reflect the needs for which parametric insurance is an efficient financing approach, which are limited to the immediate costs of the evacuation itself, and the additional costs, but for a limited time (up to a few months), incurred by the evacuated population not having access to their normal livelihoods and basic necessities. The quantum of cost for both of these is dictated mainly by the number of people evacuated, but that is modified for island volcanoes by the additional cost of off-island evacuation.

While it might seem obvious to scale the pay-out for an evacuation call by the number of people evacuated, in practice this cannot be done. Often, evacuations are called for particular zones around a volcano, and the number or people impacted is unknown. Further, having to depend on the characteristics of the evacuation call to dictate the pay-out amount brings a lot of uncertainty and great potential for time delays.

Instead, we propose to use the PEI of a volcano, known and documented in advance, as the basis for quantifying the pay-out made when an evacuation is called at a particular volcano. Analysis presented in the Component 1 Technical Report demonstrated the good general 1:1 relationship between actual evacuation size and PEI (see Figure 3.6 of the Component 1 Technical Report), although we again note that this relationship holds best for maximum evacuation size, with partial evacuations creating considerable noise beneath this.

So, our proposal includes a fixed pay-out amount per volcano per 'PEI-unit', modified to account for:

- More expensive evacuations for island volcanoes; and
- Partial evacuations[37].

Overall Structuring Framework

A simple framework is laid out here, in order to be most broadly applicable.

For any volcano, the following is required and would be documented in advance:

- Population Exposure Index (absolute number, rounded up to the nearest 1,000, say)
- Evacuation Cost Modifier (percentage, 0 to 100%)

For a country, the following is required in advance:

- List of all covered volcanoes and information listed above per volcano, as well as current VAL status
- Dollar value for PEI unit. Given the 1:1 relationship we assume between PEI and evacuation number, for 'full' evacuations, this dollar value is equivalent to a per-person evacuation cost
- Early trigger scalar (can be selected by country, but likely to be 10% or less) or fixed dollar amount for the early pay-out

The index / trigger reporting requirements are:

- VAL Index – reporting of movement from no alert to first level above
- Evacuation call:
    - Formal legal notice of evacuation call
    - Scale of evacuation (will need to be simple, with 'full' evacuation previously defined and perhaps just one or two sizes of 'partial' evacuation recognised)
    - Proof of evacuation taking place

Coverage will be on an aggregate basis across the policy period (one to multiple years are possible, although we have assumed a one-year policy period here), so that all volcanoes are included (unless explicitly excluded) and the total pay-out allowed under the policy will be potentially large enough to accommodate several evacuations at different volcanoes. The total value of the policy (maximum total

[37] We have not included this modifier in our illustrative underwriting model at this stage, due to the challenges in identifying how partial evacuations would be identified.

amount of pay-outs made under the policy during the policy term) can be chosen by the insured country.

4.2 Testing the design concept

In this section, for a number of recent volcano unrest events, including at least one from each of the five focus countries, we present the chronology of events and the timing of what would have been triggers had the parametric insurance product introduced in the previous section been in place. These examples are useful in illustrating both positive aspects and some challenges of the design.

4.2.1 Agung, Indonesia, 2017

Information for this case study comes from Global Volcanism Program bulletins[38]. Timeline:

- August 2017: VAL Normal level (background; level I).
- 14 September 2017: VAL Wasapada (advisory; level II). This would have triggered an early pay-out in this policy year.
- 15 September 2017: VAL Siaga level (watch; level III), voluntary evacuation of 50,000 begins.
- 22 September 2017: VAL Awas level (warning; level IV) evacuations of tens of thousands of people. This would have triggered an evacuation pay-out in this policy year[39].
- 21 November 2017: First ash emission.

Conclusion: This would have worked as intended. It is a good example of how ambiguous volcanoes can be, and how long it can take for even small things to start happening after the first ramp up. The cost of having displaced people for months was very high.

4.2.2 Kelut, Indonesia, 2014

Information for this case study comes from Andreastuti, *et al*. (in press)[40] and Global Volcanism Program bulletins[41]. Timeline:

- 2 February 2014: VAL raised from Normal (background; level I) to Wasapada (advisory; level II). This would have triggered an early pay-out in this policy year.
- 13 February 2014: VAL Awas level (warning; level IV) issued, self-evacuation followed by official evacuation. This would have triggered an evacuation pay-out in this policy year.

Conclusion: The insurance product in this situation would have worked as intended.

[38] http://volcano.si.edu/volcano.cfm?vn=264020#bgvn_201801
[39] It appears that all the prior evacuations were voluntary despite there being exclusion zones that included inhabited areas.
[40] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[41] https://volcano.si.edu/volcano.cfm?vn=263280

4.2.3 Merapi, Indonesia, 2010

Information for this case study comes from Mei *et al.* (2013)[42]. Timeline:

- Eruptions in 2006.
- In September 2010: VAL Wasapada (advisory; level II). At this time, it had been at Wasapada level for years.
- 20 October 2010: VAL Siaga (watch; level III). Unrest picked up again, alert level increased. This wouldn't have triggered an early pay-out under the 'standard' policy form as Merapi was already in unrest at the start of the policy period.
- 26 October 2010: VAL Awas (warning; level IV) and evacuations of tens of thousands of people. This would have triggered an evacuation pay-out in this policy year.

Conclusion: There would have been no early pay-out, as the volcano had been in unrest for several years (unless the option for any upward VAL movement to trigger the early pay-out had been used). Given the level of existing monitoring at this frequently active volcano, already in unrest, an early pay-out for enhancing monitoring and preparedness would seem to have little value at Merapi.

4.2.4 Sinabung, Indonesia, 2010-present

Information for this case study comes from Gunawan *et al*. (in press)[43], Global Volcanism Program bulletins[44] and Andreastuti, *et al*. (in press)[45]. Timeline:

- Early August 2010: VAL Normal (background; level I).
- 29 August 2010: VAL Awas (warning; level IV) – highest level (went from background to highest level in one issuance). Locals evacuated. This would have triggered an early pay-out in this policy year.
- 23 September 2010: VAL Siaga (watch; level III).

Comment: It is unclear what VAL was between 2010 and 2013, but it doesn't appear to have been back at Normal level.

- September 2013: Activity resumed, evacuations ultimately of 17,000 people. This would have triggered an evacuation pay-out in this policy year.

Conclusion: In 2010 the early pay-out would have provided useful early funding to start monitoring. Increased resources would have probably helped in 2013 but there would have been no associated early pay-out at the time because it was already in unrest. The evacuation funding would have helped.

[42] Mei, E.T.W., Lavigne, F., Adrien, P., de Belizal, E., Brunstein, D., Grancher, D., Junun, S., Cholik, N. & Vidal, C. (2013) Lessons learned from the 2010 evacuations at Merapi volcano. Journal of Volcanology and Geothermal Research, 261: 348–365.
[43] Gunawan, H., Surono, Budianto, A., Kristianto, Prambada, O., McCausland, W., Pallister, J. & Iguchi, M. (in press) Overview of the eruptions of Sinabung eruption, 2010 and 2013–present and details of the 2013 phreatomagmatic phase. Journal of Volcanology and Geothermal Research.
[44] https://volcano.si.edu/volcano.cfm?vn=261080
[45] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

4.2.5 Pinatubo, Philippines, 1991

Information for this case study comes from Punongbayan *et al*. (1999)[46]. Note that when unrest started, Pinatubo had no VAL system and was not monitored. In fact, it wasn't even recorded as a volcano locally, and so might have been excluded from an insurance policy[47]. Our case study treats Pinatubo as being covered by the policy at the time. Timeline:

- August 1990: Local reports of unusual activity. If there were a 'pre-VAL increase' trigger, this would have come into force then. A PHIVOLCS team was sent to make observations and they concluded there was no volcanic unrest which, in today's terms, would have meant no increase in VAL from background.
- Early April 1991: New local report of unusual activity. Again, if there were a 'pre-VAL increase' trigger, this would have come into force then. A PHIVOLCS team was sent to make observations and they initially suspected it was hydrothermal activity but installed a seismometer to collect more information. It was ambiguous if the unusual activity was volcanic or geothermal, and a precautionary evacuation was recommended within 10 km of the summit, with about 5,000 people evacuated. This would have triggered an evacuation pay-out in this policy year, though were a partial evacuation scaling factor to have been included in the policy terms then there would not have been a full pay-out.
- Mid May 1991: A volcano alert level system was established for Pinatubo, set at Level 2, which corresponds to Moderate level of seismicity, other unrest with positive evidence for involvement of magma. A few days later, a definitive interpretation was made that the unrest was volcanic in nature (not hydrothermal). This would have triggered an early pay-out in this policy year.
- June 1991: Widespread evacuations before / during Plinian eruption to 40 km of summit, including evacuation of existing evacuation camps. This would not have triggered an evacuation pay-out unless the earlier evacuation had occurred in a prior policy period or only a partial pay-out had been made for the April evacuation, in which case the 'balance' of the evacuation pay-out amount would have been available[48].

Conclusion: This illustrates the complexities of unrest situations, particularly at unknown and / or unmonitored volcanoes.

4.2.6 Rabaul, Papua New Guinea, 1994

Information for this case study comes from McKee *et al*. (2017)[49]. Timeline:

- 18 September 1994 at 6 pm: VAL Stage 2 (eruption within months). This would have triggered an early pay-out in this policy year.
- 18 September 1994 late afternoon: Self-evacuation begins.
- 18 September 1994 at 11 pm: Official evacuation commences. This would have triggered an evacuation pay-out in this policy year.

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46 https://pubs.usgs.gov/pinatubo/punong2/
47 We have used the VOTW global volcano listing as the basis for policy formulation; additional volcanoes could be added by a client country during policy customisation, so long as the risk analysis included such newly-added volcanoes.
48 This assumes that the partial evacuation pay-out mechanism allows for an annual limit but multiple partial evacuations qualify up to that limit.
49 McKee, C., Itikarai, I. & Davies, H. (2017) Instrumental Volcano Surveillance and Community Awareness in the Lead-Up to the 1994 Eruptions at Rabaul, Papua New Guinea. *In*: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.

- 19 September 1994 at 2 am: VAL Stage 3 recommended (eruption within weeks to days), but delayed as evacuations judged to be proceeding smoothly.
- 19 September 1994 at 7 am: VAL Stage 3 and 4 declared simultaneous (eruption within weeks to days, eruption within days to hours); the eruption at Tavurvur had already started by then.

Conclusion: The rapid escalation would have prevented even fast-flowing parametrically triggered funding from being useful for pre-eruption preparedness, although post-evacuation funding would still have been very useful in ongoing crisis management. It is notable that in retrospect there was volcanic unrest detected by instrumentation, but this was not appreciated at the time. From the above-cited paper - “maintenance and equipment problems led to a lack of telemetered data from tiltmeters and tide gauges by late 1993 which rendered the reliable interpretation of available ground deformation data more difficult. These deficiencies conspired to impede the generation of warning messages from RVO.”

4.2.7 Niuafo’ou, Tonga, 1946

Information for this case study comes from Rogers (1981)[50]. Note that this is the last major eruption in Tonga for which any relevant information is available. Timeline:

- 9 September 1946: Eruption occurred, destroying local radio capabilities and removing means of communicating with the outside world.
- 16 September 1946: Plane flyover undertaken at request of Tongan government, concerned by lack of radio contact. Pilots reported volcanic activity and destruction of part of village. We evaluate that in the same situation now, government / TGS would issue a media statement, which <u>could trigger an early pay-out</u> depending on policy formulation for Tonga, which doesn’t have a formal VAL system.
- 20 September 1946: First official visit, determination that no immediate danger, no further assistance required. The decision not to evacuate was based on economics and political realities – it would cost too much, there weren’t the resources available to evacuate transportation wise, and as the eruption didn’t seem to be over it was seen like evacuation should be saved for a desperate measure.
- 5 October 1946: Islanders vote on whether or not to evacuate (official results were that 1,078 wanted to evacuate and 228 wanted to remain; unofficial results were that 615 wanted to evacuate, 280 wanted to remain, and 171 abstained). Vote made with understanding that government would support evacuation costs, and those who remained would receive no assistance.
- 8 October 1946: Results communicated by radio to government. An official evacuation is ordered. <u>This would have triggered an evacuation pay-out in this policy year</u>.
- 22 October 1946 onwards: Tonga Police Magistrate arrives with evacuation order, and things get super political with lots of leadership and population resistance to the order.

Conclusion: Economic cost was one of the major factors contributing to the initial decision not to evacuate, showing the importance of having adequate resources available to undertake evacuation efforts.

[50] Rogers, G. (1981) The evacuation of Niuafo’ ou, an outlier in the kingdom of Tonga, The Journal of Pacific History, 16:3, 149-163.

4.2.8 Ambae, Vanuatu, 2017/18

Information for this case study comes from N. Deligne personal recollection and VMGD bulletins[51]. Timeline:

- Sometime before April 2017: VAL 2[52], and had likely been at this level for months or years. Thus, the early pay-out would have been a considerable time before 2017.
- 6 September 2017: VAL 3 (minor eruption state).
- 23 September 2017: VAL 4 (moderate eruption state).

Comment: At this time there was a lot of uncertainty about what would happen next, and uncertainty about whether evacuations were warranted. It is possible that with more scientific information a different call may have been made. When the VAL was raised to VAL 3, this was the time an early pay-out would have been useful. This would be possible to include in the policy as an upward VAL movement trigger for volcanoes already in unrest[53].

- 28 September – 6 October 2017: Evacuation of the island due to life-safety concerns. This would have triggered an evacuation pay-out in this policy year.
- November 2017: Repatriation.
- August 2018: Second evacuation of island, this time due to habitability concerns. It cannot be stated whether this would have triggered an evacuation pay-out, as it might have been in the same policy year as the Sep/Oct 2017 evacuation (in which case it would be ineligible) and / or it might have been ineligible because the population had been already evacuated at the start of the policy year.

Conclusions: There would have been a pay-out for the first evacuation but probably not for the second, and no early pay-out under the standard policy form – a pay-out which could have been important for funding more monitoring which might have better informed whether or not to call the first evacuation.

4.3 Basis risk

Basis risk is a feature of all insurance and is generally defined as the difference between the expectation of what a given policy will provide in terms of a pay-out for a given event and the actual pay-out received by the insured. In indemnity insurance, the 'fine print' in a policy document was generally the cause of the basis risk, and substantial progress has been made by regulators in eliminating the fine print. This enables insured parties to have reasonable expectations and requires insurers to meet those reasonable expectations, thus greatly reducing basis risk.

Basis risk in parametric insurance is generally cited as a key drawback, and large differences between the timing and scale of pay-outs and the timing and scale of the needs which those pay-outs are aimed at mitigating certainly make insurance an inefficient risk financing tool. Basis risk in parametric insurance instruments is often evaluated relative to 'what an indemnity policy would have paid out',

[51] https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin
[52] The 19 April 2017 bulletin includes '*The Alert Level for Ambae volcano remains at Level 2. This means that the volcanic activity is in the major unrest stage*.'
[53] This highlights that particular conditions should dictate whether this option is included in policy formulation – it would have been useful at Ambae, but not at Merapi in 2010, for example.

assuming that an indemnity policy is reasonably available and that the expectations of the client encountering the basis risk have been set by the standards of an indemnity policy.

For a volcanic unrest product at the sovereign level, there is no equivalent indemnity product through which to establish any expectation, and the costs associated with volcanic unrest, including evacuations, are very poorly known. So, while it is certainly important to avoid the inefficiencies of paying the additional cost of premiums above the pure risk cost[54] for pay-outs which arrive when they are not needed and don't arrive when they are, the greater challenge in managing basis risk in the particular situation of parametric insurance for volcanic unrest is in managing the expectations of the client.

Given the design criteria outlined above, those expectations of the client that need to be managed will be those of the quantum of pay-outs rather than when they occur, given that both of the triggers being used are directly recognising conditions under which additional costs will need to be incurred to protect an at-risk population around a volcano.

4.4 Conflict of interest concerns

Earlier in this section, we outlined the general circumstances around the conflict of interest situation where the sovereign client of the parametric insurance policy is also ultimately responsible for the agency, or agencies, arbitrating the indices being used to trigger pay-outs under the policy. Below, we summarise information from the volcano observatory visit reports relevant to understanding of the agency or agencies responsible for both setting of VAL and calling of evacuations in each of the five focus countries, and go on to provide information from a global perspective, as the basis for building a case to ultimate risk takers that the conflict of interest issue should not impact in any substantial way on the operations of the parametric policy.

Indonesia

- *Volcano monitoring responsibility*: CVGHM
- *Responsibility for setting VAL*: CVGHM
- *Evacuation responsibility*: Regional emergency management authorities (BPBD) and local authorities (e.g., Sultan, mayor) are usually responsible for evacuations. Large scale response activities and resourcing are coordinated at the national level by the emergency management agency (BNPB)
- *Involvement of volcano observatory in evacuation decisions*: CVGHM suggest evacuation zones to the authorities

Papua New Guinea

- *Volcano monitoring responsibility*: Rabaul Volcano Observatory (RVO) is responsible for volcano monitoring across all of Papua New Guinea
- *Responsibility for setting VAL*: National Disaster Centre, advised by RVO via the Department of Mineral Policy and Geohazards Management. During a volcanic crisis, the RVO Director presents

[54] The pure risk cost is the estimated value of pay-outs that will be made during the policy period, when averaged over a long time period. If you purchase an insurance policy at a premium cost equal to the pure risk cost then, over the long term, you will get all of your premium back in pay-outs. Because the pure risk cost is immutable

a recommendation for the VAL to the Department of Mineral Policy and Geohazards Management (DMPGM; RVO is part of this department). The DMPGM then makes recommendations to the National Disaster Centre (NDC). The NDC then approves the VAL and the new VAL is then passed on the relevant Provincial Disaster Committee (PDC); the PDC is a coordinating committee and consists of representatives of the Provincial Disaster Office and relevant provincial stakeholders (e.g., utilities companies, NGOs, private sector, media)

- *Evacuation responsibility*: The National Disaster Centre and relevant Provincial Disaster Office
- *Involvement of volcano observatory in evacuation decisions*: RVO is not responsible for evacuation decisions but provides volcano status updates to the government during a crisis.

Philippines

- *Volcano monitoring responsibility*: PHIVOLCS
- *Responsibility for setting VAL*: PHIVOLCS
- *Evacuation responsibility*: Civil authorities are responsible for evacuations. Authorities have pre-determined evacuation criteria based on the VAL for each volcano
- *Involvement of volcano observatory in evacuation decisions*: PHIVOLCS set the VAL and provides volcano status updates to the government during a crisis

Tonga

- *Volcano monitoring responsibility*: Tonga Geological Services (TGS) of the Ministry of Lands and Natural Resources (MLNR)
- *Responsibility for setting VAL*: No VAL system in place. Once an eruption is confirmed, TGS issues a media release
- *Evacuation responsibility*: The Emergency Management Committee (EMC), chaired by the Minister responsible for National Emergency Management Office (NEMO)
- *Involvement of volcano observatory in evacuation decisions*: NEMO calls a meeting of the EMC, and the EMC discusses the threat. TGS (volcano observatory) provides information and advice to NEMO relevant decision making about evacuations

Vanuatu

- *Volcano monitoring responsibility*: The Vanuatu Meteorology and Geohazards Department (VMGD), which is a department within the Ministry of Climate Change Adaptation, Meteorology, Geo-Hazards, Energy, Environment and Disaster Management, is responsible for all volcano monitoring in Vanuatu
- *Responsibility for setting VAL*: VMGD
- *Evacuation responsibility*: National Disaster Management Office (NDMO)

- *Involvement of volcano observatory in evacuation decisions*: VMGD provides volcano status updates to the government during a crisis

Global perspective

To address the moral hazard issue from a global perspective, we considered the potential role of ethical professional codes that might apply to an organisation (i.e. a volcano observatory) or an individual scientist. Formal codes of course exist in many professional arenas for individuals, such as medicine and engineering. Indeed, accreditation or chartered status might be required to practice the profession. Unfortunately, no pertinent international equivalent schemes or formal standards exist in volcanology. Individual scientists may belong to professional organisations in their specific discipline and might have chartered status or accreditation as a geologist or engineer for example. However, many geoscientists do not have such professional qualifications from a professional association or equivalent.

In volcanology the only one organisation with international credibility is the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), which is an association of the International Union of Geodesy and Geophysics (IUGG), which is itself one of the Unions of the International Council of Scientific Unions (ICSU). All ICSU bodies have international standing being, for example, recognised by the United Nations. The World Organisation of Volcano Observatories (WOVO) is a Commission of IAVCEI. IAVCEI runs on very limited funding, is based around an individual membership, and its activities are largely supported by volunteerism. Much of IAVCEI activity concerns academic matters, but it has increasingly played an important role in broader issues related to mitigation of volcanic eruption impacts, disaster risk reduction and volcanic crisis management. IAVCEI is the principal international forum for discourse on volcanic risk reduction and runs a number of Commissions related to these topics. WOVO has historically been a weak Commission with very little activity.

IAVCEI has developed two very helpful and important documents which can be seen as standards for volcanologists and *de facto* ethical codes of practice. A protocol was developed by an IAVCEI sub-committee for crisis protocols and on professional conduct of scientists during volcanic crises (Newhall *et al.*, 1999)[55]. The protocols were broadly supported by the community but there were critics (Geist & Garcia, 2000)[56]. In 2015 IAVCEI set up a Task Group on Crisis Protocols and published guidelines on the roles and responsibilities of scientists involved in volcanic hazard evaluation, risk mitigation and crisis response on the IAVCEI website[57]:

Both the 1999 and 2015 protocols are voluntary, so they do not come under any professional standards. Nonetheless they provide a widely accepted set of principles on behaviour and roles of scientists in volcanic emergencies. The 1999 protocols were framed in terms of failures and how to avoid them. The most pertinent failures in the context of parametric insurance are:

- Failure to value diverse scientific expertise, approach, and experience.

[55] Newhall, C., Aramaki, S., Barberi, F., Blong, R., Calvache, M., Cheminee, J.L., Punongbayan, R., Siebe, C., Simkin, T., Sparks, R.S.J. & Tjetjep, W. (1999) IAVCEI Subcommittee for crisis protocols: professional conduct of scientists during volcanic crises. Bulletin of Volcanology, 60: 323 - 334.
[56] Geist, D. & Garcia, M.O. (2000) Role of science and independent research during volcanic eruptions. Bulletin of Volcanology, 62: 59-61.
[57] https://www.iavceivolcano.org/iavcei-products/iavcei-guidelines/12-iavcei-guidelines-on-the-roles-and-responsibilities-of-scientists-involved-in-volcanic-hazard-evaluation-risk-mitigation-and-crisis-response.html

- Failure to work as a single scientific team, and thus loss of potential synergism, i.e., loss of a cooperative result that is greater than the sum of individual results. This relates to situations where there is more than one team and it is unclear who is responsible. However, such failure could occur within a team.
- Failure of scientists to use a single voice for public statements. This might develop if there is a dispute about whether an evacuation is necessary or not.
- There was also discussion about various failures of leadership and here a failure of leadership might lead to a poor decision or recommendation to evacuate. Leadership failure might include: lack of skill or experience; poor management skills for example.

The 2015 guidelines are more general but are still primarily focused on individuals rather than organisations. The most relevant part of the guidelines is:

"IAVCEI recommends that scientists: i) fulfil their responsibilities in good faith and to the best of their abilities, working to facilitate informed decisions by civil protection authorities and at-risk individuals; ii) safeguard not only their own legal status, but also the status and credibility of their advice which should be independent, neutral, objective, unbiased and value-free; iii) when communicating volcano hazard information be aware and respectful of applicable protocols and procedures, and all relevant legal requirements and cultural issues."

While we do not consider that adherence to the IAVCEI protocols and guidelines can be usefully included in an insurance policy contract as they are voluntary and have no legal status, it might be that efforts could be made to work with IAVCEI and WOVO to develop and strengthen them. This is discussed further in Section 7.

5 Probabilistic analysis

This section describes the process required to build a probabilistic trigger occurrence profile for the selected indices, which can then be used as the basis for structuring and estimating the pure risk cost and other characteristics of the parametric insurance coverage. The illustrative database and the underwriting model are provided along with this report as excel spreadsheets, further described in Annexe 4.

5.1 Analytical framework

Because both indices are used only for a binary trigger, the only probability required – for a particular volcano or for any volcano in a particular country – is that of a trigger happening in any one year.

There are three scenarios that need to have a probability assigned:

- **Probability 1**: *Unrest sufficient for VAL to be raised from background to first level above.* (If there were to be special cases included, allowing for increase of VAL at volcanoes already in unrest, these would require a probability of occurrence too.)
- **Probability 2**: *Evacuation call following raising of VAL.* (This is a probability conditional on VAL having been raised.)
- **Probability 3**: *Evacuation call without any prior raising of VAL*. (This includes, in the case of volcanoes already in unrest, any evacuation call.)

Ideally, one would undertake the probabilistic analysis at each individual volcano, but the historical dataset is too sparse to support such an approach. An expert elicitation process could be undertaken, but this would be expensive if done for each volcano, and the uncertainty at the resolution of the individual volcano would be very high. On the other hand, treating all volcanoes in a given country the same is almost always going to be too generalised an approach.

A hybrid approach is therefore recommended, where a subset of volcanoes is removed from the main set for a given country and those volcanoes are analysed either individually or in groups. The subset would comprise some or all of the following:

- Volcanoes with relatively large PEI, as these are potential 'severity' events which will have an outsized impact on the overall risk profile so deserve special attention.
- Volcanoes which attract the additional evacuation cost modifier, as these too are potential 'severity' events.
- Volcanoes with high historical rates of unrest recognition and / or evacuation calls, as these are potential 'frequency' events which again will have an outsized impact on the overall risk profile so deserve special attention.
- Volcanoes which are already above background activity levels at the start of the policy period, as these either will only be eligible for the evacuation call trigger or will require specific probability analysis for a specific VAL movement case (if such is included in the policy).

The remaining ‘main group’ is treated as a single analytical set and shares the same probabilities for each of the three triggers, probabilities which are estimated *en masse*.

For the purpose of clarity, the above differentiations are made only for analytical purposes; the real-time triggers and pay-out calculations are made specifically for the volcano in question and are completely independent of any modelling assumptions.

We describe in Section 6 the real-world mechanisms that might be set up to complete an actual probabilistic analysis for a country in advance of placement of a parametric insurance policy, and the parallel ‘customisation’ that would be required by the country taking out the policy. Below we describe worked examples for each of the five focus countries for illustrative purposes only. As is described in Section 6, it is beyond the scope of this project to complete a full probabilistic analysis given the need for both insurer and insured entity participation.

5.2 Practical application of framework

We have compiled an illustrative dataset which includes all of the characteristics of individual (and groups of) volcanoes and at the country level, for all five focus countries, necessary to complete a probabilistic risk analysis and price / underwrite a parametric insurance policy.

We have included assumptions about coverage design (Figure 5.1), including the early trigger scalar / fixed dollar amount, the multiplier for high evacuation cost volcanoes (on Figure 5.2), a dollar value per PEI unit (for calculating final pay-outs) and the total annual aggregate policy limits. We note that such coverage design decisions would rest with the client country through the ‘customisation’ of their policy, so that the assumptions we make here are purely for demonstration purposes and have not been made in consultation with the respective governments.

All Volcanoes	# Volcanoes	Early Trigger Scalar Fixed or Variable with PEI	Variable Early Trigger Scalar (%)	Fixed Early Trigger Amount ($)	Higher Evac Cost Multiplier (%)	Dollar Val per PEI Unit ($)	Coverage Limit ($)	Deductible ($)
Indonesia	127							
PNG	49							
Philippines	42							
Tonga	20							
Vanuatu	14							

Figure 5.1 Customisable coverage parameters required for policy structuring and underwriting analysis.

We have also completed illustrative estimates of the probabilities for new unrest, evacuation following new unrest (this is a conditional probability), and evacuation at volcanoes either currently in unrest or at which no VAL movement is declared prior to an evacuation call (Figure 5.2).

	Ave / Act PEI	# volcanoes	Prob 1: Unrest	Prob 2: Evac after unrest (conditnl on P1)	Prob 3: Evac no unrest (or existing unrest)
Main Group					
Any volcano	93,179	95			
In Unrest Group		High Evac Cost Flag			
Agung	131,000	0			
Banda Api	6,000	0			
Dempo	19,000	0			
Dukono	10,000	0			
Gamalama	200,000	0			
Gamkonora	16,000	0			
Ibu	18,000	0			
Karangetang	5,000	0			
Kerinci	48,000	0			
Krakatau	21,000	0			
Lewotolo	20,000	0			
Lokon-Empung	123,000	0			
Marapi	105,000	0			
Merapi	458,000	0			
Paluweh	2,000	0			
Rinjani	133,000	0			
Sangeang Api	5,000	0			
Semeru	108,000	0			
Sinabung	38,000	0			
Soputan	94,000	0			
Tengger Caldera	189,000	0			
Individual Consideration Group					
Batur	474,000	0			
Dieng Volcanic Complex	1,123,000	0			
Gede-Pangrango	352,000	0			
Guntur	434,000	0			
Kelut	214,000	0			
Malang Plain	2,345,000	0			
Merbabu	442,000	0			
Penanggungan	678,000	0			
Sumbing	6,000	0			
Sundoro	608,000	0			
Tangkubanparahu	845,000	0			

Figure 5.2 Probability fields and other volcano characteristics required for the underwriting analysis. This example is for Indonesia and illustrates the splitting of volcanoes into three sets; a main group, the individual volcanoes currently in unrest, and the other 'special cases' for which individual attention was deemed necessary (i.e. those for which generalised assumptions are not warranted, as described in the text).

We have previously highlighted some of the challenges in estimating probabilities of new unrest and of evacuations across all five focus countries, challenges which would be faced in almost all countries in the world. Approaches to address these challenges for the purposes of underwriting of an actual insurance policy are described in Section 6.

For the illustrative examples presented here (with actual data provided in Annexe 4 and accompanying excel spreadsheets), we have derived key information from the evacuation database presented in the Component 1 report and database, as well as from other sources, mainly volcano observatories themselves. The utilised information is described briefly below:

- **New unrest**: For all countries we have completed the listing of volcanoes which are currently at a VAL level above the lowest level. Vanuatu currently has the highest proportion of its volcanoes in unrest (6 of 14, ~43%)[58], with Indonesia at ~17% (21 of 127)[59] and Philippines at about 5% (2 of 42)[60]. PNG is unknown[61]. Tonga has no VAL system and there are no current notices of unrest.

- **Upward VAL movement**: We have reviewed information sources which might allow compilation of the history of VAL movements at volcanoes in the five focus countries in order to evaluate whether or not there might be sufficient data to guide estimation of upward VAL movement probability. We found that the only relevant data, beyond the very recent data (maximum of a couple of years) available in public-facing volcano observatory archives, is contained within the monthly Bulletin of the Global Volcanism Network[62], from where extraction of relevant data has not been completed. We believe that a database of VAL movements going back (though not necessarily complete) for 50 years could be compiled given appropriate resourcing.
- **Evacuations**: We have used information from the evacuations database compiled and presented in the Component 1 Technical Report, which we believe to be reasonably complete for the past 50 years, sufficient at the country level to guide our probabilistic estimates in their totality. Where records are available for a longer historical period, we have also considered that information (e.g. for Tonga, where there are no evacuations in the last 50 years, but multiple evacuations recorded further back in history).

Based on this compilation of information, the underwriting model has been completed with all necessary probability estimates to generate an illustrative risk profile of the proposed parametric insurance policy for each of the five focus countries.

We note again that the assigning of probabilities to VAL movements and evacuation calls is inherently difficult given the general absence of relevant historical databases (partly addressed in this project through compilation of the evacuation database) and the huge challenges in quantitative modelling of unrest and conditions which might prompt evacuation calls at any single volcano, let alone for all the volcanoes in a given country. The implications of this, and possible remedies, are discussed in Section 6.

5.3 Underwriting analysis

Our underwriting model takes the probabilities for each of the possible three triggers occurring at any of the volcanoes in a given country and simulates 100,000 years of those triggers and the resulting pay-outs given the policy structuring assumptions.

In this model, we have limited the number of triggers at any one volcano to one ‘early’ trigger and one evacuation call trigger. For volcanoes already above background VAL level, only one evacuation trigger is allowed.

For each country, we have generated a ‘ground-up’ loss profile[63] and we have also applied an annual deductible and coverage limit. We do not believe that a per-event deductible is suitable in this case, as small pay-outs are an integral part of the functioning of the policy; an annual deductible may be useful and can be adjusted in the final structuring stage as can the coverage limit.

[58] https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/current-volcanic-activity
[59] https://magma.vsi.esdm.go.id/
[60] https://www.phivolcs.dost.gov.ph/index.php/volcano-hazard/volcano-bulletins3
[61] No public information available for PNG. At the time of writing, we are awaiting confirmation of this number from RVO.
[62] This archive is described in the Component 1 Technical Report.
[63] This is the full loss profile of the parametric insurance policy, absent any deductible, policy limit or other structuring features.

5.3.1 General assumptions

For the purposes of demonstration of the model and to generate some illustrative results, the following assumptions are made uniformly across all five focus countries for those parameters which would normally be selected by the client country during the policy customisation process (and which are further described in Section 6.1):

- *Early Trigger Pay-out*: We have taken this to be variable and the scalar used is 5% (so the early trigger would pay out 5% of what a full evacuation trigger would pay out for that volcano).
- *Higher Evacuation Cost Multiplier*: 100% (so for those volcanoes flagged as having higher than normal evacuation costs, such as volcanoes which require off-island evacuation, the evacuation pay-out will be the normal pay-out plus an additional 100% of the normal pay-out).
- *Dollar Value per PEI Unit*: $10 for Indonesia and the Philippines, $50 for PNG, Tonga and Vanuatu. The $10 value means that the evacuation call trigger pay-out amount at a volcano with a PEI of 10,000 will be $100,000.
- *Deductible*: This has been fixed at one ‘average evacuation pay-out’ (i.e. pay-out amount for evacuation at one volcano with the average PEI of all volcanoes in that country).
- *Coverage Limit*: This has been fixed at the higher of five times the ‘average evacuation pay-out’ (i.e. pay-outs for evacuations at five volcanoes each with the average PEI of all volcanoes in that country) and the evacuation pay-out at the volcano with the largest PEI in the country.

We have not taken into account the possibility of ‘partial evacuations’ so that the probability estimates are made for full evacuations and each evacuation call trigger in the model prompts a full pay-out amount calculated for that volcano. The case of partial evacuations and resulting triggers and pay-outs is further discussed in Section 6.4.

5.3.2 Results

Illustrative results from the underwriting modelling are provided below for all five focus countries. We provide statistics for the ground-up loss profile as well as for an assumed set of coverage conditions (annual deductible and coverage limit). An exceedance probability curve for both the ground-up (in red) and coverage (in blue) losses is also provided. Full underwriting models in excel accompany this report, as described in Annexe 4.

It must be noted that these results are for demonstration purposes only; the probabilities for trigger events used for this demonstration are highly preliminary and have not been sense-checked with in-country experts or amongst a broad group of international experts, and the coverage condition assumptions have also not been reviewed by any representatives of the countries.

The assessment of individual probabilities for triggering events will be a critical part of product implementation, and approaches to completing this are discussed in Section 6. Country customisation of other input parameters will also be important during the implementation phase.

Indonesia

Indonesia		
	Ground-up	**Coverage**
Expected Loss	1,827,404	937,623
SD	2,680,659	2,340,027
CoV	1.47	2.50
5-yr	2,576,526	1,113,534
10-yr	4,687,589	3,224,597
25-yr	7,016,758	5,553,766
50-yr	9,148,764	7,685,772
100-yr	11,931,268	10,468,276
Deductible		1,462,992
Coverage Limit		23,450,000

Table 5.1 Illustrative risk profile statistics for ground-up 'losses' and insurance coverage pay-outs for Indonesia.

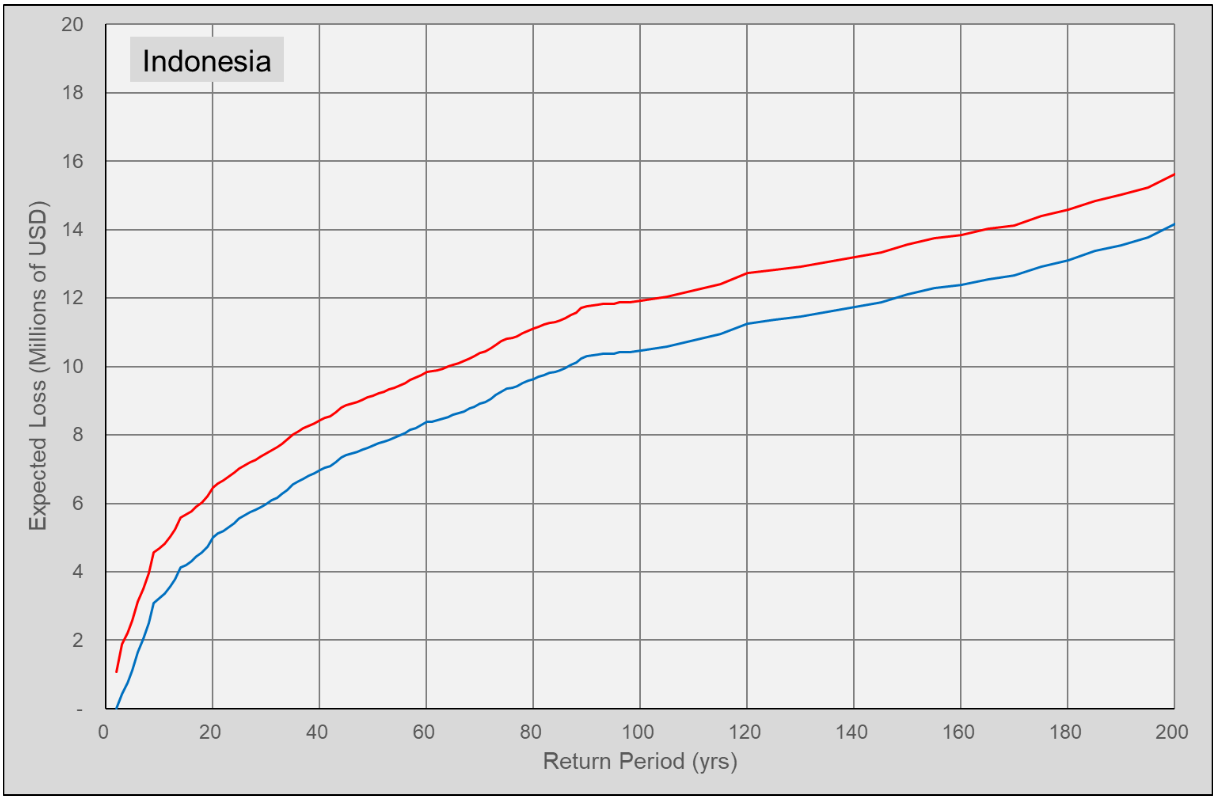

Figure 5.3 Illustrative ground-up and coverage exceedance probability curves for Indonesia.

Papua New Guinea

Papua New Guinea		
	Ground-up	**Coverage**
Expected Loss	169,246	71,780
SD	426,300	364,160
CoV	2.52	5.07
5-yr	206,500	-
10-yr	341,333	27,048
25-yr	590,000	275,714
50-yr	2,625,000	2,310,714
100-yr	2,644,667	2,330,381
Deductible		314,286
Coverage Limit		2,500,000

Table 5.2 Illustrative risk profile statistics for ground-up 'losses' and insurance coverage pay-outs for Papua New Guinea.

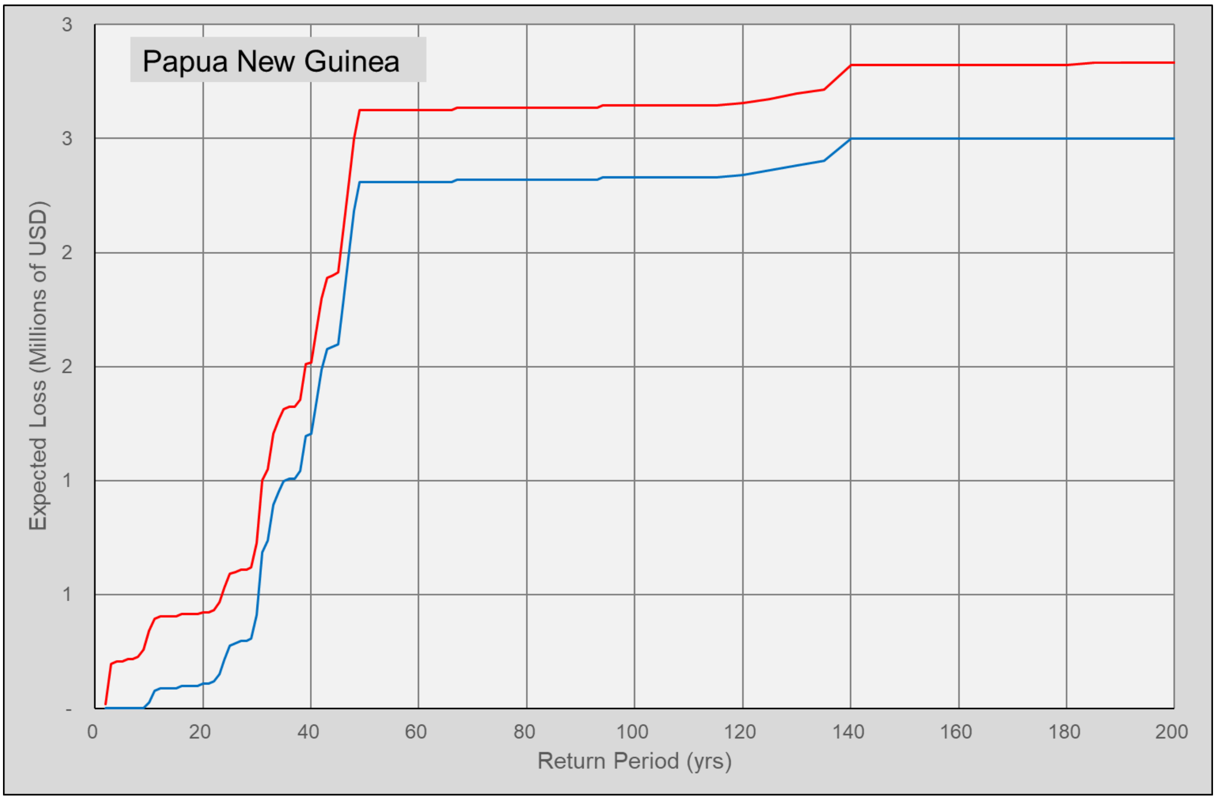

Figure 5.4 Illustrative ground-up and coverage exceedance probability curves for Papua New Guinea.

Philippines

Philippines		
	Ground-up	**Coverage**
Expected Loss	1,425,457	594,165
SD	1,871,733	1,448,414
CoV	1.31	2.44
5-yr	2,930,000	1,365,238
10-yr	3,754,542	2,189,780
25-yr	4,579,083	3,014,321
50-yr	5,364,361	3,799,599
100-yr	9,424,042	7,859,280
Deductible		1,564,762
Coverage Limit		14,130,000

Table 5.3 Illustrative risk profile statistics for ground-up 'losses' and insurance coverage pay-outs for the Philippines.

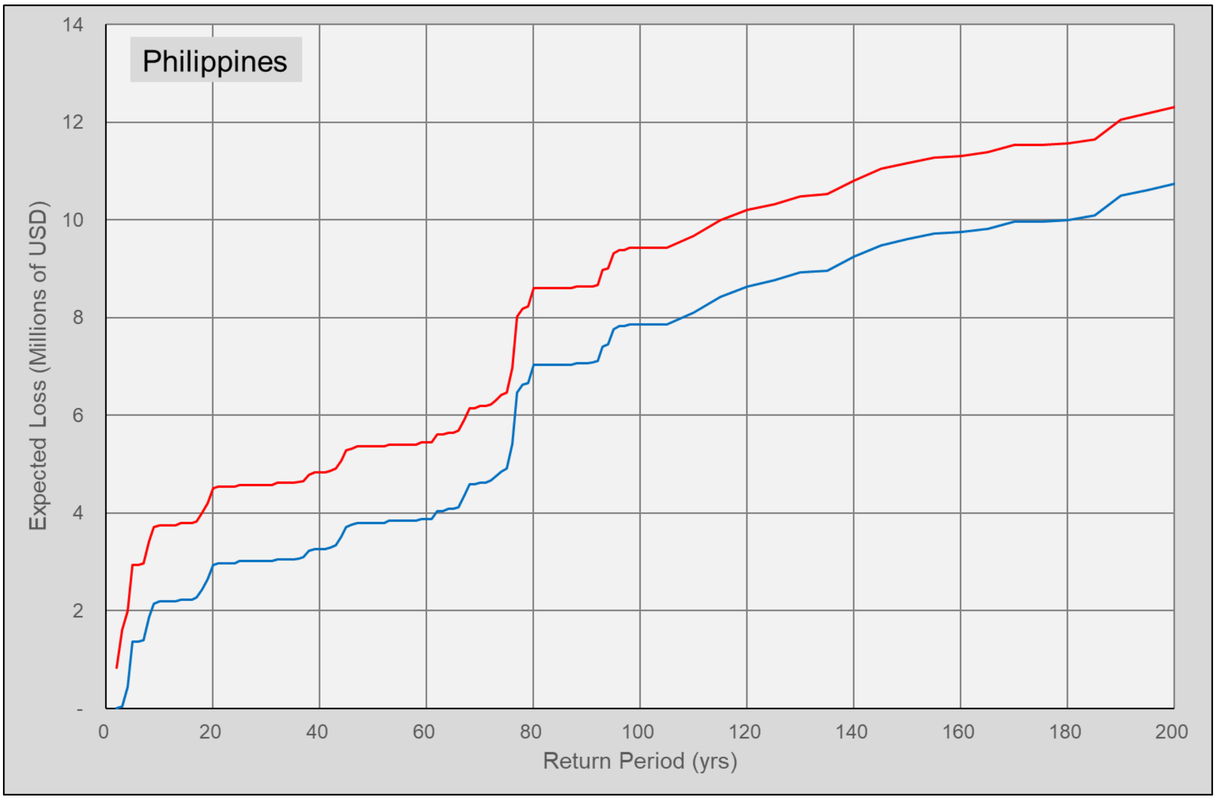

Figure 5.5 Illustrative ground-up and coverage exceedance probability curves for the Philippines.

Tonga

Tonga		
	Ground-up	**Coverage**
Expected Loss	8,542	776
SD	18,111	6,508
CoV	2.12	8.38
5-yr	4,167	-
10-yr	43,750	-
25-yr	45,833	-
50-yr	50,000	2,500
100-yr	87,500	40,000
Deductible		47,500
Coverage Limit		237,500

Table 5.4 Illustrative risk profile statistics for ground-up 'losses' and insurance coverage pay-outs for Tonga.

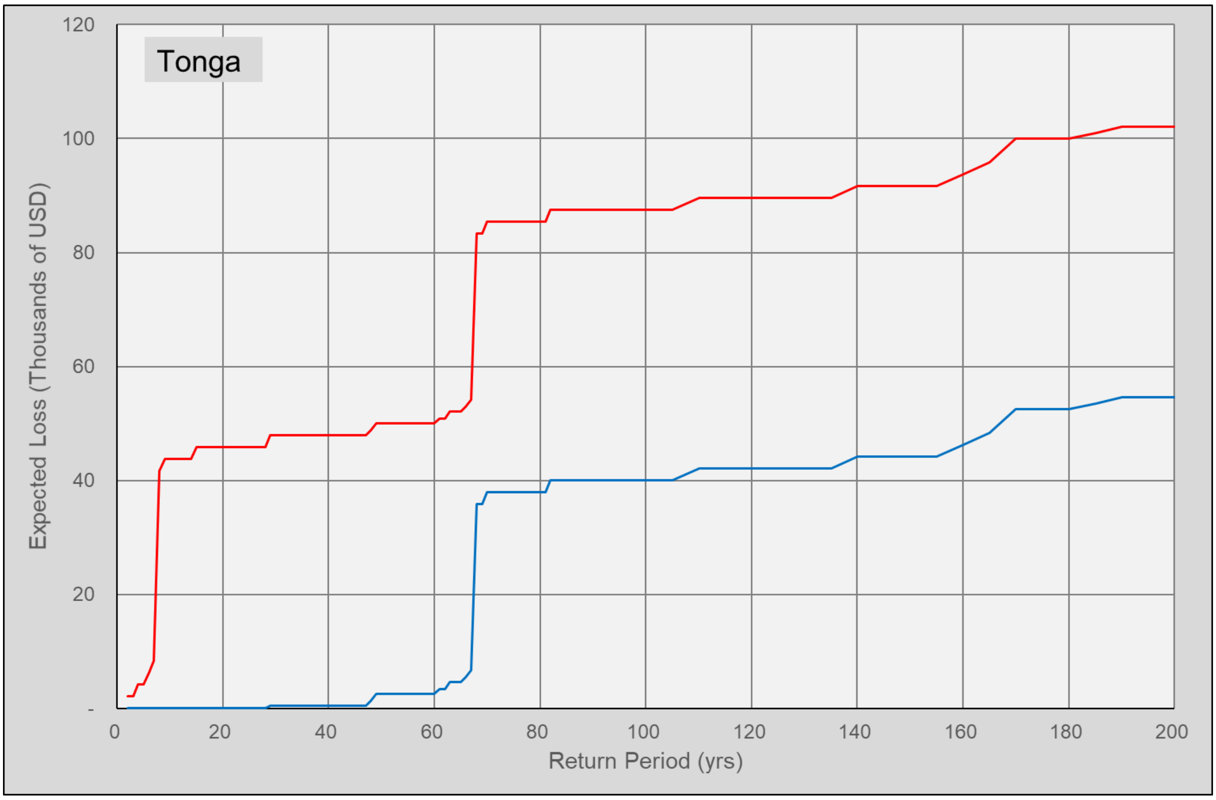

Figure 5.6 Illustrative ground-up and coverage exceedance probability curves for Tonga.

Vanuatu

Vanuatu		
	Ground-up	**Coverage**
Expected Loss	82,706	21,057
SD	97,446	61,614
CoV	1.18	2.93
5-yr	161,071	28,929
10-yr	176,786	44,643
25-yr	286,429	154,286
50-yr	411,786	279,643
100-yr	444,286	312,143
Deductible		132,143
Coverage Limit		660,714

Table 5.5 Illustrative risk profile statistics for ground-up 'losses' and insurance coverage pay-outs for Vanuatu.

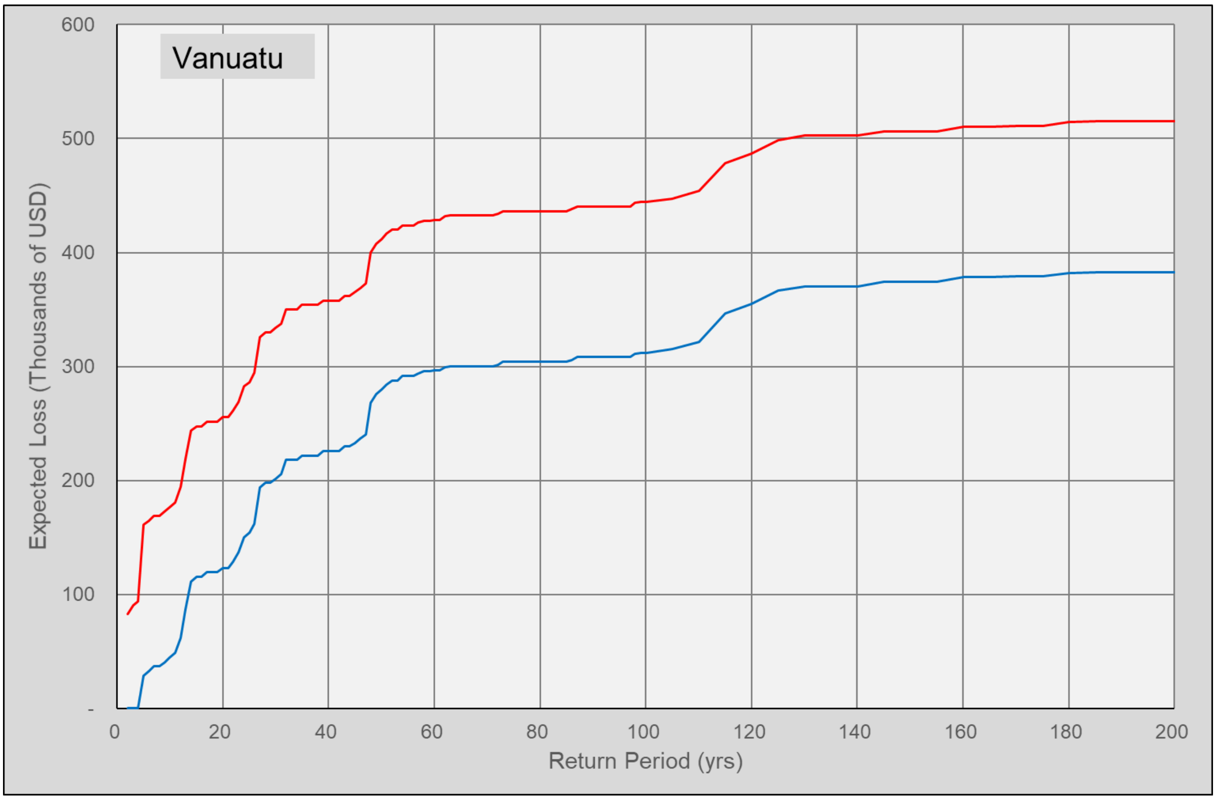

Figure 5.7 Illustrative ground-up and coverage exceedance probability curves for Vanuatu.

6 Implementation

In this section, we present a detailed term sheet which would form the basis for insurance policy wording, a table of information required for the policy schedule, and a listing of items which would need to form part of the index / trigger reporting mechanism.

We then outline a possible methodology for achieving a consensus on the trigger probability assignment, critical to finding willing risk-takers offering a price for risk transfer which makes sense for the potential sovereign buyers of this unrest product.

A following section describes the concepts that come into play when such a parametric policy as is being described here is priced by the ultimate risk-takers in the market.

Finally, we discuss three elements of implementation which will be important to plan for during any preparation phase: the risk transfer structuring (including the primary insurance vehicle for underwriting and the secondary insurance vehicle or market(s) for ultimately holding the risk); the narrative around the coverage and the particular features of the risk and the risk transfer policy form; and, finally, implementation of the secondary conditionalities which will need to accompany the policy issuance, including use of funds, proof of loss, etc.

6.1 Term Sheet

A draft Term Sheet for the unrest product is provided as Table 6.1.

Unrest Product Term Sheet	
Policy Name	Parametric Insurance for Volcanic Unrest using Volcanic Alert Level and Evacuation Call indices
Policy Form	Insurance (could be derivative, but both indices as used inherently create the circumstances of additional cost to the government, so direct link is inherent)
Buyer / Insured	Sovereign government
Seller / Insurer	Regional pool, could be direct to reinsurance / capital markets if sufficient scale. Very unlikely to be through domestic carrier unless required as a front[64]
Structure	Two trigger types, each with different pay-out level at each individual volcano in covered area. Either trigger can occur multiple times under the policy
Covered volcanoes and geographies	National coverage, covering early VAL movement at any volcano and any evacuation call. Volcanoes not at background VAL at start of policy period are listed in Schedule and only the evacuation call trigger operates at those volcanoes
Policy Period	12 months incepting at [**] (time specified, in GMT) *[Could incept at any time (i.e. no seasonality)]*

[64] A ‘front’ is a local insurer used for regulatory purposes but which does not hold any risk.

Index Measures	1. Upward movement of VAL from a background level (no unrest), as publicly reported by the relevant reporting agency listed in the schedule 2. Issuance of an Evacuation Call as publicly reported by the relevant reporting agency listed in the schedule
VAL Reporting Agency	As defined in the schedule *[Official agency mandated in sovereign law to issue volcano alert levels. Would need to take account of potential changes in name or form of mandated agency during the policy period.]*
Evacuation Call Reporting Agency	As defined in the schedule *[Official agency mandated in sovereign law to issue an Evacuation Call. Would need to take account of potential changes in name or form of mandated agency during the policy period.]*
Qualifying Event	A period of volcanic unrest at a given volcano in the covered area at the start of which either one of the index measures meet the defined trigger (i.e. upward VAL movement from background level or Evacuation Call made) and for which the event start date falls within the policy period.
Event Start Date	Date on which the first upward VAL movement from background level or an Evacuation Call is made. Each event is volcano-specific.
Consecutive Qualifying Events	For volcanoes not in unrest at policy inception, one Event which starts with an upward VAL movement is a Qualifying Event, which can also include an Evacuation Call trigger. A second Qualifying Event in the Policy Period can only occur if the event commences with an Evacuation Call. These Events can occur in any order. A maximum of one Event of each type is a Qualifying Event in any one Policy Period. For volcanoes already in unrest at policy inception, only the first Event which commences with an Evacuation Call is a Qualifying Event
Base VAL	For each volcano, as defined in the Schedule
Aggregate Claim Amount [USD]	The sum of all Claim amounts for all Qualifying Events in the Policy Period
Event Limit [USD]	Sub-limit will apply for upward VAL movement trigger at each volcano, see VAL Trigger Payment Amount Event limit as per Schedule, which will detail the PEI at all volcanoes in country and the scaling factor (i.e. relationship between PEI and pay-out), as well as flagging volcanoes at which the high evacuation cost multiplier applies
Aggregate Policy Limit [for all volcanos for the Full Policy Period]	Listed in the Schedule In no circumstances will the aggregate payment amount exceed the aggregate policy limit
VAL Trigger Payment Amount [USD]	For each qualifying event, the VAL Trigger Payment Amount will be either a fixed amount as listed in the Schedule or, if a variable amount is indicated in the Schedule, then it will be the VAL Trigger Scaling Factor multiplied by the Evacuation Trigger Payment Amount.
VAL Trigger Scaling Factor [%]	As listed in the Schedule

Volcano PEI	For each volcano, as listed in the Schedule
Evacuation Trigger Payment Amount [USD]	For each Qualifying Event occurring during policy period, an Evacuation Trigger Payment Amount will be payable in the event of an Evacuation Call as follows: *Volcano PEI x PEI to Pay-out Scaling Amount x [High Evacuation Cost Modifier (for flagged volcanoes only)] x Partial Evacuation Modifier*
PEI to Pay-out Scaling Amount [USD]	As listed in the Schedule
High Evacuation Cost Flag	As listed in the Schedule, volcanoes with high evacuation cost are flagged
High Evacuation Cost Modifier [%]	As listed in the Schedule, only applies at volcanoes with High Evacuation Cost Flag
Partial Evacuation Modifier	This will be reported by the Calculation Agent or Reporting Agency at the time of or soon after an Evacuation Call has been made, and will act to reduce the Evacuation Trigger Payment Amount if only a partial evacuation is called.
Total Payment Amount	The Total Payment Amount shall equal the sum of the VAL Trigger Payment Amount and / or Evacuation Trigger Payment Amount for each Qualifying Event subject to the Policy Limit
Index Monitoring	Likely undertaken by both buyer and primary carrier, with either able to call for the Calculation / Verification Agent to undertake any formal process required for a pay-out to occur
Calculation or Verification Agent	[TBD]
Claim Calculation Dates	[TBD] – should be very quick (one to a few days) once public statement is issued on VAL Movement or Evacuation Call
Claim Payment Dates	For each qualifying event, claim payments will be made on the [seventh] business day immediately following each claim calculation date.
Proof of Loss Clause	Some proof that an evacuation has taken place will be required. Some size criteria will also be required to establish whether a particular Evacuation Call was a full or partial evacuation (based on pre-defined criteria)

Table 6.1 Draft Term Sheet for the unrest product.

6.1.1 Information for Policy Schedule

Table 6.2 lists the information that will be required to be in the Policy Schedule.

Policy Schedule Requirements	
Volcano PEI	Each known volcano (listed in accepted global database) will need a PEI assigned. Here we use the absolute value of PEI as provided in the Component 1 Database
Policy Period	Date of Policy inception and duration of coverage
VAL Reporting Agency	The reporting agency - this will be whatever official agency is mandated in sovereign law to issue Volcano Alert Levels
Evacuation Call Reporting Agency	The reporting agency must be specified - this will be whatever official agency is mandated in sovereign law to issue Evacuation Calls
Volcanoes at non-base Level VAL	Any volcanoes which have a VAL which is not at the base level at the policy start date will be listed
Volcanoes with Evacuation Cost Modifier	Any volcanoes which have are flagged as high evacuation cost
VAL Trigger Fixed Pay-out Amount [USD]	If a fixed pay-out amount is selected for the VAL trigger then this will be indicated as well as the amount of that fixed pay-out.
VAL Trigger Scaling Factor [%]	The scaling factor applied to calculate the pay-out for a VAL movement trigger, relative to a 'full' Evacuation Call trigger
PEI to Pay-out Scaling Amount [USD]	This is the value paid out per PEI unit for an Evacuation Call trigger
Evacuation Cost Modifier	Any volcanoes which have a cost modifier for evacuation must be listed along with the modifier
Full Evacuation Definition	For each volcano, a definition of a full evacuation will be required, so that the Partial Evacuation Modifier can be applied when the full evacuation definition is not met
Deductible [USD]	The amount of the total pay-outs calculated under the policy retained by the Insured
Aggregate Policy Limit [USD]	This is the total amount covered for the entire policy, and is a limit in the total amount of pay-outs that can be made under the policy for Events taking place during the Policy Period

Table 6.2 Information required for Policy Schedule.

6.2 Methodology for trigger probability assessment

In Section 5 of this report, we have presented a risk assessment and underwriting model within which the proposed parametric volcano unrest product can be analysed and priced, with coverage customised to meet the needs of each individual sovereign client. We have completed an underwriting exercise and presented illustrative summaries of the resulting risk profiles for each of the five focus countries. In so doing, we have made two sets of assumptions; one around the customisable parameters which a client would normally select and the other around the assignment of trigger probabilities.

The customisable parameters have a generally linear effect on the overall underwriting and pricing process – if a country wants twice as much of an Evacuation Pay-out per PEI unit then, all other things being equal, such a policy will cost around twice as much. (It won't always be exactly twice as much because the Early Pay-out trigger is effectively priced separately and doesn't necessarily scale with the Evacuation Pay-out amount.) Because of this linear effect, the selection of these customisable parameters has no significant effect on the per-risk pricing, and can therefore be left largely to the client to choose (within some boundaries of reasonableness).

In contrast, the assignment of required trigger probabilities, as described in Section 5, is absolutely critical to the overall risk assessment, underwriting process, pricing and, ultimately, the value for money proposition of the product to the potential client. Usually, data is available and accessible to both a client (usually supported by expert intermediaries) and the ultimate risk-taker(s) (with in-house expertise), these data providing both historical experience (so allowing for an 'as-if' analysis of the policy performance) and, often, likely future experience generated via stochastic modelling.

In the case of the two unrest triggers proposed for this product, the former data source is both rather to highly incomplete and only available for a relatively short duration (compared to the overall trigger frequency) and the latter data source is not available at all. We therefore need a non-conventional approach to reaching a consensus view of risk which will enable a sovereign client to achieve comfort that they are getting value for money in the insurance transaction and the ultimate risk taker(s) to achieve comfort that they are being adequately rewarded for taking risk.

The following are the two key components of reaching such consensus:

- **Data**: It is to the benefit of all clients that all existing data is made available in an accessible form. As we have described elsewhere, data on VAL movements and evacuations is usually not entered into a database within an individual observatory or country, let alone globally. The Smithsonian GVP has a 50-year archive of monthly narrative reports, derived from on-the-ground sources, out of which information on both evacuations and VAL movements can be derived. As part of this project, we have populated an evacuation database which can provide the raw evacuation frequencies at the country level (and, for a few volcanoes, at the volcano level) needed to guide the assignment of trigger probabilities, as described in Annexe 4. VAL movements are much more difficult to derive from the GVP Bulletins, but our review suggests that this would be feasible given adequate resources, and we believe that it would be critical to undertake such work, either for a particular country or, preferably more broadly, prior to a final pre-placement risk analysis being completed.
- **Expert Judgement**: Assigning probabilities to VAL movements and evacuation calls for individual or groups of volcanoes, given the poor data available to guide such assignments, is challenging and prone to high uncertainty and, therefore, variability. While there may be a historical guide to the overall total probability of, say, an evacuation call in a given country in any one year, the

distribution of that total probability amongst a country's volcanoes will still greatly impact on the overall risk assessment. We propose that an expert judgement process is required to assign probabilities within the modelling framework described in Section 5. This process would comprise a panel of, say, three experts, one appointed by the client (and required to have excellent local knowledge), one by the ultimate risk taker(s) and an independent chairperson. This group would convene to complete a risk analysis for a particular country, with the chairperson responsible for overseeing the collection and review of all available and relevant data. It seems likely that a consensus could be reached without overly formalising the expert judgement process, although full EJ methods could be used if necessary. The resulting probability assignments would be agreed between client and risk taker as the basis for pricing.

As discussed in Section 6.4.2 below, we believe that only this transparent and collaborative consideration of risk, resulting in an agreed view of risk for a particular policy in a particular country, would result in the closing of a parametric insurance product for volcanic unrest.

6.3 Market approach to pricing

There are as many approaches to pricing of insurance as there are underwriters, but re/insurance pricing can be broken down into three elements for the purposes of analysing the main drivers of price under particular conditions. These three elements are:

- **Expected loss**, including uncertainty around the estimation of that expected loss;
- **Capital load**, to cover the cost to the insurer of allocating capital to cover potential claims during the policy period; and
- **Expense load**, to cover the costs of technical work and, in most cases, brokerage and claim settlement costs also.

With regard to the volcano unrest product described in detail in this report, we can drill more deeply into each of these three elements in order to identify the key driver(s) of likely price for the risk being transferred. In the remainder of this section, we will use 'price' as a descriptor of per-risk cost, by which we mean the ultimate cost of risk transfer paid by the client relative to the client's view of the expected loss. In this case and as further elaborated below, expected loss is an adequate, though not complete, descriptor of the quantum and characteristics of the risk being transferred; in other cases, more comprehensive descriptors of risk may be required to appropriately capture 'per-risk pricing'.

6.3.1 Expected Loss

Expected loss (EL), also referred to as average annual loss (AAL) or pure risk, is the expected annual pay-out amount on a particular insurance contract, when averaged over a sufficient period of time to include a full range of potential pay-out scenarios. It forms the floor for the cost of an insurance policy (excepting particular circumstances which do not apply in this case); at the very minimum, an insurer will need to collect in premium what it expects to pay out in claims when averaged over a sufficiently long period of time.

In many insurance settings, a risk-taker will base its estimate of EL on historical claims data, supplemented by actuarial analysis. For most catastrophe risk, the historical time period is insufficient to include a full range of potential pay-out scenarios, so catastrophe risk models are used to generate replacement stochastic claims data as a basis for the actuarial analysis and estimation of EL.

In both these cases, a client and a risk-taker can often reach a similar view of EL, or at least constrain a range of EL, where the risk-taker will be at the higher end of the range and the client at the lower end. In the reinsurance setting at least, one of the key tasks of a broker is to maintain as narrow a range of EL as possible, so that the client and risk-taker views of risk are as close to one another as possible.

In this regard, one of the key advantages of parametric insurance is that the driver of EL is the hazard itself, rather than the ultimate loss / claim amount. Hazard understanding and analytics are generally better-constrained than total loss, as additional uncertainties in exposure and vulnerability are effectively removed. This reduction in the importance of relatively uncertain variables is particularly helpful in developing world settings and / or for innovative insurance products, where: a) claims data is sparse to non-existent; and b) there is generally a lack of exposure and vulnerability data at an appropriate resolution. Quantifying hazard does not face the same challenges because hazard models, based on physical science rules which are constant globally, are easily adapted to different geographies with little or no change in the level of uncertainty around model outputs.

Constraining the risk-taker's view of risk is critical to managing the cost of risk transfer. Uncertainty in the analysis of pure risk provides insurers with the ability to take a conservative view and potentially reach an EL estimate which is so much higher than the client's view of risk that the EL difference will become the dominant driver of price relative to the client's view of risk (rather than the other loadings that will be added, which are usually seen as the main drivers of price).

6.3.2 Capital Load

Insurers who have portfolios with high co-variant risk are required to hold a lot of capital to cover that risk; the general global standard for regulators is enough claims-paying capacity to cover a series of losses in any one underwriting year which has a 1 in 200 probability of occurring. Insurer ratings are also based substantially on ultimate claims-paying capacity. Holding a large amount of capital, which must be available to pay claims at any time, but is actually very unlikely to be needed, is expensive. Insurers manage this cost by diversifying their books, both by line of business and by geography, and / or by purchasing reinsurance. Reinsurers use the same diversification methods, but at a global rather than local or regional geographical scale.

For peak catastrophe risk zones, the capital load on insurance price is relatively high due to risk accumulation. However, for non-peak zones, and especially for unusual perils, the capital load is often small to non-existent due to the diversifying nature of such risk; little or no additional capital need be held to cover the new risk because it is uncorrelated with any other elements of the portfolio.

Thus, for volcano-related risk in Asia-Pacific, we would anticipate that there would be no capital loading element in the policy pricing. It is more likely that a capital load becomes a more significant part of the overall pricing as the quantum of risk transfer becomes larger, but this is unlikely to come into play for the scale of risk transfer envisaged under the VIP project.

One additional point to note is that the capital load generally includes the profit element of pricing; in the case of innovative sovereign re/insurance transactions in emerging and developing countries, we do not tend to see any additional capital loading to accommodate a profit element. This is not to say that risk-takers do not treat such transactions as fully commercial, but the value materialises through non-financial mechanisms such as the gaining of experience and the optics of being at the forefront of innovation and participating in the global development space.

6.3.3 Expense Load

Re/insurers will add an expense load to their expected loss estimate to cover both known expenses associated with a particular transaction as well as to recoup internal costs associated with the transaction (e.g. R&D, risk analytics, client development and management). For indemnity risk transfer transactions, expense load will also include claims adjustment and settlement costs while for parametric risk transfer transactions, it will include calculation agent costs, noting that other claims settlement costs are generally trivial.

Many sovereign insurance programmes in the development space cover most or all transaction-related expenses separately – and when they don't, those costs are added to the premium cost in a fully transparent manner. Re/insurers generally do not add a substantial expense load to cover their own internal costs in these sorts of deals, although this is usually because the deals are presented with comprehensive modelling and analytics already completed and able to be shared.

We would note that the more open and transparent the modelling and analytics behind a deal, and the more detailed and presentable the package of risk is, the lower the ultimate expense load that will need to be paid.

6.3.4 Conclusion

The VIP project generally, and the proposed unrest product in particular, represent a unique programme / transaction within the re/insurance marketplace. Not only will markets not have priced a package of risk much like the unrest product for any peril, they will also not have encountered an approach to risk analytics and EL estimation anything like that being proposed here. We therefore must build up a defensible view of potential pricing by looking at each of the technical pricing elements described above.

The reason for proposing the collaborative underwriting approach described elsewhere in this report is to achieve a consensus on EL for a particular coverage. Without this collaborative approach, the uncertainty on EL could be huge, and therefore the per-risk pricing – say as a multiple of the client's view of EL – could be very high indeed.

We believe that if the approach suggested is used, the re/insurer view of risk can be controlled to be within a few tens of percent, rather than the hundreds of percent that might otherwise be seen. The other technical elements of the pricing are much easier to constrain, and, based on the experience of one of the consortium partners (WTW) with substantial transactional experience in the sovereign, parametric and development space, we estimate that factors for capital plus 'internal' expense loading of 10 to 25% could be achieved – to which would need to be added the (potentially fixed) costs of brokerage and calculation agent services, if these were not funded through other means.

Table 6.3 summarises potential pricing elements in three different scenarios as an illustration of the narrative above. We have assumed that the primary risk taker would be a risk pool or other domestic or regional entity and that the ultimate risk-taker would be the global reinsurance markets. We note that these illustrations of potential premium pricing do not include recouping of any of the operational costs of the primary risk taker, which would usually include general operating overhead (or fronting fee if the primary risk taker is purely fronting), brokerage / risk transfer advisory, and calculation agent costs.

	Best Case	Medial Case	Worst Case
Client view of Expected Loss (EL)	1,000,000	1,000,000	1,000,000
Risk-taker uncertainty on EL	10%	25%	100%
Risk-taker view of EL	1,100,000	1,250,000	2,000,000
Capital Load	5%	10%	15%
Internal Expense Load	5%	10%	15%
Price	1,155,000	1,375,000	2,300,000
Multiple over client EL	1.16	1.38	2.30

Table 6.3 Illustrative summary of potential pricing elements in three scenarios.

In the best case, EL uncertainty is minimised, and other loads are at levels seen in other comparable programmes, achieving a multiple which is in the range of that achieved for PCRIC and for ARC Ltd. In the medial case, the loads reflect more likely levels given the particular circumstances of the volcano unrest product. The worst case illustrates the way in which high uncertainty in the EL estimation feeds through to a large increase in price.

6.4 Other implementation issues

6.4.1 Risk transfer vehicle(s)

While each individual case may vary, it seems that such a volcanic unrest parametric insurance policy, as is presented here, would be underwritten most effectively by one of the regional sovereign risk pools (i.e. CCRIF SPC in the Caribbean, PCRIC in the Pacific and ARC in Africa). These vehicles are already set up to operate parametric insurance policies, and are effectively not-for-profit or mutual structures in which the policy holding – or 'member' – countries have a stake in the operations of the insurer and receive lowest sustainable premium pricing.

Depending on the scale of the risk transfer, and for countries not eligible for membership of a sovereign risk pool (in this case, Indonesia and the Philippines), direct access to the global risk markets may be possible. However, generally such access will be more advantageous if routed through a risk pool, which gathers scale and diversification, and all have existing, strong relationships with a wide variety of global markets for parametric risk (with at least 25 separate risk markets participating in just the three regional sovereign parametric risk pools).

It is presumed, given the policy is being held at the sovereign level, that local insurance regulations either won't apply or would be waived; such regulations generally require the primary underwriting entity to be licensed in the domicile where the risk sits and sometimes also controls the nature of the ultimate risk takers (i.e. restricting access to global risk markets). Having to conform to local regulations, which often do not recognise parametric insurance, is administratively burdensome and adds significant frictional costs to operations and transactions.

Should the quantum of risk transfer under the insurance policy be small, it is possible that the risk pool underwriting the risk could retain the risk, as it will be a diversifier within any current portfolio held by any of the risk pools. The pool as underwriter may be able to look more favourably on uncertainty in the risk analysis for this product, which will be a key factor in determining the per-risk premium cost. Managing the risk of pricing pain due to risk quantification uncertainty is discussed in the following section.

6.4.2 Narrative for risk-takers

Uncertainty around the evaluation of the ‘pure risk cost’ of an insurance programme is a critical factor in the pricing of coverage, as described in Section 6.3. For new policy types and more generally in the areas of the world where insurance penetration is low, the ‘uncertainty load’ is usually high, making insurance ‘expensive’ – certainly on a risk-adjusted basis.

One of the key benefits of parametric insurance is that the uncertainty in the pure risk cost is embedded in the selected indices and the probabilities around when those indices will reach their trigger level(s). For many natural hazards, there is a good understanding globally of the probabilities of key intensity measurements; for example, the likelihood of getting 200 km/h winds in Port Vila is relatively well understood, and the uncertainty around that probability is quite low. This low uncertainty in the hazard probability translates to low uncertainty in the risk analysis of a parametric product where, using the same example, wind speed is the sole variable input.

This in turn means that per-risk pricing for parametric risk in the developing world is often very competitive, as other parts of the normal insurance pricing calculation, especially the capital load, are low because of the diversifying nature of the risk and the attractiveness of involvement in new insurance markets.

The indices we have found to be the only ones feasible for a volcanic unrest product at the present time are both strikingly different from any index currently used in any parametric insurance contract in the public domain, for two main reasons:

- The Moral Hazard reason: While some of the moral hazard components of this situation, where the index arbiter is also the client of the insurance product, can be managed by contractual mechanisms within the insurance policy itself, some must be left to trust, and that trust must effectively be given by the ultimate risk taker to the client.
- The Uncertainty reason: We have a very limited history of how the selected indices have moved in the past, and it is very challenging to build quantitative models to represent their behaviour, given the extreme complexity of information which feeds into the decision-making behind the index movements. We therefore have to build a story around the robustness of the risk analysis so that it is trusted by the ultimate risk taker, and they will consequently not add a large uncertainty loading to the cost of insurance, which would be passed on to the client in the form of high primary premium cost, likely making the policy economically inefficient – or ‘unaffordable’.

While there are no silver bullets to solving these two problems, there are favourable circumstances in place at present to make the challenge less daunting than it might otherwise be. The global risk markets are interested in developing markets and innovative solutions, and they have demonstrated appetite for parametric risk across a range of hazards and geographies, which means that an audience can be gathered to at least listen.

In the case of both of these challenges, transparency will be critical. A risk analysis done behind closed doors by experts, including those in-country (who are likely to be the most expert) will not be accepted on face value by those not in the room. If the risk analysis is difficult to interrogate, the ultimate risk takers probably won't bother, and will apply a high to extreme uncertainty load. Having the ultimate risk takers in the room – or at least an independent observer with some technical knowledge – or international experts they have appointed – or both – would go a long way to solving the trust issue on the risk assessment side. Section 6.2 details a possible process for achieving this transparency goal.

Transparency over the systems in place which govern the index movements will also be crucial; a lot of the necessary work for the five focus countries is presented in this report, and we feel a compelling case can be made that moral hazard can be managed and should not impact on appetite for or pricing of the risk. This case could be enhanced by a requirement for volcano observatories setting VALs to conform to international guidelines and protocols as discussed in Section 4.4.

6.4.3 Additional implementation factors

Here we briefly introduce a few matters which will need further consideration, some from a general perspective and some from the perspective of a particular client country.

- **Calculation Agent functions**: Given the simplicity of the indices and binary triggers, the Calculation Agent function can be a very light one. It should include at least one party independent of both buyer and seller to confirm that an official VAL movement has taken place and / or an official evacuation call has been made. In both cases, it is likely that information will be publicly available, but confirmation from the primary source should also be obtained. This role is not the usual technical function of a Calculation Agent for a parametric contract, and consideration of the most appropriate institution to take on this role will be important.
- **Control on use of funds**: One of the big benefits of parametric insurance is the availability of funds quickly – in this case, before the main damaging event as actually occurred, to support preparedness and life-saving evacuations. However, available funds have to be deployed to reap this benefit, and increasingly in sovereign parametric programmes, use of funds controls have been used to help ensure best early deployment of pay-outs. The African Risk Capacity (ARC) has the hardest controls on use of its pay-outs, and contingency planning support forms a substantial part of ARC's operational workload. While ARC's approach is not particularly relevant to the volcanic unrest scenario, it will be important to ensure that pay-out funds, should they be triggered, reach the part of the government structure that is best placed to make early use of those funds for action – and that there has been some planning for how the funds would be used under different scenarios.
- **Confirmation of evacuation characteristics**: In addition to requiring proof that an evacuation which has been called is actually taking place, there is a need in the current policy formulation to arbitrate between a 'full' evacuation, however that is defined, and a partial evacuation, which would attract a smaller pay-out. This element of the policy will need to be carefully considered on a case-by-case basis, as the rules cannot be generalised, and one must avoid the need to have the size of an evacuation be known with any accuracy for a pay-out to be made. Arbitration of a partial versus full evacuation will need to be simple, and could take different forms depending on circumstances.

7 Recommendations for further work

Here we provide recommendations for further work. Some of these items (e.g., capacity building, moving towards regulatory oversight) would strengthen national capabilities to respond to volcanic crises, while others are more directly related to the refinement of parametric insurance products.

We note that will provide a separate roadmap will be provided early in 2019. This will articulate the co-benefits of implementing parametric insurance products within a wider framework of improving countries' abilities to better mitigate the impacts of volcanic eruptions, considering findings from both Component 2 and 3 work streams of the project.

7.1 Supporting volcano observatories

Fit-for-purpose volcano monitoring coupled with appropriate communication of warning messages, community preparedness and government response capability is the proven way to reduce the number and frequency of fatalities due to volcanic activity. Fundamentally, improved understanding of a volcanic system and the processes likely to precede an eruption will decrease the chance of an ultimately unwarranted evacuation.

The following subsections highlight five key ways to support volcano observatory (VO) operations.

7.1.1 Increasing redundancy in staff expertise

Breadth and depth of staff expertise is critical so that there isn't a single point of failure if a staff member is unavailable. VO staff training programmes have been operating in a somewhat *ad hoc* fashion for several decades, supported by developed-world academic institutions and observatories, particularly via the Center for the Study of Active Volcanoes at the University of Hawaiʻi at Hilo (with support from the University of Hawaiʻi at Manoa and the joint USGS-U.S. Agency for International Development Volcano Disaster Assistance Program), and GNS Science. However, such programmes have not reached a sufficient volume, nor do they support constant updating of technical knowledge or social-science advances in volcano crisis management.

7.1.2 Capacity building of staff

Our discussions with VOs in the five focus countries suggest there is an urgent need for resources to build capability. As one example, some VOs lack specialised technical expertise to process and interpret satellite data and so cannot fully take advantage of the opportunities for improved monitoring and early warning provided by Earth Observation systems. Capability building can take many forms and can be supported by, for example: workshops to share best practice; visits to centres of excellence by staff for technical training; visits by experts to observatories to give short courses or provide bespoke training; and publication of syntheses of key topics that are easily accessible.

7.1.3 Increased real-time instrumentation and resources for long term maintenance

Many of the world's high-risk volcanoes either have rudimentary monitoring or are not monitored at all. In such cases there may be insufficient background observations to apply VAL systems. It will be up to national VOs to decide on priorities for improved instrumentation. A useful approach might be to have nationally agreed and VO-led targets for improved instrumentation, as has been done in Indonesia. As an example, it might be a target to have a dedicated volcano seismometer on every volcano and a network of three seismometers on every high threat volcano[65], with these networks integrated into a national seismic network.

However, increasing the number of instruments is of little value if there are no resources for long term maintenance, a challenge with well-meaning donations of instruments to resource-poor countries without provisions for maintenance, repairs and resourcing. Thus, national strategies for improving monitoring capacity must include plans for long-term sustainability.

7.1.4 Increased diversity of monitoring methods

The more different kinds of measurements that can be deployed, the greater the chances are of providing timely early warning, making reliable hazards forecasts and enabling robust decisions related to changes of alert level and evacuations.

There are four main ‘pillars’ of monitoring (Annexe 1): seismology, geodesy, geochemistry, and Earth Observation (EO). At present, with the exception of a limited number of well-monitored volcanoes, volcano monitoring in the region is limited to geophysical methods and visual observations. Perhaps the greatest scope for improving capability is through E), as with ongoing advances in this field, some forms of geodetical and geochemical data can be provided. Indeed, EO may revolutionise monitoring of volcanoes within the coming decades. As we have already stated, the main barrier to realising this potential is to build technical expertise within VOs and operationalising protocols for data interpretation.

7.1.5 Strengthening international collaboration between VOs

There are current initiatives in the international community, especially for EO and, to a lesser extent, gas geochemical monitoring, directed towards capability and resource building within VOs. There are also efforts in the international community to share best practice as in the Volcano Observatory Best Practice workshops.

Currently there is rather limited and somewhat ad hoc collaboration between VOs, although the framework exists for meaningful collaborations and with some work, regulatory guidance. The World Organisation of Volcano Observatories (WOVO) is a voluntary body consisting of 80 observatories, but, in the absence of dedicated funding and staff, WOVO is an ineffectual organisation with no mandate.

At present, many observatories are strongly independent with their own ways of doing things. For example, the formats and protocols of collecting data vary greatly and can be incompatible, making development of a global monitoring database difficult to achieve. There are no international standards or enforceable codes of conduct for either VOs or individual scientists; the IAVCEI codes of conduct are voluntary, although often respected.

We suggest that financial support is needed for WOVO which would enable better cooperation and sharing of good practice, data and resources. The International Civil Aviation Organisation (ICAO), a UN-mandated group, and the Volcanic Ash Advisory Centres (VAACs) have been advocating for a strong WOVO for several years to ensure consistency of service to the aviation sector. A strengthened WOVO could develop agreed codes of practice building on the voluntary IAVCEI codes and might help to address the moral hazards issues discussed in Section 4.4.

[65] e.g. https://volcanoes.usgs.gov/vhp/nvews.html

We note there are bilateral or multilateral agreements and collaborations that work well (Table 2.4), and have been developed, strengthened and tested over the past years to decades.

7.2 Establishing ‘background’ activity

Too often volcanoes become instrumented during unrest, which makes it difficult to establish ‘background’ activity at a volcano. Instrumentation of high Population Exposure Index volcanoes, or volcanoes identified as high priority through another assessment approach, during dormancy will provide extremely valuable baseline information with which to detect unrest. Campaign surveys (geodesy, seismicity, gas, soil gas, water chemistry, etc.) would also contribute to a greater understanding of ‘background’ activity.

As understanding the past eruptive activity of a volcano is critical to anticipating the likely range of future activity, geologic investigations of understudied volcanoes is key, as it will indicate the past extent of volcanic hazards from the volcano. Such investigation involves mapping volcanic products (e.g., lahar, pyroclastic density current and ashfall deposits), establishing the chronology of past eruptions and establishing the frequency and magnitude of activity by dating select eruptions. This will allow for science-based advice when evacuation decisions are being made and evacuation zones are being designated.

7.3 Using parametric triggers for non-insurance financing

Volcano observatories require data to confirm unrest, heightened unrest, or minor eruptive activity is occurring prior to raising the VAL. For under-monitored volcanoes, the first indication something unusual is happening is from local reports (Table 2.2). There is scope for considering how internal triggers could prompt minor pay-outs from the government to investigate possible unrest (Section 2.5.3). The candidate indicator most in line with this requirement would be a local report of unusual activity. This could prompt payment to support the field visit of observatory staff, collection of campaign data, or installation of temporary instruments to assess whether or not there is volcanic unrest and, if yes, the prognosis for future activity.

7.4 Product refinement

Refinement of the potential parametric insurance product for volcano unrest, if the concept is pursued in one or more of the focus countries, would mainly need to focus on the probability estimation – striking a balance between independence (to build trust for the ultimate risk taker) and best-available expertise. Setting up a process to do this for each individual country may be challenging from both a cost and organisational perspective, so consideration should be given to planning a process which is flexible enough to allow for local experts, client representatives and multiple ultimate risk takers, but also has a fixed ‘core’ (expertise and administration of process) to enable more efficient operations, potentially for multiple countries in a single ‘sitting’.

Policy structure and selection of some of the financial elements (customisation) by the client will also be necessary, but this is well-rehearsed as it happens, to some extent at least, for all parametric policies being underwritten by the three multi-sovereign parametric risk pools, usually every year.

Two particular features of the product may need to be considered and fully developed on a case-by-case basis; the addition of the Early Pay-out trigger for upward VAL movement at volcanoes already in unrest, and the ability to have partial pay-outs under the Evacuation Call trigger. The former is quite straightforward in technical terms although moral hazard may be more of a concern for movements of VAL at volcanoes already in unrest, while the latter is dependent on a reliable way of independently assessing whether an evacuation is ‘partial’ or ‘full’ relative to a pre-agreed benchmark.

7.5 Databases and further research

Much of our analysis and evaluation of concepts for parametric tools for volcanic unrest in this feasibility study has relied on open source databases. The analysis is underpinned by basic research on volcanic phenomena and hazards as well as more applied research on, for example, volcanic emergency management.

There are major gaps in the databases, which reflect inadequate resourcing of efforts to develop global databases on volcanic hazards and risk, as well as missing or inadequate data. For example, we identified that little previous work had been done to assemble and analyse data on evacuations. We developed such a database in this project derived largely from basic data in the Smithsonian Institution’s VOTW database.

There is thus a future need for a much more comprehensive database to understand the dynamics and drivers of evacuations through forensic and statistical analysis. Our study also proposes to use PEI to scale parametric pay-outs. PEI, however, remains a rather crude measure of exposure, and more research is needed to evaluate fully its efficacy as an exposure measure and its relationship to actual needs in the event of unrest episodes and evacuations.

Annexe 1: State-of-the-art for volcano monitoring

Geophysical methods

Geophysical techniques measure signals at the ground surface that are symptomatic of processes occurring at depth, and also can be used to monitor surface processes, including but not limited to pyroclastic density currents, landslides, and volcanic plumes. Traditionally, most geophysical techniques require emplaced monitoring equipment, or at least frequent monitoring campaigns. Over the last two decades, remote sensing methodologies have become increasingly used. The spatial and temporal coverage of monitoring equipment typically depends on the resources available to the monitoring organisation, though sometimes political or geographical boundaries limit access to the area of interest.

Seismology

Seismic monitoring is the most widely used and scientifically mature geophysical monitoring technique at volcanoes. Seismic signals (e.g., discrete earthquakes or continuous tremor) are caused by a range of physical processes, such as subsurface magma or fluid migration creating fractures, magma or hydrothermal fluids causing tremor, or eruptive activity at the surface.

In its simplest form, seismic monitoring can indicate the intensity of volcanic activity or unrest. As volcanic seismicity is localised and often low-magnitude, the sensitivity of the monitoring instruments reduces with distance from the volcano. Seismic monitoring is preferentially conducted using a network of at least three instruments (seismometers), since a single seismometer will provide little information about the location of the seismic source. As volcanoes are often located in tectonically active regions, locating earthquakes that are linked to potential volcanic activity (and monitoring their progression) is particularly important as it may allow the discrimination between tectonic and volcanic earthquakes. Operating a network of seismometers also introduces redundancy into the network, allowing some level of seismic detection if part of the network is non-operational.

Overall, seismic monitoring is the most valuable, near real-time, volcanic monitoring technique; it is more widely used to monitor changes in volcanic activity than any other technique.

Geodesy

The second most commonly used geophysical monitoring technique is geodesy, which detects changes in ground deformation that generally indicate changes in subsurface pressure. Positive changes in subsurface pressure can be due to several different processes including: ascent of magma within a magma reservoir, formation of a new intrusion, or liberation of fluids (gas) within magma as consequence of crystallisation and changes in hydrothermal fluid circulation (usually due to heating and / or gas discharge from magma). In contrast, subsidence is usually attributed to decreasing subsurface pressure. Other causes of ground deformation include slope instability, large (and generally shallow) earthquakes, and tectonic movements in some cases connected with volcanism.

Traditionally, geodetic techniques were not often used in real-time; measurement precision could generally only provide information about longer-term patterns of volcanic activity, on the scale of weeks to years, and data was collected via campaign-style ground surveying. However, steady improvements in the global GPS system and associated calculation techniques enable continuous, real-time GPS monitoring to be useful on temporal scales of hours to days. Engineering instruments such as tiltmeters and strain meters are also able to provide continuous and real-time ground deformation information in certain cases. Ground deformation is also increasingly monitored using satellite remote sensing, further described later.

Acoustic

In the same way that seismometers measure ground vibration, acoustic sensors measure pressure fluctuations caused by transient, unstable fluid motions. Volcanic eruptions often produce pressure waves with frequencies <20 Hz, which is below the range of human hearing, also known as infrasound. Acoustic sensors are therefore principally used to detect surface activity, such as volcanic eruptions, and are often paired with seismic monitoring networks.

As with seismic monitoring, acoustic sensor sensitivity decreases with distance from the source, though specialised instruments can adequately detect acoustic signals at great distances (100s of km). Acoustic monitoring instruments are also deployed as networks, usually of at least three instruments. Since eruption source locality is usually evident, infrasound networks are commonly used to characterise and quantify eruptive activity and mechanisms. Acoustic monitoring data are collected in real-time in most cases and are able to resolve signals on the scale of seconds to minutes.

Other geophysical techniques

The aforementioned techniques represent only the most commonly used of geophysical monitoring activities that can be used to monitor volcanic activity. Other techniques include micro-gravity and magnetics. These techniques are usually collected only intermittently and are usually intended for studying longer-term volcanic processes, on the scale of months to years.

Volcanic geochemical monitoring

Monitoring volcanic gases emitted at the surface is a widely used strategy as it can provide information about processes at depth, such as the influx and emplacement of magma and changes in fluid pathways. Geochemical monitoring can detect subtle changes that may not be detected by geophysical techniques. Geochemical techniques are used to complement geophysical methods and visual observations in volcano monitoring efforts. Geochemical changes can be on their own ambiguous; for example, a decrease in SO_2 emissions may indicate a decline in activity or might mean the build-up of pressure prior to an explosion.

Two key parameters are measured; the chemical composition of volcanic gases and the emission rate at the surface. The former often requires direct sampling and lab analysis, although technological developments are beginning to provide more real-time alternatives for some geochemical elements (e.g. multigas detection instruments). Gas emission rate is often measured using ground-based remote sensing techniques (e.g. DOAS, FlySpec and COSPEC spectrometry instruments), and is mostly concerned with the emission of sulphur dioxide (SO_2), because it is normally not present in the atmosphere so is easy to measure. The most common volcanic gases (water and CO_2) are abundant in the atmosphere so much harder to monitor. Near-real time data acquisition is possible provided there are favourable wind conditions and ambient sunlight.

When volcanic gases are discharged into lakes or hot springs at the surface (instead of open vents or fumaroles), water composition can be monitored. In most cases, water sampling requires direct sampling and lab analysis. As with gas sampling, the techniques usually aim at detecting changes occurring on long temporal scales, as few geochemical monitoring techniques are available in real-time.

Satellite-based remote sensing

Over the past couple of decades, space borne techniques have increasingly been used to monitor volcanoes. These techniques usually consist of some form of imagery captured from space, whether in the visible or other spectra (e.g., IR, thermal, radar). They are increasingly used to monitor ground deformation (e.g., InSAR), ground temperature (e.g. detection of active lava flows or lakes), or capture changes in ground vegetation (possibly related to geochemical processes). Other techniques measure the concentration or emission of a particular type of gas or particles in the atmosphere (e.g., SO_2 emission rate, ash concentration).

The greatest advantages of satellite remote sensing are surface coverage (vs. point measurements with other techniques) and the reliable nature of the data stream. Its greatest challenges are poor temporal resolution (in many but not all cases) and, depending on the technique, a dependence on favourable atmospheric or ground conditions.

Unlike most ground-based monitoring data that are acquired by the nationally-mandated volcano monitoring agencies, satellite remote sensing data / imagery are usually captured and provided by space agencies (dominated by OECD countries) and made available – freely or via purchase - through some arrangements with research organisations. Data processing can be resource intensive, and requires highly specialised knowledge to process and interpret. As a result, most observatories are often more interested in using data already processed by partner organisation, rather than raw data. Several ongoing initiatives have the goal of providing continuous time series of volcano-related data generated by consistent, peer-reviewed algorithms on a global basis; volcano hot spot and ash cloud monitoring are the most advanced in this regard.

During unrest and eruption, satellites may be used to detect volcanic ash in the atmosphere, changes in morphology (such as dome collapse) and the area covered by pyroclastic flows and lahars. In this section, we briefly summarise the capabilities and limitations of Earth Observation data for measuring volcanic phenomena and as a means to provide early warning, with reference to their potential utility for parametric insurance.

Ground Deformation

Interferometric Satellite Radar (InSAR) uses the phase change of two successive radar images to map the range change between satellite and ground surface at high resolution. Several satellite systems capable of measuring ground deformation are currently available but the most suitable is the European Space Agency Sentinel-1 constellation which aims to provide free and continuous monitoring for the next 20 years. Sentinel-1A was launched in 2015 and with two operational satellites, repeat intervals are 6 to 24 days depending on geographic location.

Baseline measurements back to the early 1990s are available from a range of satellites, but primarily from the European Space Agency Envisat mission (2003-2011) and Japanese Space Agency ALOS-1 mission (2007-2010). Analysis of past satellite detections of unrest show a statistically significant correlation to eruption over decadal timescales, with volcanoes at which satellites have detected deformation being 5 times more likely to have erupted than those which have not[66]. Due to the

[66] Biggs, J., Ebmeier, S.K., Aspinall, W.P., Lu, Z., Pritchard, M.E., Sparks, R.S.J. & Mather, T.A. (2014) Global link between deformation and volcanic eruption quantified by satellite imagery. Nature, 5:3571.

irregular and infrequent acquisition of satellite data prior to Sentinel-1, it is challenging to quantify the timing of these precursors, but deformation is dominantly pre-eruptive[67] in contrast to degassing and thermal anomalies which are typically co-eruptive. Due to their spatial coverage, satellite measurements are more likely to capture deformation associated with non-magmatic processes than ground-based systems, such as the settling of recent deposits, hydrothermal activity or gravity-driven collapse[68].

The major limitations of satellite InSAR are:

- A loss of coherence in vegetated areas which increases with time between acquisitions and slope; and
- Atmospheric artefacts at high relief edifices caused by stratification in tropospheric water vapour[69].

Both of these are especially prevalent in the tropical regions of Asia-Pacific and have limited the utility of these methods in the past. L-band satellites operate at a longer wavelength (23 cm) than the more common C-band alternative (5.8 cm) so are less affected by vegetation. Consequently, most historical reports of deformation in the Asia-Pacific region were made using the limited-duration L-band ALOS-1 mission (2007-2011) rather than the C-band ERS1/2 (1993-2000) and Envisat (2003-2011) satellites. Although another L-band satellite, ALOS-2 was launched in 2014, data are restricted and no further deformation studies have yet been published. The NASA-ISRO NiSAR satellite due for launch in 2021 will be the first open-access L-band mission and holds significant potential for volcano monitoring in tropical regions such as Asia-Pacific. The C-band satellite constellation Sentinel-1 (2015-2035) has much shorter revisits (6 to 24 days) than older C-band systems (35 day minimum). and has shown some improvement in coherence. A systematic study has yet to be carried out covering the five focus countries of this project, but examples of 12 day Sentinel-1 interferograms at Agung and Rabaul volcanoes are shown in Figure A1.1.

[67] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T. & Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research, 365:28-56.
[68] Ebmeier, S.K., Andrews, B.J., Araya, M.C., Arnold, D.W.D., Biggs, J., Cooper, C., Cottrell, E., Furtney. M., Hickey. J., Jay, J., Lloyd, R., Parker, A.L., Pritchard, M.E., Robertson, E., Venzke, E. & Williamson, J.L. (2018) Synthesis of global satellite observations of magmatic and volcanic deformation: implications for volcano monitoring & the lateral extent of magmatic domains. Journal of Applied Volcanology, 7:2.
[69] Ebmeier, S.K., Biggs, J., Mather, T.A. & Amelung, F. (2013) Applicability of InSAR to tropical volcanoes: insights from Central America. Geological Society London Special Publications, 380: 15–37.

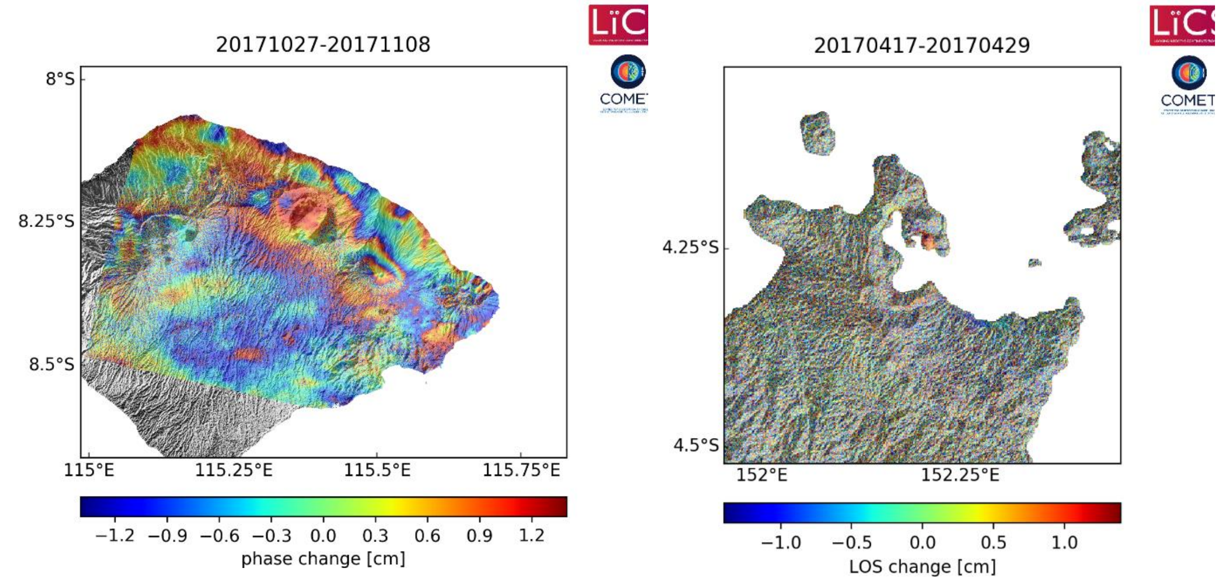

Figure A1.1 Example 12 day Sentinel-1 C-band interferograms from Asia-Pacific generated by the automated LiCSAR processing system. The grey areas are outside the frame or incoherent signals caused by dense tropical vegetation. Each coloured fringe corresponds to 2.8 cm of apparent deformation. Left panel - Agung volcano, Indonesia where the fringes are likely caused by atmospheric artefacts rather than surface deformation. Right panel - Rabaul volcano, Papua New Guinea which is almost entirely incoherent.

The second challenge is that the radar waves pass through the atmosphere and are strongly affected by water vapour. Since tropospheric water vapour is strongly stratified, pixels at the peak of tall volcanoes experience less of a delay than those at the base, forming an artefact correlated to topography with an equivalent magnitude of several centimetres of deformation[70,71]. This artefact can easily be mistaken for surface deformation by inexperienced scientists, as was the case during the 2017 unrest at Agung (see case studies). A range of methods exist for carrying out atmospheric corrections[72], but many rely on external datasets that are rarely available in developing countries (e.g., dense GPS networks[73]). The most promising approach for the routine application of atmospheric corrections is the use of high-resolution weather models such as from ECMWF[74] which are available in real time. These need to be interpolated in both space and time using a Digital Elevation Model but an

[70] Ebmeier, S.K., Biggs, J., Mather, T.A. & Amelung, F. (2013) Applicability of InSAR to tropical volcanoes: insights from Central America. Geological Society London Special Publications, 380: 15–37.
[71] Parker, A.L., Biggs, J., Walters, R.J., Ebmeier, S.K., Wright, T.J., Teanby, N.A. & Lu, Z. (2015) Systematic assessment of atmospheric uncertainties for InSAR data at volcanic arcs using large-scale atmospheric models: Application to the Cascade volcanoes, United States. Remote Sensing of Environment, 170:102-114.
[72] Bekaert, D.P.S., Walters, R.J., Wright, T.J., Hooper, A.J. & Parker, D.J. (2015) Statistical comparison of InSAR tropospheric correction techniques. Remote Sensing of Environment, 170: 40-47.
[73] Li, Z., Muller, J-P., Cross, P. & Fielding, E.J. (2005) Interferometric synthetic aperture radar (InSAR) atmospheric correction: GPS, Moderate Resolution Imaging Spectroradiometer (MODIS), and InSAR integration. Journal of Geophysical Research Solid Earth, 110(B3).
[74] European Centre for Medium-range Weather Forecasting

online service, the Generic Atmospheric Correction Online Service (GACOS), is being developed and could be applied to volcanoes globally[75;76].

Thus, although SAR data is routinely acquired and has promise as a routine monitoring tool for volcano deformation, significant expertise is required to process and analyse the data appropriately. If a developing country were to develop a routine service for monitoring volcano deformation remotely, significant investment in training is required to ensure that the scientists involved have the expertise and experience required to analyse the data properly. If satellite-detections of deformation are to be used as a criterion for recognising unrest, it may be necessary to define a system of external verification or accreditation.

Degassing

Satellite measurements of volcanic degassing focus primarily on SO_2 emissions because they are easily detectable by instruments designed to measure atmospheric properties such as ozone, water vapour and cloud cover, even though they contribute <5% of the volcanic flux. Consequently, measurements of volcanic SO_2 have been made routinely since 1978[77], while satellite detections of other volcanic gas species including H_2S[78], HCl, BrO[79] and CO_2 have only been made occasionally and for recent eruptions. Thus, the only gas for which satellite measurements can be made with the accuracy or frequency to be considered in the context of parametric indexing is SO_2.

Measurements of volcanic SO_2 make use of spectral absorption bands at either Infrared (IR) or Ultaviolet (UV) wavelengths. UV instruments such as the Ozone Mapping Instrument (OMI) are low spatial resolution (~50 km) and are limited to night-time or high-latitude winter. For OMI, the detection limit is ~6 kt/yr or 16 t/day with uncertainties on annual fluxes estimated to be ~55% for sources emitting >100 kt/yr and >67% for under 50 kt/yr[80]. IR instruments such as the Infrared Atmospheric Sounding Interferometer (IASI) have limited sensitivity to SO_2 in the lower troposphere and hence dominantly records large explosive eruptions[81].

The global archive of satellite SO_2 measurements currently includes >700 eruptions at 110 volcanoes[82], and 91 volcanoes with passive (non-eruptive) degassing, of which less than half had prior ground-based measurements[83]. The flux associated with eruptions shows interannual variability, with peaks associated with major eruptions and a cumulative total of >100 Tg since 1978[84]. In contrast, the passive degassing flux is an order of magnitude higher and remains remarkably stable at ~23 Tg/yr for

[75] Yu, C., Li, Z., Penna, N.T. & Crippa, P. (2018) Generic atmospheric correction model for Interferometric Synthetic Aperture Radar observations. Journal of Geophysical Research: Solid Earth.
[76] Albino, F., Biggs, J. & Syahbana, D.K. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali. Nature Communications. In Review.
[77] Carn, S.A., Clarisse, L. & Prata, A.J. (2016) Multi-decadal satellite measurements of global volcanic degassing. Journal of Volcanology and Geothermal Research, 311: 99-134.
[78] Clarisse, L., Coheur, P-F., Chefdeville, S., Lacour, J-L., Hurtmans, D. & Clerbaux, C. (2011) Infrared satellite observations of hydrogen sulfide in the volcanic plume of the August 2008 Kasatochi eruption. Geophysical Research Letters, 38(10).
[79] Theys, N., Van Roozendael, M., Dils, B., Hendrick, F., Hao, N. & De Mazière, M. (2009) First satellite detection of volcanic bromine monoxide emission after the Kasatochi eruption. Geophysical Research Letters, 36(3).
[80] Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. & Krotkov, N.A. (2017) A decade of global volcanic SO_2 emissions measured from space. Scientific Reports, 7:44095.
[81] Taylor, I.A., Preston, J., Carboni, C., Mather, T.A., Grainger, R.G., Theys, N., Hidalgo, S. & McCormick Kilbride, B. (2018) Exploring the Utility of IASI for Monitoring Volcanic SO_2 Emissions. Journal of Geophysical Research Atmospheres, 123(10):5588-5606.
[82] Carn, S.A., Clarisse, L. & Prata, A.J. (2016) Multi-decadal satellite measurements of global volcanic degassing. Journal of Volcanology and Geothermal Research, 311: 99-134.
[83] Carn, S.A., Clarisse, L. & Prata, A.J. (2016) Multi-decadal satellite measurements of global volcanic degassing. Journal of Volcanology and Geothermal Research, 311: 99-134.
[84] Carn, S.A., Clarisse, L. & Prata, A.J. (2016) Multi-decadal satellite measurements of global volcanic degassing. Journal of Volcanology and Geothermal Research, 311: 99-134.

the last decade[85,86]. The most significant individual event remains the 1991 eruption of Pinatubo, Philippines which released 18 ± 4 Tg of SO_2[87], while the lava lake at Ambrym in Vanuatu has been the most persistent source of degassing in the last decade[88].

Increases in SO_2 flux prior to eruptions have been detected by satellite at a few case examples: Alu Dalafilla, Ethiopia; Aso, Japan and Sarychev Peak, Kuril Islands[89], but a global study found that >95% of satellite detections of SO_2 emissions are co-eruptive[90]. Fluxes of SO_2 from large eruptions are well-constrained, with detections made for all reported VEI4+ eruptions since 1978, but lower-magnitude events are less well constrained with detections at only <20% of eruptions VEI<=2[91]. Persistent low-level degassing has local impacts on vegetation and air quality and if levels exceed World Health Organisation limits, could be considered a criterion for evacuation[92].

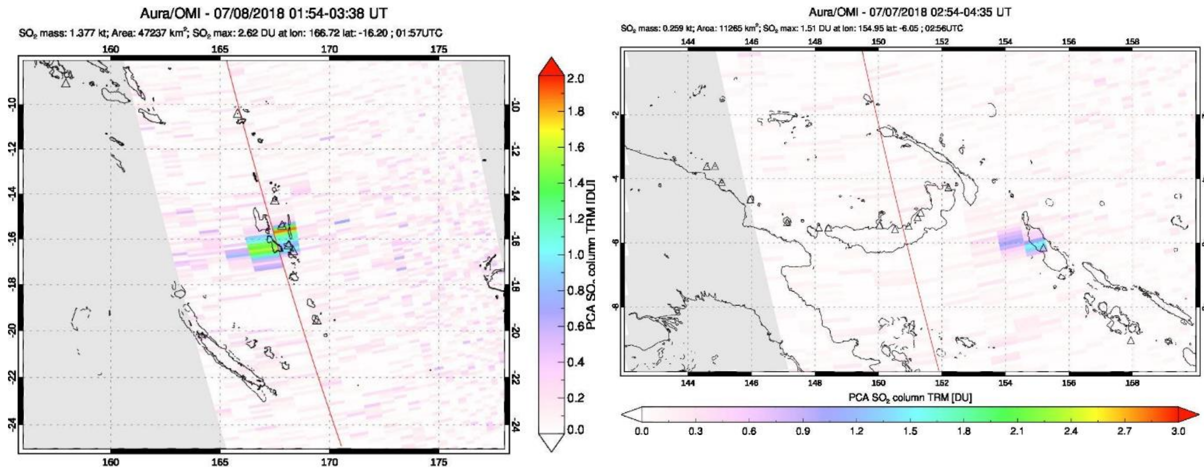

Figure A1.2 Example OMI images showing daily regional SO_2 emissions in July 2018 taken from the NASA Global Sulfur Dioxide Monitoring Programme. Left - Vanuatu on 8 July with emissions from Aoba and Ambrym clearly visible. Right - Papua New Guinea on 7 July with emissions from Bagana clearly visible.

The interpretation of volcanic SO_2 observations from both satellite and ground-based methods is inherently ambiguous. An increase in SO_2 output could mean that gas is being released more easily

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[85] Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. & Krotkov, N.A. (2017) A decade of global volcanic SO_2 emissions measured from space. Scientific Reports, 7:44095.
[86] McCormick, B.T., Edmonds, M., Mather, T.A. & Carn, S.A. (2012) First synoptic analysis of volcanic degassing in Papua New Guinea. Geochemistry, Geophysics, Geosystems, 13(3).
[87] Guo, S., Bluth, G.J.S., Rose, W.I., Watson, I.M. & Prata, A.J. (2004) Re-evaluation of SO_2 release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors. Geochemistry, Geophysics, Geosystems, 5(4).
[88] Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. & Krotkov, N.A. (2017) A decade of global volcanic SO_2 emissions measured from space. Scientific Reports, 7:44095.
[89] Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. & Krotkov, N.A. (2017) A decade of global volcanic SO_2 emissions measured from space. Scientific Reports, 7:44095.
[90] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T. & Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research, 365:28-56.
[91] Carn, S.A., Clarisse, L. & Prata, A.J. (2016) Multi-decadal satellite measurements of global volcanic degassing. Journal of Volcanology and Geothermal Research, 311: 99-134.
[92] Ilyinskaya, E., Schmidt, A., Mather, T.A., Pope, F.D., Witham, C., Baxter, P., Jóhannsson, T., Pfeffer, M., Barsotti, S., Singh, A. & Sanderson, P. (2017) Understanding the environmental impacts of large fissure eruptions: Aerosol and gas emissions from the 2014–2015 Holuhraun eruption (Iceland). Earth and Planetary Science Letters, 472:309-322.

so there is less chance of a major explosive activity or that more gas is coming into the system increasing the chances or an eruption. A decrease could mean either a decrease in volcanic gas supply and hence a decrease in the probability of an eruption or that gas is being trapped underground, potentially a sign of an impending explosive eruption. Thus, interpretation of SO_2 data needs to be made in the context of other kinds of monitoring information and the specific circumstances of particular volcanoes and eruptions. However, the detection of SO_2 emissions above any background at a dormant volcano is very likely evidence of the onset of unrest.

Thermal

Thermal anomalies associated with lava flows and fumaroles can be detected using Thermal Infrared (TIR) or Middle Infrared (MID) satellite sensors. Two distinct categories exist:

- High temporal / low spatial resolution systems such as MODIS which has sub-daily repeats but 1 km resolution; and
- High spatial / low temporal resolution systems such as ASTER which has a 90 m resolution, but revisit intervals of 16 days at the equator.

The MODVOLC system uses MODIS data to provide alerts when the Normalised Thermal Index exceeds a threshold, and primarily identifies high-temperature anomalies associated with active lava, be it in the form of flows, domes, lakes or confined to vents[93;94]. Since 2000, MODVOLC has detected thermal anomalies at 93 volcanoes[95], of which two-thirds are associated with effusive lava flow forming eruptions and a quarter with lava lakes[96]. The spatial resolution is too low to estimate the temperature of the anomaly or to identify low-temperature features associated with geothermal or hydrothermal systems. The global baseline radiant flux is on the order of 1 to 4×10^{15} J/month, with episodic increases associated with mafic lava-flow-forming eruptions[97] such as the 2014-2015 eruption of Bardarbunga, Iceland[98]. MIROVA (Middle InfraRed Observations of Volcanic Activity) also uses MODIS data but provides higher sensitivity for detecting small thermal anomalies and is therefore useful for studying eruption dynamics at long-lived systems[99,100].

The high spatial resolution of ASTER means sensors saturate during an eruption, and detections are often caused by low-temperature thermal anomalies associated with fumaroles and low magnitude eruptions. As yet, no systematic global catalogue of low-temperature thermal anomalies has been released, but a 10-year regional study of 150 volcanoes in Latin America detected 35 volcanoes with anomalies of at least 4K above background, mostly associated with fumarole activity[101]. Elevated

[93] Wright, R., Flynn, L. P., Garbeil, H., Harris, A. J. & Pilger, E. (2004) MODVOLC: near-real-time thermal monitoring of global volcanism. Journal of Volcanology and Geothermal Research, 135(1-2):29-49.
[94] Wright, R. (2016) MODVOLC: 14 years of autonomous observations of effusive volcanism from space. Geological Society, London, Special Publications, 426(1):23-53.
[95] Wright, R. (2016) MODVOLC: 14 years of autonomous observations of effusive volcanism from space. Geological Society, London, Special Publications, 426(1):23-53.
[96] Wright, R. (2016) MODVOLC: 14 years of autonomous observations of effusive volcanism from space. Geological Society, London, Special Publications, 426(1):23-53.
[97] Wright, R., Blackett, M. & Hill-Butler, C. (2015) Some observations regarding the thermal flux from Earth's erupting volcanoes for the period of 2000 to 2014. Geophysical Research Letters, 42(2):282-289.
[98] Bonny, E., Thordarson, T., Wright, R., Höskuldsson, A. & Jónsdóttir, I. (2018) The Volume of Lava Erupted during the 2014 to 2015 Eruption at Holuhraun, Iceland: a Comparison between Satellite-and Ground-Based Measurements. Journal of Geophysical Research, Solid Earth.
[99] Coppola, D., Macedo, O., Ramos, D., Finizola, A., Delle Donne, D., Del Carpio, J., ... & Apaza, F. (2015) Magma extrusion during the Ubinas 2013–2014 eruptive crisis based on satellite thermal imaging (MIROVA) and ground-based monitoring. Journal of Volcanology and Geothermal Research, 302:199-210.
[100] Coppola, D., Laiolo, M. & Cigolini, C. (2016) Fifteen years of thermal activity at Vanuatu's volcanoes (2000–2015) revealed by MIROVA. Journal of Volcanology and Geothermal Research, 322:6-19.
[101] Jay, J. A., Welch, M., Pritchard, M. E., Mares, P. J., Mnich, M. E., Melkonian, A. K., ... & Clavero, J. (2013) Volcanic hotspots of the central and southern Andes as seen from space by ASTER and MODVOLC between the years 2000 and 2010. Geological Society, London, Special Publications, 380:SP380-1.

thermal fluxes have been identified prior to some eruptions[102,103], but a global compilation found that the majority of detected thermal anomalies are co-eruptive[104].

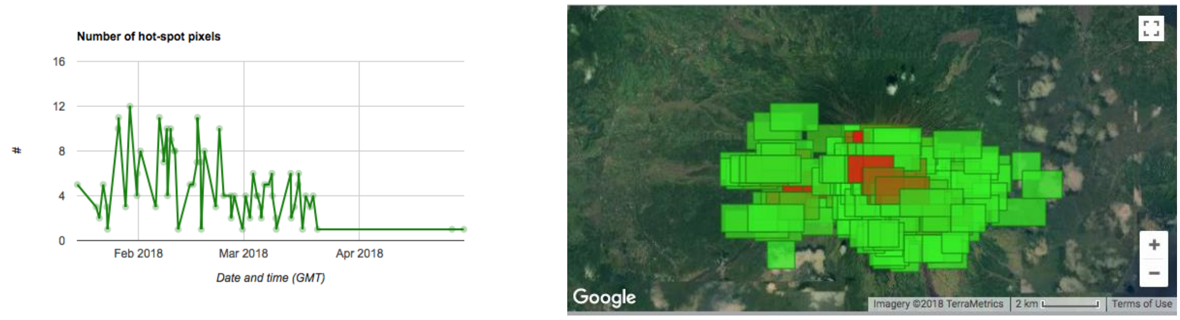

Figure A1.3 Thermal alerts issued for Mayon, Phillipines by the MODVOLC system[105] during the Jan-March 2018 eruption.

Latency Periods

Given the need for real-time or near real-time indicators as input to parametric indices, the time taken for satellite observations to be made and processed is a critical consideration. However, this needs to be balanced against the need for a robust metric than can be routinely produced and the need for a validation process for subjective interpretations. For satellite data, the time taken to assess a metric is composed of three components:

- *Acquisition*. The acquisition time depends on the revisit period of the satellite and the acquisition plan of the space agency. Data for optical mapping and the detection of high-temperature thermal anomalies and SO_2 fluxes are routinely acquired several times per day but can be limited by cloud cover. In contrast, the repeat intervals for deformation (InSAR) and low-temperature thermal anomalies is on the order of days to weeks.
- *Processing*. The processing time includes the time taken by the space agency to download and distribute the data, as well as the time to convert the imagery into a useful product (e.g., from radar image to interferogram, or from hyperspectral data to SO_2 flux). Where open-access or existing data policies exist, data are typically available less than a day after acquisition, but where new data access agreements need to be negotiated, new proposals can take months to review. While the computational component of data processing is typically on the order of hours, the data processing time likely depends on the availability of suitable expertise. Systems such as MODVOLC for high temperature thermal anomalies, NASA’s Global Volcano Sulfur Monitoring Program for SO_2 fluxes and the LiCSAR Sentinel-1 processor for volcano deformation (in development) aim to automate the processing globally, thus removing the need for local expertise,

[102] Reath, K. A., Ramsey, M. S., Dehn, J. & Webley, P. W. (2016) Predicting eruptions from precursory activity using remote sensing data hybridization. Journal of Volcanology and Geothermal Research, 321:18-30.
[103] Coppola, D., Laiolo, M. & Cigolini, C. (2016) Fifteen years of thermal activity at Vanuatu's volcanoes (2000–2015) revealed by MIROVA. Journal of Volcanology and Geothermal Research, 322:6-19.
[104] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T. & Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research, 365:28-56.
[105] http://modis.higp.hawaii.edu/

but working with other systems, or refining data beyond global products may require software and expertise not typically available in developing countries.

- *Analysis*. Finally, the design of parametric insurance products needs to take into account the time and expertise required to analyse the data and translate it into the required metric. Few volcano observatories in developing countries have a satellite data specialist and often rely on the international community to, for example, distinguish between atmospheric artefacts and volcanic deformation in InSAR data. Similarly, a strong understanding of measurement uncertainties is required for the analysis of trends in high temporal resolution data, and many of the reported trends are only considered robust after months of work by satellite experts. If satellite data is to be used in parametric insurance, the policy would need to require the insured country to build capacity and expertise, or to identify a partner with whom they will work, and a system of accreditation or external validation would need to be established.

Table A1.1 provides a summary of the key characteristics of monitoring data sets from EO.

	Satellite	Acquisition	Processing	Analysis
High-T Thermal	Terra / Aqua	Sub-daily	Automated 12-18 hrs MODVOLC / MIROVA	Automated alerts issued
Low-T Thermal	ASTER	~16 days	Google Earth Engine	Expertise required
Deformation	Sentinel-1	6 - 12 days	Automation in development LiCSAR	Expertise required to distinguish atmospheric artefacts and model deformation source
SO_2 (UV)	OMI	Sub-daily	Automated 1-2 days Global Volcano Sulfur Monitoring Programme	Regional time series of SO_2 mass produced automatically.
SO_2 (IR)	IASI	Sub-daily	Expertise required	Expertise required

Table A1.1 Summary of characteristics of satellite volcano monitoring data streams.

EO case studies for focus countries

We first provide an overview of satellite detections (see Figure A1.4) before discussing select case studies from the region.

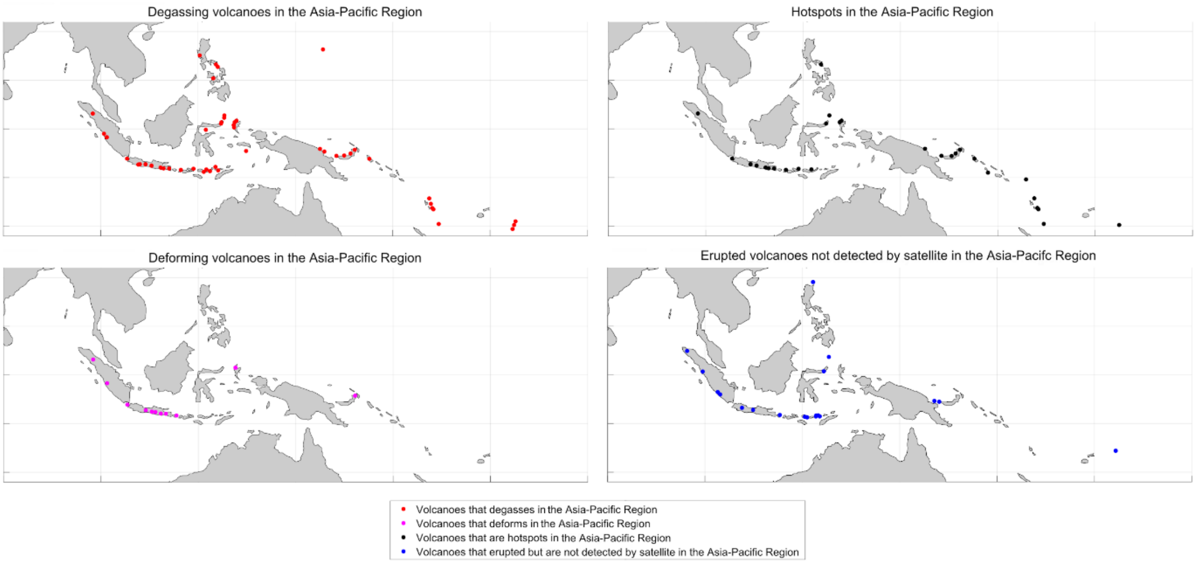

Figure A1.4 Archive of Earth Observation data for Asia-Pacific updated from Furtney *et al.* (2018)[106], showing a) volcanoes with detected degassing, b) volcanoes with detected deformation, c) volcanoes with detected thermal anomalies and d) volcanoes with eruptions that have not been detected by satellite.

Satellite Detections

Deformation has been detected by satellite at 11 volcanoes in the 5 target countries. Ten of these were volcanoes in Indonesia[107;108;109;110]), plus Rabaul in Papua New Guinea[111]. The number of detections is severely limited by the tropical conditions.

The five target countries are among the largest emitters of volcanic SO_2 globally. SO_2 detections have been made at 49 volcanoes in the region. This includes six of the ten largest SO_2 emitters from 2005-2015[112]: Ambrym, Vanuatu (7.4±11.3 kt/day); Bagana, PNG (3.8±10.9 kt/day); Ambae, Vanuatu

[106] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T. & Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research, 365:28-56.
[107] Chaussard, E. & Amelung, F. (2012) Precursory inflation of shallow magma reservoirs at west Sunda volcanoes detected by InSAR. Geophysical Research Letters, 39(21).
[108] Philibosian, B. & Simons, M. (2011) A survey of volcanic deformation on Java using ALOS PALSAR interferometric time series. Geochemistry, Geophysics, Geosystems, 12(11).
[109] Agustan, Kimata, F., Abidin, H. Z. & Pamitro, Y. E. (2010) Measuring ground deformation of the tropical volcano, Ibu, using ALOS-PALSAR data. Remote Sensing Letters, 1(1):37-44.
[110] Saepuloh, A., Urai, M., Aisyah, N., Widiwijayanti, C. & Jousset, P. (2013) Interpretation of ground surface changes prior to the 2010 large eruption of Merapi volcano using ALOS/PALSAR, ASTER TIR and gas emission data. Journal of Volcanology and Geothermal Research, 261:130-143.
[111] Garthwaite, M. C., Lawrie, S., Saunders, S. J., Ampana, S. & Parks, M. (2015, September) Pre-and post-eruptive deformation at the Rabaul Caldera, Papua New Guinea modelled using PALSAR time series. In IEEE 5th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR) (pp. 649-653). IEEE.
[112] Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. & Krotkov, N.A. (2017) A decade of global volcanic SO_2 emissions measured from space. Scientific Reports, 7:44095.

(2.9±1.2 kt/day); Tavurvur, PNG (1.7 ±2.5 kt/day); Dukono, Indonesia 2.7 ±0.6; Manam, PNG (1.5 ±0.8 kt/day). Conversely, there are notable degassing gaps in regions with a history of large SO_2-rich explosive eruptions (e.g. Agung, Samalas and Tambora), suggesting that gas is accumulating in reservoirs rather than being released to the atmosphere[113].

MODVOLC alerts are triggered by active, high-temperature lava at the surface, and the records are dominated by mafic lava-flow forming eruptions and lava lakes. In the 5 focus countries, alerts have been issued for 26 volcanoes[114], with anomalies at a further 2 volcanoes subsequently detected[115]. The greatest radiative flux in the region is from the lava lake at Ambrym, Vanuatu, which is ranked tenth globally for 2000-2015[116]. A systematic review of available ASTER images spanning eruptions without any prior satellite detections found possible anomalies at a further 7 volcanoes in Indonesia (Awu, Dempo, Lewotobi, Marapi, Peuet Sague, Sirung and Tangkubanparahu) which may correspond to low temperature features[117]. MIROVA has been used to study the long-term dynamics of the 5 volcanoes in Vanuatu, including thermal cycles associated with Strombolian activity at Yasur and a gradual increase in thermal output associated with pressurisation of the magma system at Ambrym[118].

Eruptions not detected

Satellite techniques have detected 78% of eruptions globally since 1978, but a small number remain undetected, many of which are low magnitude or occurred during the early years of satellite monitoring when detection thresholds were high[119]. A significant proportion of these lie in the Asia-Pacific region: in the 5 focus countries there have been 53 eruptions at 19 volcanoes with no form of satellite detection (Fig A1.4d), about one third of the 137 eruptions at 55 volcanoes globally. Of these, only two VEI 3 or greater eruptions have occurred without satellite detections, both of which were in the Lesser Sunda Islands (Ranakah 1987-1989 and Leroboleng 2003). Both of these had a population exposure of PEI 5 (as described in the Component 1 Technical Report), and although no fatalities were recorded, the eruption of Ranakah caused the evacuation of 4,200 people. In the last 10 years only 4 eruptions occurred without satellite detections, and these were all VEI 0-1. Of these two have high population exposure (PEI 7) - Tangkubanparahu in 2013 and Dieng in 2009 - the other two have moderate population exposures Dempo in 2009 (PEI 4) and Iliwerung in 2013 (PEI 3), but no fatalities or evacuations were reported.

[113] Carn, S.A., Fioletov, V.E., McLinden, C.A., Li, C. & Krotkov, N.A. (2017) A decade of global volcanic SO_2 emissions measured from space. Scientific Reports, 7:44095.
[114] Wright, R., Blackett, M. & Hill-Butler, C. (2015) Some observations regarding the thermal flux from Earth's erupting volcanoes for the period of 2000 to 2014. Geophysical Research Letters, 42(2):282-289.
[115] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T., Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research 365:28-56.
[116] Wright, R. (2016) MODVOLC: 14 years of autonomous observations of effusive volcanism from space. Geological Society, London, Special Publications, 426(1):23-53.
[117] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T., Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research 365:28-56.
[118] Coppola, D., Laiolo, M. & Cigolini, C. (2016) Fifteen years of thermal activity at Vanuatu's volcanoes (2000–2015) revealed by MIROVA. Journal of Volcanology and Geothermal Research, 322:6-19.
[119] Furtney, M.A., Pritchard, M.E., Biggs, J., Carn, S.A., Ebmeier, S.K., Jay, J.A., McCormick Kilbride, B.T., Reath, K.A. (2018) Synthesizing multi-sensor, multi-satellite, multi-decadal datasets for global volcano monitoring. Journal of Volcanology and Geothermal Research 365:28-56.

Case Studies

Volcanic Eruption: Merapi, 2010

The 2010 eruption of Merapi, Indonesia was the first time that remote sensing played an important role alongside ground-based monitoring in forecasting[120,121]. The eruption began with an explosive eruption on 26 November, followed by smaller explosive eruptions on 29 October - 1 November and a period of rapid dome growth on 1 - 4 November. The paroxysmal eruption occurred on 4 - 5 November and produced extensive pyroclastic flows to distances of 16 km. Lahars and floods associated with the erosion of the new deposits continued for some time.

The eruption occurred during the rainy season, and optical satellite data were of little use due to the persistent cloud cover, but access to RADARSAT-2 and TerraSAR-X SAR data was provided by the Disaster Charter. The SAR images showed that the eruption on the 26 October destroyed the 2006 lava dome, created a new summit crater and generated pyroclastic flows extending 8 km from the summit. The SAR images were then used to estimate the rate of dome growth to be 25 m^3s^{-1}, at least an order of magnitude greater than previous dome-building eruptions at Merapi. Immediately after the paroxysmal eruption, the SAR images showed that the dome had disappeared leaving a 400 m wide summit crater and were used to map the extent of the flows. SAR images showed the growth of a new dome on 6 November in only 12 hours (35 m^3s^{-1}) after which dome growth stopped[122].

The satellite-based near real time estimates of lava extrusion rate, combined with rapid and large increases in seismic energy, were used as the basis for an event tree analysis which indicated a significant probability of a very large explosive eruption. This analysis enabled the Indonesian Geological Agency's Center for Volcanology and Geologic Hazard Mitigation (CVGHM) to issue warnings, and the decision to extend the evacuation zone from 15 to 20 km on 4 November is credited with saving 10,000 to 20,000 lives[123].

Volcanic Unrest: Agung, 2017

Agung Volcano on the Indonesian island of Bali awakened in August 2017 after 50 years of dormancy. During September and October, the intense seismicity and fumarole activity at the summit caused CVGHM to increase the alert to its highest level and ~140,000 people were evacuated. Seismicity declined in late October and the first lava flow and effusions did not begin until late November[124].

When the period of unrest began, the seismic monitoring network consisted of two short-period stations on the south flank of Agung, with two additional short-period stations on the neighbouring Batur caldera (~18 km away). There were 5 continuous GPS stations, but none were actively transmitting data[125]. However, satellite data provided frequent images of the summit region, and a retrospective analysis showed that steaming had been visible since September 2016, with a rapid

[120] Surono, Jousset, P., Pallister, J., Boichu, M., Buongiorno, M.F., Budisantoso, A., ... & Lavigne, F. (2012) The 2010 explosive eruption of Java's Merapi volcano — a '100-year' event. Journal of Volcanology and Geothermal Research, 241–242:121-135.
[121] Pallister, J. S., Schneider, D. J., Griswold, J. P., Keeler, R. H., Burton, W. C., Noyles, C., ... & Ratdomopurbo, A. (2013) Merapi 2010 eruption—Chronology and extrusion rates monitored with satellite radar and used in eruption forecasting. Journal of Volcanology and Geothermal Research, 261:144-152.
[122] Pallister, J. S., Schneider, D. J., Griswold, J. P., Keeler, R. H., Burton, W. C., Noyles, C., ... & Ratdomopurbo, A. (2013) Merapi 2010 eruption—Chronology and extrusion rates monitored with satellite radar and used in eruption forecasting. Journal of Volcanology and Geothermal Research, 261:144-152.
[123] Surono, Jousset, P., Pallister, J., Boichu, M., Buongiorno, M.F., Budisantoso, A., ... & Lavigne, F. (2012) The 2010 explosive eruption of Java's Merapi volcano — a '100-year' event. Journal of Volcanology and Geothermal Research, 241–242:121-135.
[124] Albino, F., Biggs, J., Syahbana, D.K. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali. Nature Communications. In Review.
[125] Albino, F., Biggs, J., Syahbana, D.K. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali. Nature Communications. In Review.

increase in extent in September 2017. A lava dome was first observed on 21 November, and it expanded into a 130 m thick pancake-shaped lava flow by 30 November (Syahbana *et al.*, in prep[126]). No further extrusion was seen over the next few months, but minor explosions continued to modify the surface of the flow.

InSAR data from the Sentinel-1 satellite were freely available during the seismic crises (e.g. Figure A1.5) and were processed by many groups internationally. The first interferograms from acquisitions on 18 and 21 September showed a large anomaly centred on Agung volcano, which would correspond to ~15 cm of deformation. However, analysis of previous interferograms and neighbouring edifices showed that such patterns are common and are attributed to atmospheric artefacts. Nonetheless, deformation was widely but spuriously reported, both to the volcano observatory and through social media. The Generic Atmospheric Correction Online Service (GACOS) was used to demonstrate that the apparent deformation was caused by an atmospheric artefact associated with stratified tropospheric delays and distributed the outputs on 26 September[127]. At the time, individual interferograms did not show significant deformation following correction. However, reanalysis of the time-series of data in February 2018 demonstrated genuine deformation on the north flank. Finite element modelling attributed this deformation to the intrusion of a deep dyke linking the systems at Agung and Batur[128].

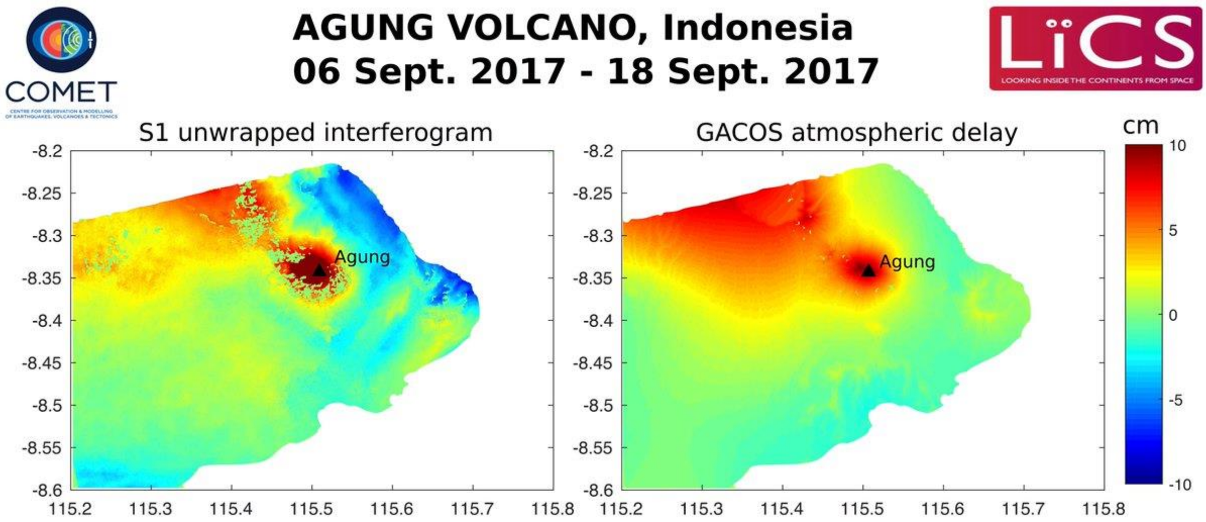

Figure A1.5 Sentinel-1 interferograms and atmospheric corrections produced during the Sept-Oct 2017 seismic crisis at Agung Volcano, Indonesia.

[126] Albino, F., Biggs, J., Syahbana, D.K. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali. Nature Communications. In Review.
[127] Albino, F., Biggs, J., Syahbana, D.K. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali. Nature Communications. In Review.
[128] Albino, F., Biggs, J., Syahbana, D.K. Dyke intrusion between neighbouring arc volcanoes responsible for 2017 pre-eruptive seismic swarm at Agung, Bali. Nature Communications. In Review.

EO conclusions

Data Availability and Sustainability

The potential use of remote sensing observations in volcano monitoring is widely accepted, and satellite data is now routinely used to track activity at a small number of volcanoes. However, it is not yet practical or efficient to routinely collect and analyse data from every satellite on every pass over every volcano around the world. In 2012, the Santorini report from the International Forum of Satellite Earth Observation and Geohazards proposed the ambitious and long-term goal of combining international capabilities to provide an integrated approach to disaster risk[129]. For volcanoes, the report recommends an observing strategy that would focus satellite observations at volcanoes depending on their level of activity. Specifically, it recommends that all Holocene volcanoes should have global background observations, which is defined as quarterly. All restless volcanoes should have weekly observations with daily observations at erupting volcanoes. The report identified the need for long-term sustainability and capacity-building to improve uptake of the satellite data by end-users who work in disaster risk reduction. The objectives of the Santorini report are not currently feasible on a global basis, but several initiatives are working towards that goal and are described here. However, all these efforts operate on a voluntary basis and the lack of mandated agencies for delivering consistent products provides a significant threat to sustainability.

When designing parametric insurance products for developing countries, it is important to consider not just the availability, but also the cost of the data required to trigger pay-outs. Publicly-funded space agencies, such as NASA and ESA, typically distribute their data free-of-charge through an easy-to-access webportal. These provide the backbone of the systems described above. However, satellites operated by commercially-funded space agencies are often useful, either by increasing the number of overpasses for time-critical responses or providing a unique capability. The Space Agencies currently provide two access routes to data for disaster management that are free of charge: the International Charter on Space and Disasters (hereafter the Charter) and the Committee for Earth Observing Satellites Working Group on Disasters (CEOS).

In case of a crisis situation, the Charter can be triggered by an authorised used, typically the relevant national disaster management authority, and participating space agencies contribute space-derived data and products on a voluntary basis. Charter activations are restricted to fast-onset disasters of natural or technological origin and the request for activation can also only be made and accepted within the emergency response phase (up to 10 days after the disaster has occurred). Thus, Charter data provided in response to large explosive eruption could be used to map flows for parametric insurance (see Component 3 Technical Report), but the Charter would be unlikely to be activated during a prolonged period of volcanic unrest. There were two activations for volcanic events within the five focus countries during 2018, both in January, one for Mayon in the Philippines and the other for Kadovar in PNG. Prior to this, the last activation in the five focus countries was for Sinabung in Indonesia in January 2014.

CEOS, an umbrella organisation spanning numerous space agencies established a Working Group on Disasters in 2011 and in 2014 initiated three pilot projects on Volcanoes, Earthquakes and Floods. The volcano pilot focussed on a regional study of unrest and eruption in Latin America, a proof-of-concept study for how an integrated, international, global remote sensing monitoring effort might be

[129] Ferrucci, F., Prata, F., Amelung, F., Bawden, G., Biggs, J., ... & Norbury, D. (2012) Perspectives concerning satellite EO and geohazard risk management: volcanic hazards. In P. Bally (Ed.), The International Forum on Satellite EO and Geohazards, The Santorini Conference, 21–23 May 2012, European Space Agency, Santorini, Greece.

implemented[130]. During its 4-year duration, the project identified deformation at 26 volcanoes, including 18 of the 28 volcanoes that erupted. The eruptions without deformation were less than 2 on the VEI scale. Volcano observatories requested satellite observations at a further 7 volcanoes, but no deformation was detected.

The next phase of the CEOS project is a 'Demonstrator' that will be global in scale, providing access to data and resources for the 5 focus countries covered here (amongst many others). In order to prioritise observations, the USGS Powell Center Volcano Remote Sensing Group classified the world's volcanoes into five categories based on:

- Their Population Exposure Index (PEI);
- Eruptions since:
  - 1990;
  - 2012; and
- Reports of unrest by:
  - Ground-based observations; or
  - By satellite.

In the five focus countries considered here, 260 volcanoes were classified at group C or above (quarterly observations) of which 57 were category A1 (weekly observations).

Barriers to uptake in developing countries

Although satellite data has been used for studying volcanoes since the late 1970s, it is only in recent years that it has been used as a tool for decision making. In developing countries, the satellite observations are still largely provided and interpreted by international organisations such as the UK-based Centre for the Observation and Modelling of Volcanoes Earthquakes and Tectonics (COMET) or the US-based Volcano Disaster Assistance Program. In order to assess the barriers to uptake, the CEOS Volcanoes Working Group sent a short questionnaire to a range of developing countries. The questionnaire was designed to build an understanding of their current operational use of remote sensing, the issues they face and what could be beneficial to them. 10 responses from 7 different countries in SE Asia, Latin America, Africa and the Caribbean were received. Interestingly, even where more than one response was gathered from the same institution, answers sometimes differed. These differences did not arise in the usefulness of tools, but in the understanding of what was currently used and even the number of volcanoes involved. Results of this survey are summarised in Table A1.2.

[130] Pritchard, M. E., Biggs, J., Wauthier, C., Sansosti, E., Arnold, D. W. D., Delgado, F., ... & Wnuk, K. (2018) Towards coordinated regional multi-satellite InSAR volcano observations: results from the Latin America pilot project. Journal of Applied Volcanology, 7(1):5.

Issue	Explanation	Possible Solutions	Example
Awareness	Some observatories are not fully aware of the types of remote sensing available to them or where to access the data.	Collaboration; capacity building.	Turkey. Despite a strong governmental body (MTA) working on geology, including some volcanology, there is no monitoring institute.
Reliability of sources	The internet and particularly social media means the world is more connected than ever before. Data are frequently posted online, especially during eruption crises, but observatories must ensure they originate from a reliable source.	Accreditation or external verification.	Agung, 2017. InSAR images showing perceived deformation were posted on Twitter by non-experts. These images were in fact showing artefacts due to atmospheric effects.
Cost of data	Some remotely-sensed data and software for analysis is prohibitively expensive.	International initiatives for data sharing (e.g. CEOS).	High resolution radar images from X-band satellites such as TerraSAR-X or CosmoSkyMed.
Human resources	Training in specialist areas such as satellite data retrieval is costly. There may be no redundancy within a country, with one expert and no back-up.	Capacity building.	In-country short courses, workshops associated with conferences (e.g. IAVCEI) and investment in postgraduate degrees.
Computing resources	Processing data can require significant computing resources, including (often costly) specialist software, fast computers with powerful processors, large amounts of data storage space.	Automated processing systems.	MODVOLC, NASA Sulphur Dioxide Monitoring Homepage, COMET, LicSAR.
Power supply and internet	Power can be unreliable in many countries, and particularly at remote observatories. Internet access and speed may be insufficient to download large data files.	Automated processing systems which deliver small file size email or text alerts.	MODVOLC?
Timeliness	In rapidly-developing unrest or eruption situations, timely access to data is crucial. Some data cannot be accessed in real-time or near real-time. The download and processing time of other data renders this inappropriate.	Automated processing systems.	MODVOLC, NASA Sulfur Dioxide Monitoring Homepage, COMET LicSAR.
Background knowledge	To understand the unrest at a volcano, some knowledge of background activity is required, to identify levels above background. Eruptive history is also important to understand the type of activity that might be expected at a particular volcano.	Automated processing systems.	

Issue	Explanation	Possible Solutions	Example
Ground truth	Ground-truthing can be required to verify what is seen through remote-sensing. This requires on-the-ground expertise, human and economic resources.	Collaboration.	

Table A1.2 Summary of issues with EO usage in developing world volcano observatories.

Potential for use of EO data in parametric insurance

- Volcanic deformation would be very useful as part of an unrest product, but challenging to apply in tropical regions without high level expertise.
- Numerous detections of SO_2 in the region, include large eruptions (e.g. Pinatubo) and passive degassing (e.g. Ambrym), SO_2 could be used as part of a volcanic unrest index.
- Automated sub-daily thermal alerts (e.g. MODVOLC) are useful for identifying high-temperature anomalies associated with lava effusion and could be used as part of flow mapping for an eruption product. In contrast, high-resolution thermal images have potential to be used as an indicator of unrest but are not routinely available.
- Satellite observations could be particularly key at long dormant volcanoes, many of which may not have much, if any, other monitoring. Annual surveys could be carried out to establish baseline behaviours and / or detect unrest at a very early stage.
- Parametric insurances could be used as a motivator to improve capacity and capability so that expertise is developed either in-house or in-country.
- We recognise considerable long-term potential, but further investment is required in automated analysis and capacity building.
- We conclude that:
  - Satellite data could, in the future, provide elements of a broad indicator dataset upon which quantitative unrest indices could be founded, but that at present, and specifically in the five focus countries, measurements are insufficiently automated and / or robust and latency is too long for EO to play such a role.
  - There is also some potential for satellite data to directly underpin an early trigger in an unrest parametric insurance product, particularly for volcanoes which are not otherwise monitored. However, again, the quality and frequency of satellite observations are insufficient at present to make this a viable option.
  - EO data will be useful for mapping post-eruption deposits, and that use-case will be covered separately in the Component 3 Technical Report.

Annexe 2: Volcano Alert Level systems in focus countries

This annexe describes the Volcano Alert Level (VAL) systems used in the project countries, based on in-country interviews, publicly available document analysis, and published scientific literature.

Indonesia

Indonesia uses one VAL system for its 127 active volcanoes, i.e. those that show some signs of activity (Table 2.1). The VAL system, depending on source, may include two columns ('level of volcanic activity' and 'indication')[131] or three columns (addition of 'community response')[132]. There are four alert levels – Normal, Advisory (Waspada), Watch (Siaga) and Warning (Awas). The level of volcanic activity is described for each alert level in the table. It is unclear whether the 'official' VAL system has these response actions in it or not, but nonetheless, mandatory actions for certain stakeholders are linked to the VAL[133],[134].

Level of volcanic activity	Indication	Community response
Normal level	Visual observations and instrumental records show normal fluctuations and no change of activity. Hazards in the form of poisonous gas may be present near vents, depending on the volcano's characteristic activity.	Communities in Hazard Zones (HZs) I and II may carry out daily activities. Communities in HZ III may carry out daily activities as long as they are in compliance with regulatory requirements from local government according to the technical recommendation of the Geological Agency, Ministry of Energy and Mineral Resources.
Waspada level (advisory)	According to visual observations and instrumental records, there are indications of increasing volcanic activity.	Communities in HZ I and II may carry out their normal activities, but must keep alert. For communities in HZ III it is recommended that they do not to carry out daily activities in areas near summit craters or other vents.

[131] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. *In*: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.
[132] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[133] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. *In*: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.
[134] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

Siaga level (watch)	According to visual observations and instrumental records, there are prominent indications of increasing volcanic activity. Eruptions may take place, but do not threaten settlements and/or activities of communities near the volcano.	Community in HZ I should improve their awareness and must not carry out activities along river valleys that originate at or near the volcano's summit. Communities in HZ II should start to prepare for evacuation and await an evacuation order from the local government according to the technical recommendation of the Geological Agency, Ministry of Energy and Mineral Resources. Communities in HZ III are not permitted to carry out daily activities and should prepare to evacuate.
Awas level (warning)	According to visual observations and instrumental records, there are significant indications of ongoing volcanic activity, with eruptions that potentially threaten settlements and or communities around the volcano.	Communities in HZ I, II, and III are to immediately to evacuate by the order of local government, according to technical recommendation from Geological Agency, Ministry of Energy and Mineral Resources.

Table A2.1 VAL system used in Indonesia, with linked community response actions (from Table 1 in Andreastuti *et al.*, 2017a)[135].

The VAL system has little in the way of forecasting, and generally describes the current level of activity. However, there is inference of trends (e.g. "indications of increasing volcanic activity") in activity.

Setting the VAL, and roles and responsibilities

The Center for Volcanology and Geological Hazard Mitigation (CVGHM), part of the Indonesian Geological Agency, Ministry of Energy and Mineral Resources, is responsible for conducting research into volcanic processes and hazards, monitoring unrest, and issuing the alert levels, notifications and warnings, as well as communicating about mitigation strategies[136,137]. Of the 127 active volcanoes, 68 are monitored through 12 regional centres. Each centre monitors between two and seven volcanoes, and communicates alerts. CVGHM has the mandate to assign a VAL and provide recommendations for evacuation to the National Disaster Management Agency (BNPB), Regional Disaster Management Agencies (BPBD) and local governments. Disaster mitigation at the national level is coordinated by BNPB, however local authorities are responsible for conducting evacuations[138]:

[135] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[136] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. *In*: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.
[137] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[138] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. *In*: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.

> *"Indonesia has a unique involvement of scientists in mitigation actions related to volcanic eruptions. As a mandate holder, CVGHM is responsible not only for monitoring and volcano hazard evaluation, but also for mitigation of volcanic hazards, as alert levels are directly tied to mitigation actions and areas recommended for evacuation are specified in formal CVGHM notifications. Scientists and decision makers who issue volcano alert levels are in the same institution. Scientists from different institutions may provide input based on research but do not to issue alert levels. Further, decision makers communicate directly with disaster managers, such as BNPB and BPBD and provide specific recommendations regarding mitigation actions. BNPB and BPBD arrange, prepare, and through local authorities enact mitigation plans."*

Other institutions have previously issued statements to the mass media, which caused problems and "panic" among the public[139].

Communication and uses of the VAL

Monitoring information is included in reports with alert level notifications. These reports are communicated to stakeholders, and National, Provincial and Local Disaster Management Agencies. The frequency of the reports varies with the alert level[140]:

Normal = monthly

Advisory = fortnightly

Watch = daily

Warning = 6 hourly.

During Watch and Warning levels, communication with the public and stakeholders increases in frequency and amongst stakeholders (Figure A2.1), with messages disseminated using television, radio, text messages and telephones.

[139] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. *In*: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.

[140] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

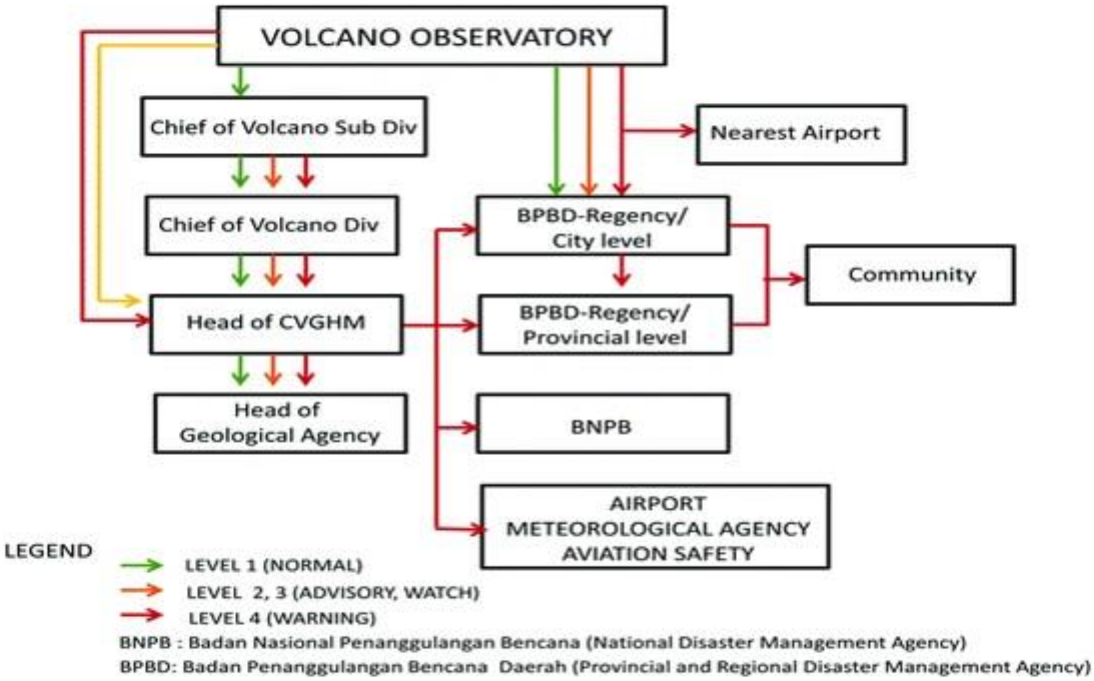

Figure A2.1 Information flow in Indonesia in relation to the Volcanic Alert Level (from Andreastuti et al. 2017b)[141].

The alert level information, condition of the volcano, and mitigation recommendations are disseminated to communities by handy talky (portable radio) and community radios (e.g. there are 13 community radio stations around Kelud volcano, nine of which use handy talky[142]. Further details on the socialisation of volcano information with the community, and the importance of the cultural context, are available[143],[144].

Mitigation actions are linked to the VALs (Tables A2.1 and A2.2). Andreastuti et al. (2017b)[145] describe the following actions in general:

> *"For Normal, Advisory and Watch levels these activities include socialization, preparation of contingency plans, simulations (e.g., table top exercises), and evacuation drills. When the highest alert level (Warning) is declared, evacuation of people in a specified threatened area is recommended by CVGHM, and the local authorities take the action to evacuate the people."*

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[141] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. In: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.
[142] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[143] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. In: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.
[144] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[145] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

At Sinabung, during the ‘normal’ VAL, socialisation and training of local community leaders took place with CVGHM to improve their understanding of hazards and risk[146]. This socialisation process increased as activity increased. Throughout Indonesia, at the ‘Normal’ alert level, a Disaster Management Plan is formulated to strengthen policy and strategy, adopt an information and early warning system, and steps are developed to implement the plan during a crisis[147]. Further mitigation actions associated with VALs are shown in Table A2.2.

Hazard maps, at least for Sinabung and Kelud volcanoes, have three hazard zones[148], which seem to be linked to the community response actions shown in Figure 1. For highly populated volcanoes that tend to have pyroclastic flows (such as Sinabung and Merapi), mitigation measures such as evacuations are based on sectors of the volcanoes to minimise disruption to people’s livelihoods[149].

[146] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[147] Andreastuti, S., Budianto, A. & Paripurno, E.T. (2017) Integrating social and physical perspectives of mitigation policy and practice in Indonesia. In: Fearnley, C.J., Bird, D., Jolly, G., Haynes, K. & McGuire, B. (Eds.) Observing the Volcano World: Volcanic Crisis Communication. Springer, Cham. pp 307-320.
[148] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[149] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

Alert level	Policy	Strategy	Actors	Action	Action by community
Warning (Awas)	Implementation of Disaster Mitigation System	Strengthening communication and coordination	Civil authorities (national, provincial and regional), decision makers, policy makers	1. Activation of contingency plan 2. Provide continuous and updated information 3. Share information	Use information to interpret and take action
Watch (Siaga)	Strengthening hazard information and early warning system	1. Development of information system 2. Checking of early warning system		1. Prepare to activate contingency plan 2. Contingency plan updating & exercises	Carry out updating of data in contingency plan and conduct exercises
Advisory (Waspada)	Strengthening policy and strategy	1. Improvement of collaboration among disaster mitigation institutions 2. Strengthening dissemination of information and early warning systems		1. Formulation of contingency and evacuation plans 2. Formulation of simulation (TTX, CPX), and evacuation drill	Conduct exercise/simulation/evacuation drill
Normal	Formulation of disaster management plan	1. Transparency of programs, funding, implementation, evaluation 2. Public, media, institutional education 3. Explore culture and local resources 4. Utilize local resources 5. Research, mapping	Scientific community & responsible agencies	1. Building good communication between government and media 2. Encourage capacity improvement and community empowerment 3. Encourage community participation to enable understanding of hazard and disaster information 4. Build information and knowledge management systems 5. Develop database 6. Formulate evacuation model	1. Build good communication among community members, and between communities and government 2. Understand hazard and disaster information and actively participate in capacity improvement 3. Be involved in building information and knowledge management systems

Table A2.2 Agency actions associated with each Volcanic Alert Level in Indonesia (from Andreastuti *et al.*, 2017a)[150].

[150] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

Examples of use

The episode of activity at Sinabung volcano during 2013-2015 provides us with an example of the use of the VALs in comparison to monitoring data, eruptions, and mitigation actions. At least 1700 people were relocated, there was a high cost of emergency management, and at least 16 people were killed[151]. Wright *et al.* (in press)[152] apply a probabilistic event tree to Sinabung Volcano during an active sequence in 2013-14, and describe the observation and monitoring data on which they base their estimates (Figure A2.2).

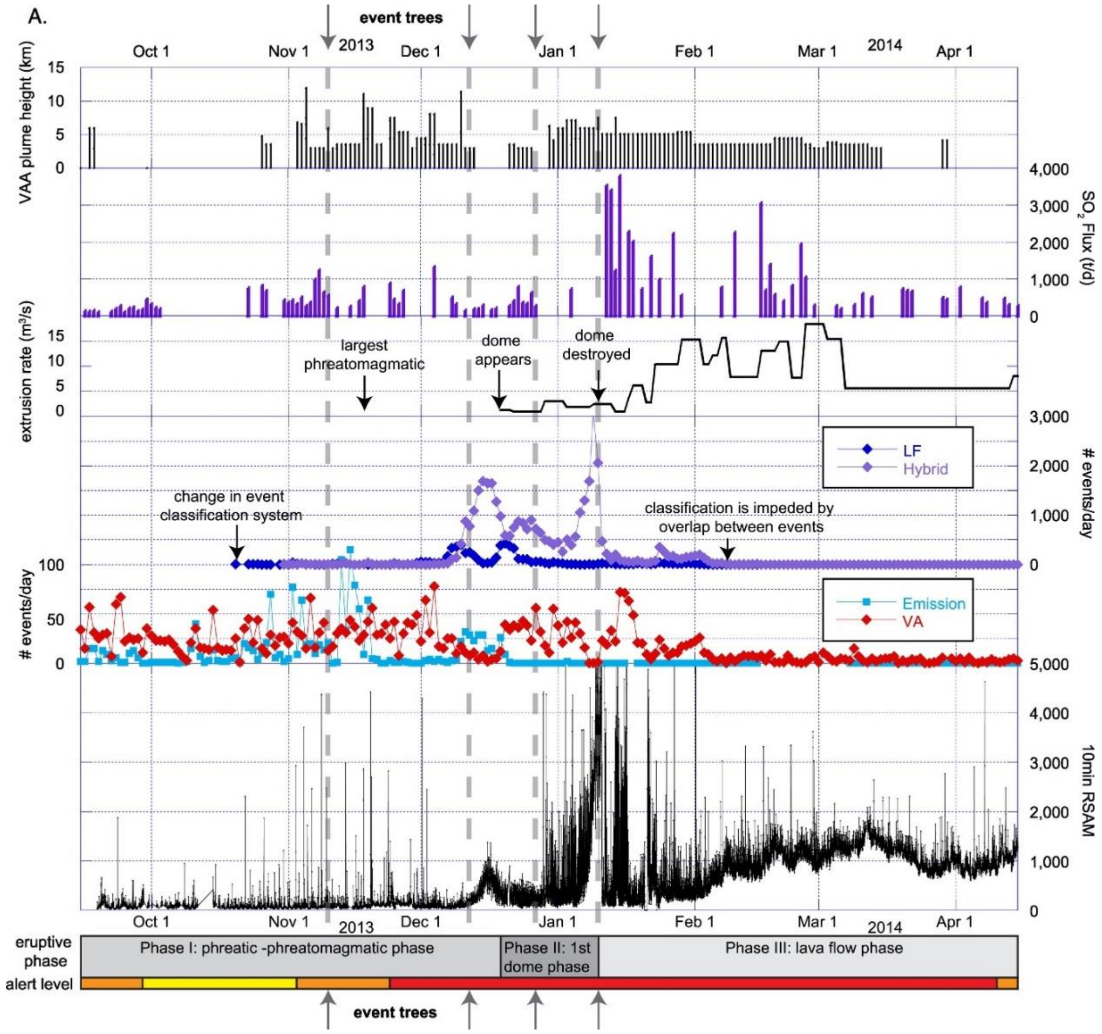

Figure A2.2 CNGHM alert levels for Sinabung Volcano in 2013-14 in comparison to observation/monitoring data. From Wright *et al.* (in press, figure 3a)[153]. Yellow (level 2) = advisory, orange (level 3) = watch, and red (level 4) = warning.

[151] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[152] Wright, H.M.N., Pallister, J.S., McCausland, W.A., Griswold, J.P., Andreastuti, S., Budianto, A., Primulyana, S., Gunawan, H., 2013 VDAP team & CVGHM event tree team (in press) Construction of probabilistic event trees for eruption forecasting at Sinabung volcano, Indonesia 2013–14. Journal of Volcanology and Geothermal Research.
[153] Wright, H.M.N., Pallister, J.S., McCausland, W.A., Griswold, J.P., Andreastuti, S., Budianto, A., Primulyana, S., Gunawan, H., 2013 VDAP team & CVGHM event tree team (in press) Construction of probabilistic event trees for eruption forecasting at Sinabung volcano, Indonesia 2013–14. Journal of Volcanology and Geothermal Research.

They also describe the eruption activity, changes to the alert level, and exclusion zone parameters. Andreastuti *et al.* (2017a)[154] describe the exclusion zones during that time, and the hazard maps.

The following is an extract from Wright et al. (in press)[155], about alert level changes and evacuations made during Sinabung volcanic activity in 2013-14.

> *"The volcanic alert level changed several times during 2013–5, both increasing and decreasing in response to activity level variation… These changes included:*
>
> ***September 15, 2013** 03:00 (WIB): from Levels 2 to 3. At this time, an exclusion zone with a radius of 3 km from the crater was instituted, including the village of Sukameriah.*
>
> ***September 29, 2013** 11:00 from Levels 3 to 2. The exclusion zone decreased to a 2 km radius, while the longer term process of relocating the population of the three closest villages began.*
>
> ***November 3, 2013** 03:00 from Levels 2 to 3. The exclusion zone again increased to a 3 km radius. Residents in four villages were evacuated.*
>
> ***November 24, 2013** 10:00 from Levels 3 to 4. The exclusion radius increased to 5 km. People in 17 villages and 2 hamlets were encouraged to evacuate. People in an additional area beyond 5 km to the southeast were warned about pyroclastic flow hazards. Evacuation remained in effect for the four closest villages. However, by January 10, evacuation was increased to six villages largely to the southeast of the summit.*
>
> ***April 8, 2014** 17:00 from Levels 4 to 3. The exclusion radius decreased to 3 km in all directions and to 5 km in sectors to the south and southeast. However, people living outside of this area were allowed to go back to their homes to clean their roofs and perform usual activities. Relocation of residents was prioritized for those living within the exclusion zone and then for those residents within the previous exclusion zone.*
>
> ***June 2, 2015** 23:00 from Levels 3 to 4. Since that time, the alert level of the volcano has remained at the highest level AWAS (Level 4)[156]. Over this interval, the hazard map changed twice; the sizes of hazards zones progressively increased through time[157]. Similarly, evacuation zones increased in size during the eruption, enlarging more in the south and southeast sectors than other sectors based on the likely travel path of lava margin collapse-generated PDCs.*
>
> *At the time of this writing, ten villages are in evacuation/relocation areas and have suffered severe damage or complete destruction since eruptions began, causing over 9000 people to relocate permanently[158]. Approximately 5000 families—or nearly 15,800 people—remained displaced as of April 29, 2014, according to the Badan Nasional Penanggulangan Bencana (National* Disaster Management *Agency). Only two alert level changes occurred within the interval of time covered by event trees presented herein. The November 24, 2013 alert level*

[154] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[155] Wright, H.M.N., Pallister, J.S., McCausland, W.A., Griswold, J.P., Andreastuti, S., Budianto, A., Primulyana, S., Gunawan, H., 2013 VDAP team & CVGHM event tree team (in press) Construction of probabilistic event trees for eruption forecasting at Sinabung volcano, Indonesia 2013–14. Journal of Volcanology and Geothermal Research.
[156] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[157] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[158] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.

> *increase followed the November 7–10 event tree, which forecast a continuation of explosive eruptive activity. However, none of these event trees immediately preceded an alert level change."*

The VAL has been at the highest level at Sinabung at least three times since 2013 (twice in 2013, once in 2015)[159].

Another example of the use of the alert levels, mitigation actions and hazard zone locations for an eruption at Kelud on 13 February 2014 is also given in Andreastuti *et al.* (2017a)[160]. An impressive 166,000 people evacuated after the Warning level was issued at 21:15 PM on 13 February 2014, and during the 1.5 hours before the eruption began.

Further references that may be of use including details of activity at Merapi in 1997-98[161] and 2006[162], and Gunung Agung (Bali) in 2017[163].

1b Papua New Guinea

Papua New Guinea uses bespoke volcano alert level (VAL) systems. The VAL system uses a 1 to 4 scale for all volcanoes, but the wording varies with the volcanoes.

Each alert level describes the size of the potential eruption (regardless of whether the volcano is erupting).

While the VAL system is volcano dependent, it tends to fall into two main categories: open and closed system volcanoes. VAL for open system volcanoes may focus on size/type of eruption while the VAL for closed system may focus on unrest and potential for eruption of varying sizes.

Setting the VAL, and roles and responsibilities

The RVO recommends a VAL but the decision is made at national office for emergency management (National Disaster Centre).

Communication and uses of the VAL

The VAL contains recommendation about access and exclusion areas.

Each level is tied to actions by the provincial government.

[159] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[160] Andreastuti, S., Paripurno, E.T., Gunawan, H., Budianto, A., Syahbana, D. & Pallister J. (in press) Character of community response to volcanic crises at Sinabung and Kelud volcanoes. Journal of Volcanology and Geothermal Research.
[161] Voight, B., Young, K.D., Hidayat, D., Subandrio, Purbawinata, M.A., Ratdomopurbo, A., Suharna. Panut. Sayudi, D.S., LaHusen, R., Marso, J., Murray, T.L., Iguchi, M. & Ishihara, K (2000) Deformation and seismic precursor dome-collapse and fountain-collapse nue'es ardentes at Merapi volcano, Java, Indonesia 1994–1998. Journal of Volcanology and Geothermal Research 100(1-4):261-287.
[162] Ratdomopurbo, A., Beauducel, F., Subandriyo, J., Agung Nandaka, I.G.M., Newhall, C.G., Suharna, Sayudi, D.S., Suparwaka, H. & Sunarta (2013) Overview of the 2006 eruption of Mt. Merapi. Journal of Volcanology and Geothermal Research 261:87-97.
[163] Gertisser, R., Deegan, F.M., Troll, V.R. & Preece, K (2018) When the gods are angry: volcanic crisis and eruption at Bali's great volcano. Geology Today, 34(2):62-65.

1c Philippines

The Philippines has six volcanic alert level systems, which they call Volcano Alert Signals (VAS)[164]:

- Taal Volcano Alert Signals
- Mayon Volcano Alert Signals
- Bulusan Volcano Alert Signals
- Hibok-Hibok Alert Signals
- Pinatubo Volcano Alert Signals
- Kanlaon Volcano Alert Signals

Each of these six systems are described further below, after a discussion on the similarities and differences between them.

General similarities and differences between the VALSs

All six systems have three columns – a numeric alert level, 'criteria', and 'interpretation'.

The 'alert level' ranges from 0 to 5, with 0 the lowest level of activity (with common terms of 'background', or 'quiet'), and 5 the highest (commonly using the term 'hazardous eruption'). Pinatubo's system differs slightly as it begins at 'no alert' (i.e. it does not include the number zero) and then includes levels 1 through to 5; however, several of the other systems also include the text descriptor of 'no alert' at level 0. Kanlaon, Bulusan and Mayon VAS include short text descriptors in the 'alert level' column.

The six systems all include one 'background' level (level 0). They differ in the number of unrest and eruption levels. Following level 0, Bulusan and Kanlaon VASs have five levels that include eruption descriptions (such as "sporadic explosions" in level 1). Pinatubo, Hibok-Hibok and Mayon systems have three unrest levels and two eruption levels (although Mayon's system states that "phreatic explosion or ash puffs may occur" in level 1, with no mention of eruptions in levels 2 or 3). Taal's system has four unrest levels and one eruption level. The foundation of the systems is fairly consistently based on the level of hazard. That is, even levels that include the occurrence of small eruptions are focused on the imminence of a future "hazardous eruption" (level 5).

The 'criteria' column includes descriptions of the level of volcanic activity and/or observations. These descriptions include the level of seismicity, ground deformation, gas concentrations, and steam/ash explosions, as well as eruption products. The descriptions generally do not include numerical thresholds (except for Hibok-Hibok and Pinatubo levels 5, which include eruption column height as a threshold), but rather subjective descriptors such as "slight increase in volcanic earthquake and steam/gas activity"; "notable increase"; "elevated levels"; "intensifying unrest"; "frequent strong ash explosions".

[164] PHIVOLCS (2008) PHIVOLCS Volcano Monitoring website, 9 May 2008. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

The ‘interpretation’ column includes a range of eruption forecasting information, scientific interpretation of monitoring observations, and hazard information.

Eruption forecasts use qualitative (and undefined) uncertainty terms, and time frame ranges, and are particularly used in levels two to four. Examples are:

- “Could eventually lead to an eruption” (Taal, Pinatubo, Hibok-Hibok, and Mayon VAS, level 2)
- “Eruption is possible within days to a few weeks” (Taal VAS, level 3)
- “Increasing likelihood of an eruption, possibly witin [sic] days to week [sic]” (Pinatubo and Hibok-Hibok VAS, level 3)
- “Hazardous explosive eruption likely, possible within hours to days” (Pinatubo and Hibok-Hibok VAS, level 4).

Interpretation statements often focus on the existence of a magmatic intrusion. For example, the Bulusan VAS include “sporadic explosions” (e.g. including steam/gas/ash) as early as level 1, but the ‘interpretation’ column focusses on magmatic processes and the possibility of a “high hazardous eruption” occurring. The Mayon VAS mention that “phreatic explosion or ash puffs may occur” in level 1, but level 2’s interpretation column states that it “could eventually lead to eruption”. There is clearly a focus on large, magmatic, hazardous eruptions in the VAS systems. Only Taal’s VAS takes into account decreasing activity levels, with descriptions in levels 2 and 3 about whether the trend is towards increasing or decreasing unrest.

Hazards are included in the ‘interpretation’ column in all six systems. The Taal, Pinatubo and Hibok-Hibok systems briefly mention the hazards only in level 5: “hazards in valleys and downwind” (Hibok-Hibok and Pinatubo), and “Extreme hazards to communities west of the volcano and ashfalls on downwind sectors” (Taal VAS). Kanlaon, Bulusan and Mayon VASs are more descriptive than this, and have ‘recommendations’ in the same column as ‘interpretation’ of the volcanic activity. These recommendations are mainly to prohibit access to Danger Zones, which vary in size depending on the volcano. The recommendations are set by local emergency management groups. Further details on these are given in the VAS descriptions below.

Individual Volcano Alert Signals

Taal Volcano Alert Signals

There is a VAS for Taal volcano (Figure A2.3)[165]. The VAS image was last updated on the website on probably 4 August 2014 (the more recent of two dates shown on the website). This VAS has one 'background' level (level 0), four unrest levels (1 to 4) and one eruption level (level 5). It does not include recommended actions within the table.

Alert Level	Criteria	Interpretation
0	Background, quiet	No eruption in foreseeable future.
1	Low level seismicity, fumarolic, other activity	Magmatic, tectonic or hydrothermal disturbance; no eruption imminent.
2	Low to moderate level of seismicity, persistence of local but unfelt earthquakes. Ground deformation measurements above baseline levels. Increased water and/or ground probe hole temperatures, increased bubbling at Crater Lake.	A) Probable magmatic intrusion; could eventually lead to an eruption. B) If trend declines, volcano may soon go to level 1
3	Relatively high unrest manifested by seismic swarms including increasing occurrence of low frequency earthquakes and/or harmonic tremor (some events felt). Sudden or increasing changes in temperature or bubbling activity or radon gas emission or crater lake pH. Bulging of the edifice and fissuring may accompany seismicity	A) If trend is one of increasing unrest, eruption is possible within days to a few weeks. B) If trend is one of decreasing unrest, volcano may soon go to level 2
4	Intense unrest, continuing seismic swarms, including harmonic tremor and/or "low frequency earthquakes" which are usually felt, profuse steaming along existing and perhaps new vents and fissures.	Hazardous explosive eruption is possible within days.
5	Base surges accompanied by eruption columns or lava fountaining or lava flows.	Hazardous eruption in progress. Extreme hazards to communities west of the volcano and ashfalls on downwind sectors.

Figure A2.3 Taal Volcano Alert Signals (from PHIVOLCS, 2011a)[166].

[165] PHIVOLCS (2011) Taal Volcano Alert Signal website, 9 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

[166] PHIVOLCS (2011a) Taal Volcano Alert Signal website, 9 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

Mayon Volcano Alert Signals

Mayon volcano has a VAS (Figure A2.4)[167]. The PHIVOLCS website states that this image or VALS was revised on 14 January 2018. Mayon's VAS has one level of background activity (level 0), three levels of unrest ("low", "moderate", and "relatively high" unrest), and two levels of eruptions (level 4 is labelled as "intense unrest" but includes lava eruptions; level 5 describes a "hazardous eruption" taking place). The exclusion to danger zones appears as early as level 0 for Mayon ("Entry in the 6-km radius Permanent Danger Zone (PDZ) is not advised because phreatic explosions and ash puffs may occur without precursors"). The Danger Zone is progressively increased in size (and termed the "Extended Danger Zone" or EDZ) as the VAS levels get higher.

Alert Level	Main Criteria	Interpretation/ Recommendations
0 No Alert	**Quiet.** All monitored parameters within background levels.	**No eruption in foreseeable future.** Entry in the 6-km radius Permanent Danger Zone (PDZ) is not advised because phreatic explosions and ash puffs may occur without precursors.
1 Abnormal	**Low level unrest.** Slight increase in seismicity. Slight increase in SO2 gas output above the background level. Very faint glow of the crater may occur but no conclusive evidence of magma ascent. Phreatic explosion or ash puffs may occur.	**No eruption imminent.** Activity may be hydrothermal, magmatic or tectonic in origin. No entry in the 6-km radius PDZ.
2 Increasing Unrest	**Moderate unrest.** Low to moderate level of seismic activity. Increasing SO2 flux. Faint/intermittent crater glow. Swelling of edifice may be detected. Confirmed reports of decrease in flow of wells and springs during rainy season.	**Unrest probably of magmatic origin; could eventually lead to eruption.** 6-km radius Danger Zone may be extended to 7 km in the sector where the crater rim is low.
3 Increased Tendency Towards Hazardous Eruption	**Relatively high unrest.** Volcanic quakes and tremor may become more frequent. Further increase in SO2 flux. Occurrence of rockfalls in summit area. Vigorous steaming / sustained crater glow. Persistent swelling of edifice.	**Magma is close to the crater.** If trend is one of increasing unrest, **eruption is possible within weeks.** Extension of Danger Zone in the sector where the crater rim is low will be considered.
4 Hazardous Eruption Imminent	**Intense unrest.** Persistent tremor, many "low frequency"-type earthquakes. SO2 emission level may show sustained increase or abrupt decrease. Intense crater glow. Incandescent lava dome, lava fountain, lava flow in the summit area.	**Hazardous eruption is possible within days.** Extension of Danger zone to 8 km or more in the sector where the crater rim is low will be recommended.
5 Hazardous Eruption	**Hazardous eruption ongoing.** Occurrence of pyroclastic flows, tall eruption columns and extensive ashfall.	Pyroclastic flows may sweep down along gullies and channels, especially along those fronting the low part(s) of the crater rim. Additional danger areas may be identified as eruption progresses. Danger to aircraft, by way of ash cloud encounter, depending on height of eruption column and/or wind drift.

Figure A2.4 Mayon Volcano Alert Signals (from PHIVOLCS, 2015a)[168].

[167] PHIVOLCS (2015) Mayon Volcano Alert Signal website, 29 December 2015. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[168] PHIVOLCS (2015a) Mayon Volcano Alert Signal website, 29 December 2015. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

Bulusan Volcano Alert Signals

Bulusan volcano has a VAS (Figure A2.5)[169]. The PHIVOLCS website states that this image or VALS was revised on 25 September 2014. The Bulusan VAS has one level of background activity (level 0), and five levels of eruptions, ranging from "sporadic explosions" in level 1 (which is called "low level of volcanic unrest"), to "magmatic eruption in progress" in level 5. Recommended actions are included in the table, centred around prohibited access to the Danger Zones, which start with a four-kilometre radius at level 0. The Smithsonian Global Volcanism Program website[170] indicates that the most recent use of the VAS for Bulusan was when it remained at level 1 during an eruption on 5 June 2017.

ALERT LEVEL	CRITERIA	INTERPRETATION/ RECOMMENDATION
0 Quiet or No Alert	All monitored parameters within background levels. Unremarkable level of volcanic earthquakes occurring within the volcano area. Generally weak steam emission.	Quiescence; no magmatic eruption is foreseen. However, there are hazards [1] (explosions, rockfalls and landslides) that may suddenly occur within the four-kilometer radius Permanent Danger Zone (PDZ).
1 Low Level of Volcanic Unrest	Slight increase in volcanic earthquake and steam/gas activity. Sporadic explosions from existing or new vents. Notable increase in the temperature of hot springs. Slight inflation or swelling of the edifice.	Hydrothermal, magmatic, or tectonic disturbances. The source of activity is shallow, near crater or in the vicinity of Irosin Caldera. Entry into the PDZ must be prohibited.
2 Moderate Level of Volcanic Unrest	Elevated levels of any of the following: volcanic earthquake, steam/gas emission, ground deformation and hot spring temperature. Intermittent steam/ash explosion and above baseline Sulfur Dioxide[2] (SO2) emission rates. Increased swelling of volcanic edifice.	Probable intrusion of magma at depth, which can lead to magmatic eruption. Entry within PDZ must be prohibited. Other areas within five (5) kilometers of the active vent may be included in the danger zone.
3 High Level of Volcanic Unrest	Sustained increases in the levels of volcanic earthquakes, some may be perceptible. Occurrence of low-frequency earthquakes, volcanic tremor, rumbling sounds. Forceful and voluminous steam/ash ejections. Sustained increases in SO2 emission rates, ground deformation/swelling of the edifice. Activity at the summit may involve dome growth and/or lava flow, resultant rockfall.	Magma is near or at the surface, and activity could lead to hazardous eruption in weeks. Danger zones may be expanded up to eight (8) kilometers from the active crater.
4 Hazardous Eruption Imminent	Intensifying unrest characterized by earthquake swarms and volcanic tremor, many perceptible. Frequent strong ash explosions. Sustained increase, or sudden drop, of SO2 emission. Increasing rates of ground deformation and swelling of the edifice. Lava dome growth and/or lava flow increases, with increased frequency and volume of rockfall.	Magmatic processes or effusive eruption underway, which can progress into highly hazardous eruption. Danger Zone may be extended up to nine (9) kilometers or more from the active crater.
5 Hazardous Eruption in Progress	Magmatic eruption characterized by explosive production of tall ash-laden eruption columns, or by massive collapses of summit lava dome. Generation of deadly pyroclastic flows, surges and/or lateral blasts and widespread ashfall.	Life-threatening eruption producing volcanic hazards that endanger communities. Additional danger areas may be declared as eruption progresses.

Figure A2.5 Bulusan Volcano Alert Signals. From PHIVOLCS (2011b)[171].

[169] PHIVOLCS (2011). Bulusan Volcano Alert Signals website, 9 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

[170] https://volcano.si.edu/volcano.cfm?vn=273010, accessed on 6 August 2018.

[171] PHIVOLCS (2011b). Bulusan Volcano Alert Signals website, 9 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

Hibok-Hibok Alert Signals

Hibok-Hibok has a VAS (Figure A2.6)[172]. The PHIVOLCS website does not state whether the image or the VALS has been revised since the webpage was populated (on 10 August 2011). This system has one level for background activity (level 0), three levels for unrest ("low", "low to moderate", and "relatively high and increasing unrest"), and two levels of eruptions (level 4 includes lava eruptions and/or small explosions; level 5 is for a "hazardous explosive eruption"). It does not include recommended actions.

ALERT LEVEL	CRITERIA	INTERPRETATION
No alert	Background, quiet	No eruption in foreseeable future
1	Low level seismic, fumarolic, other unrest.	Magmatic, tectonic or hydrothermal disturbance; no eruption imminent.
2	Low to moderate level of seismic, other unrest with positive evidence for involvement of magma	Probable magmatic intrusion; could eventually lead to an eruption.
3	Relatively high and increasing unrest, including numerous b-type earthquakes, accelerating ground deformation and rockfalls, increased vigor of fumaroles, gas emission	Increasing likelihood of an eruption, possibly witin days to week.
4	Intense unrest, including harmonic tremor and/or may "long period" (=low frequency) earthquakes or quiet lava emissions and/or dome growth and/or small explosions	Magma close to or at earth's surface. Hazardous explosive eruption likely, possible within hours to days
5	Hazardous explosive eruption in progress, with pyroclastic flows, surges and/or eruption column rising at least 6 km or 20,000 feet above sea level	Explosive eruption in progress. Hazards in valleys and downwind

Figure A2.6 Hibok-Hibok Volcano Alert Signals (from PHIVOLCS, 2011c)[173].

Hibok-Hibok has a last known eruption in 1953[174], with no further activity bulletins issued, and it is unknown whether the VAS has been used.

[172] PHIVOLCS (2011). Hibok-Hibok Volcano Alert Signals website, 10 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[173] PHIVOLCS (2011c). Hibok-Hibok Volcano Alert Signals website, 10 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[174] https://volcano.si.edu/volcano.cfm?vn=271080 accessed on 6 August 2018.

Pinatubo Volcano Alert Signals

Pinatubo volcano has a VAS (Figure A2.7)[175]. The PHIVOLCS website does not state whether this image or VALS has been revised since the webpage was populated (on 10 August 2011). It has one level of background activity (effectively level 0, called "no alert"), three unrest levels (1-3), and two eruption levels (4 and 5). There are no recommended actions included in this VAS.

ALERT LEVEL	CRITERIA	INTERPRETATION
No alert	Background, quiet	No eruption in foreseeable future
1	Low level seismic, fumarolic, other unrest.	Magmatic, tectonic or hydrothermal disturbance; no eruption imminent.
2	Low to moderate level of seismic, other unrest with positive evidence for involvement of magma	Probable magmatic intrusion; could eventually lead to an eruption.
3	Relatively high and increasing unrest, including numerous b-type earthquakes, accelerating ground deformation, increased vigor of fumaroles, gas emission	Increasing likelihood of an eruption, possibly witin days to week.
4	Intense unrest, including harmonic tremor and/or may "long period" (=low frequency) earthquakes or quiet lava emissions and/or dome growth and/or small explosions	Magma close to or at earth's surface. Hazardous explosive eruption likely, possible within hours to days
5	Hazardous explosive eruption in progress, with pyroclastic flows and/or eruption column rising at least 6 km or 20,000 feet above sea level	Explosive eruption in progress. Hazards in valleys and downwind

Figure A2.7 Pinatubo Volcano Alert Signals. From PHIVOLCS (2011d)[176].

[175] PHIVOLCS (2011). Pinatubo Volcano Alert Signals website, 10 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[176] PHIVOLCS (2011d). Pinatubo Volcano Alert Signals website, 10 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

The Pinatubo VAS webpage[177] includes information on how long it will take to decrease the alert level:

STAND-DOWN PROCEDURES:

In order to protect against "lull before the storm" phenomena, alert levels will be maintained for the following periods AFTER activity decreases to the next lower level:

From level 5 to level 4:	***Wait 12 hours after level 5 activity stops***
From level 4 to level 3 to 2:	***Wait 2 weeks after activity drops below level 4***
From level 3 to level 2:	***Wait 2 weeks after activity drops below level 3***

NOTE:

Ashfall will occur from secondary explosions for several years after the 1991 Plinian (calderagenic) eruption, whenever rainfall and lahars come in contact with still hot-hot 1991 pyroclastic flow deposits. These secondary explosions will occur regardless of alert level.

The most recent report of a change in alert level for Pinatubo was in early January 1995[178],[179], when the alert level was raised to 2 due to heightened seismicity indicating a possible magmatic intrusion. Interestingly, the Smithsonian article refers to Danger Zones, which are not mentioned in the VAS itself: "Although a heightened alert status was declared, PHIVOLCS believed that explosions would likely be confined to the caldera and no enlargement of the danger zone was made at this time"[180].

[177] PHIVOLCS (2011). Pinatubo Volcano Alert Signals website, 10 April 2011. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[178] Global Volcanism Program (1994). Report on Pinatubo (Philippines). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 19:12. Smithsonian Institution. Accessed from https://volcano.si.edu/volcano.cfm, on 8 August 2018.
[179] The title of the article states December 1994, but the article text describes the change as having occurred in "January". Due to other articles having been issued throughout 1994 with no mention of this event, we have presumed (with some uncertainty) that this means the change occurred in January 1995.
[180] Global Volcanism Program (1994). Report on Pinatubo (Philippines). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 19:12. Smithsonian Institution. Accessed from https://volcano.si.edu/volcano.cfm, on 8 August 2018.

Kanlaon Volcano Alert Signals

Kanlaon volcano has a VAS (Figure A2.8)[181]. The PHIVOLCS website states that this image or VALS was revised in November 2015. The Kanlaon VAS has one level of background activity (level 0), and five levels of eruptions of increasing levels of hazard, from "sporadic explosions" in level 1, through to lava extrusion at level 3, and larger eruptions at level 5. The occurrence of eruptions is not reflected in the 'alert' column labels, which describe increasing levels of unrest from level 1 to 4. Magmatic processes are the focus of this VAS, which also includes Danger Zone information as recommended actions.

ALERT	CRITERIA	INTERPRETATION/RECOMMENDATION
0 No Alert (NORMAL)	All monitored parameters within background levels. Unremarkable level of volcanic earthquakes occurring within the volcano area.	Quiescence; nno magmatic eruption is foreseen. However, there are perennial hazards (sudden explosions, rockfalls and landslides) within the four (4) kilometer-radius Permanent Danger Zone (PDZ) that may occur suddenly and without warning.
1 Low Level of Volcanic Unrest	Slight increase in volcanic earthquake and steam/gas activity. Sporadic explosions from the summit crater or new vents. Notable increase in the temperature, acidity and volcanic gas concentrations of monitored springs and fumaroles. Slight inflation or swelling of the edifice.	Hydrothermal, magmatic, or tectonic disturbances may be underway. The source of activity is shallow, near the summit crater or in the vicinity of the edifice. Entry into the PDZ must be prohibited.
2 Moderate Level of Volcanic Unrest	Elevated levels of any of the following parameters: volcanic earthquake, temperature, acidity and volcanic gas concentrations of monitored springs and fumaroles, steam and ash explosions from the summit crater or new vents, inflation or swelling of the edifice.	Probable intrusion of magma at depth, which may or may not lead to magmatic eruption. Entry within PDZ must be prohibited.
3 High Level of Volcanic Unrest	Sustained increases in the levels of volcanic earthquakes, some of which may be perceptible. More energetic and frequent steam/ash explosions. Sustained increases in the temperature, acidity and volcanic gas concentrations of springs and fumaroles, and in the levels of ground deformation or swelling of the edifice. Activity at the summit may involve sluggish lava extrusion with resultant rockfall.	Magmatic intrusion to the surface is driving unrest, with indications that hazardous eruption could occur in weeks. Danger zones may be expanded to a radius of six (6) kilometers from the summit crater or active vent.
4 Hazardous Eruption Imminent	Intensifying unrest characterized by earthquake swarms and volcanic tremor, many of which may be perceptible. Frequent strong ash explosions. Increasing rates of ground deformation and swelling of the edifice. Increasing rates of lava extrusion with increased frequency and volume of rockfall, or plugging of lava at the summit crater or active vent.	Low-level magmatic eruption underway, which can progress to highly hazardous major eruption. Danger zones may be expanded to a radius of ten (10) kilometers or more from the summit crater or active vent.
5 Hazardous Eruption in Progress	Magmatic eruption characterized by explosive production of tall ash-laden eruption columns, and/or descent and frequent failure of voluminous lava flows. Generation of deadly pyroclastic flows, surges and/or lateral blasts and widespread ashfall. Lahars generate along river channels.	Life-threatening major eruption producing volcanic hazards that endanger communities. Danger zones may be expanded to fourteen (14) kilometers as eruption progresses.

Figure A2.8 Kanlaon Volcano Alert Signals. From PHIVOLCS (2015b)[182].

[181] PHIVOLCS (2015). Kanlaon Volcano Alert Signal website, 28 December 2015. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[182] PHIVOLCS (2015b). Kanlaon Volcano Alert Signal website, 28 December 2015. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.

The Kanlaon VAS webpage[183] includes information on how long the wait will be before lowering the alert level:

- STAND-DOWN PROCEDURES
- In order to minimize unnecessary changes in declaration of Alert Levels, the following periods shall be observed:
- From Level 5 to Level 4: Wait at least 24 hours after hazardous activity stops
- From Level 4 to Level 3 or 2: Wait at least 2 weeks after activity drops below Level 4
- From Level 3 to Level 2: Wait 2 weeks after activity drops below Level 3

As of 24 April 2018, the alert level remained at 2 for Kanlaon due to “dirty white steam plumes”[184], following eruptions in 2016-17[185].

Setting the VAS, and roles and responsibilities

PHIVOLCS determines the VAS.

Communication and uses of the VAS

No information has been found on how the VAS for each of the volcanoes is communicated to the public and stakeholders.

The extent of Danger Zones seems to be triggered by changes in the VAS. For example, the Kanlaon VAS states that “Danger zones may be expanded to a radius of six (6) kilometres from the summit crater or active vent” in level 3, and that “Danger zones may be expanded to a radius of ten (10) kilometres or more from the summit crater or active vent” for level 4.

Examples of use

The Smithsonian’s Global Volcanism Program website includes examples of how the VASs have been used, as linked to volcanic activity[186].

[183] PHIVOLCS (2015). Kanlaon Volcano Alert Signal website, 28 December 2015. https://www.phivolcs.dost.gov.ph/index.php, accessed on 6 August 2018.
[184] Global Volcanism Program (2018a). Report on Kanlaon (Philippines). In: Venzke, E. (ed.), Bulletin of the Global Volcanism Network, 43:1. Smithsonian Institution. Accessed from https://volcano.si.edu/volcano.cfm?vn=272020, on 8 August 2018.
[185] Global Volcanism Program (2018b). Report on Kanlaon (Philippines). In: Sennert, S. K. (ed.), Weekly Volcanic Activity Report, 18 April – 24 April 2018. Smithsonian Institution and US Geological Survey. Accessed from https://volcano.si.edu/volcano.cfm?vn=272020, on 8 August 2018.
[186] For example, activity at Mayon Volcano in 2014 is described here: https://volcano.si.edu/volcano.cfm?vn=273030, accessed on 6 August 2018

1d Tonga

Tonga does not have a Volcano Alert Level system. During our visit to Tonga, the Head of the Tonga Geological Survey expressed openness to developing a VAL system, but noted that a previous attempt to develop and implement a system failed due to lack of government interest.

1e Vanuatu

One VAL system is used for all of Vanuatu's volcanoes. It ranges from 0 ("normal"), to 5 ("very large eruption")[187]. It has two levels for unrest (1 and 2), and three for eruptions (3 – 5), and is written in English. It is black, white and grey, and does not include any symbols.

Vanuatu's VAL System (VVALS) states that it is "based on the level of volcanic activity" (Figure A2.9). The "title" of each level is based on the general scale of volcanic activity (e.g., "minor eruption", "moderate eruption"). The "description area/distance" column of the VAL table includes the spatial extent of "danger" (e.g., "danger around the crater rim"), with increasing spatial extent of the danger described as the levels get higher.

Vanuatu Volcanic Alert Level System

Title	Level of Alert	Description Area / Distance
Very Large Eruption	5	Danger beyond caldera, on entire and sourrounding islands and also chance of flank eruption
Moderate Eruption	4	Danger on volcanic cone, caldera and all island, possibility of very large eruption and also chance of flank eruption
Minor Eruption	3	Danger on volcanic cone, within caldera and other specific area, possibility of moderate eruption and also chance of flank eruption
Major Unrest	2	Danger around the crater rim and specific area, notable/large unrest, considerable possibility of eruption and also chance of flank eruption
Signs of Volcanic Unrest	1	Notable signs of unrest Possible danger near eruptive vents
Normal	0	No signs of change in the activity Limited danger

An eruption may occur at any level and levels may not move in sequence as activity can change rapidly

This system applies to all Vanuatu's volcanoes.
The Volcanic Alert Level is set by the National Geohazards Observatory within the Vanuatu Meteorology and Geohazards Department based on the level of volcanic activity.
For more information see www.vmgd.gov.vu or email at geohazards@meteo.gov.vu or call at 24686 for alert levels and current volcanic activity.
Version 2.0, 2014.

Figure A2.9 VAL system used by Vanuatu[188].

[187] http://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/volcanic-alert-level. Accessed on 12 July 2018.
[188] http://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/volcanic-alert-level, accessed on 5 July 2018.

Due to the inclusion of the spatial extent of the danger for each level in the table, it is unclear whether the foundation of the VVALS, i.e. the primary trigger to set the VAL, is the general size of the eruption, or the spatial extent of the danger. As these are generally correlated, it is probably a minor point. The use of the word ‘danger’ (rather than ‘hazard’) is noted here, as it can indicate certain degree of expected impacts/threat or risk to the areas mentioned. This word was selected as VMGD feel strongly that locals respond better to this word than ‘hazard’. A brochure about monitoring and the VVALS[189] states that “each level represents a specific range of hazards for the exposed populations and infrastructure”. The specific hazards that are considered in setting the VAL are not defined, but are those that pose acute life-safety concerns.

A range of volcano types are specifically named in each level, including calderas, cones, and flank eruptions. Spatial extent of the danger is also indicated using “specific area”, “all island” and “sourrounding islands” [sic]. Due to the use of the spatial extent, the VVALS is generally objective (that is, VAL 4 used on two different volcanoes will appear similar in terms of spatial extent and general scale of eruption). Therefore, it’s likely that the VVALS can be robustly used over time, and at multiple volcanoes, without causing confusion with the public.

The VVALS includes forecasting language. Level 2 (major unrest) notes that there is a “considerable possibility of eruption and also chance of flank eruption”. Levels 3 and 4 note the “possibility” (without “considerable”) of an eruption relating to the size described by the next level higher. There was no definition found of what level of likelihood those terms imply. Additionally, the VVALS states that “an eruption may occur at any level, and levels may not move in sequence”. No timeframes deliberately are given for the forecasting language used in the table.

Level 0 does not define what “limited danger” means, but is understood by the local population. Level 1 (“signs of volcanic unrest”) states “possible danger near eruptive vents”, which indicates that the spatial extent of the danger is determined, but does not describe further the likelihood threshold (or severity of threat/impact threshold) used. These language choices reflect the needs of the local population and the diverse range of volcanoes in Vanuatu.

Development of the VAL system

Vanuatu’s current VAL system was revised in 2014, and the VVALS is version 2.0. The revision used New Zealand’s VAL system, which was revised at the same time[190].

Determining the VAL

The VAL is set by the National Geohazards Observatory within the Vanuatu Meteorology and Geohazards Department[191]. There are Standard Operating Procedures (SOPs) for setting the VVALS. These are in alignment with the Emergency Management SOPs[192].

The Director of the Department of Geological Hazards (exclusively) has the task of issuing a “warning and alert of imminent or constant risks from geological hazards, and determine when a warning and alert is to be lifted” (as stated on pg. 19 and 21 of the Meteorology, Geological Hazards and Climate

[189] http://www.vmgd.gov.vu/vmgd/images/geo-media/docs/volcano_monitoring.pdf, accessed on 12 July 2018 from http://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/resources
[190] Potter, S.H., Jolly, G.E., Neall, V.E., Johnston, D.M., Scott, B.J. (2014) Communicating the status of volcanic activity: revising New Zealand’s volcanic alert level system. Journal of Applied Volcanology, 3:13.
[191] http://www.vmgd.gov.vu
[192] Pers. comm. Graham Leonard, GNS Science.

Change Act No. 25 of 2016[193]). They also have the function of developing programs to support early warning systems for geological hazards, and to "support regional efforts for disseminating general warnings to the public, and specific warnings and information to aircraft and ships" (pg. 20), as well as to tourists. The Director also has the function of co-operating with relevant regional and international organisations and support the principle of free exchange of relevant data about geological hazards. The precautionary principle is applied when undertaking these functions. The Act (pg. 6) specifically states that:

> *"In the event of a threat of damage […] or a risk to human safety and health from […] geological hazards […], the lack of scientific evidence certainty [sic] regarding the extent of adverse effects is not used as a pretext to prevent or avoid a decision being made to respond to or to minimise the potential adverse effects or risks."*

Communication and uses of the VAL

In general, the Meteorology, Geological Hazards and Climate Change Act No. 25 of 2016 (pg. 5) aims to:

> *"Ensure that the government and the public are informed of matters related to weather, climate and geological hazards, and are able to make effective use of such information and data, and to respond to warnings and alerts about such events, in order to protect the environment and the safety and welfare of the community."*

The VVALS does not include any language that specifically relates to actions to be taken, such as evacuation, as that is outside the mandate of VMGD.

There is no link between the VVALS and hazard maps. There were linkages in the previous VAL system, but this was removed in the 2014 review[194].

[193] http://www.vmgd.gov.vu/vmgd/images/admin-media/docs/Official-Gazette-No.-6-of-2017-dated-1-February-2017.pdf Accessed on 2 August 2018
[194] Pers. comm. Graham Leonard, GNS Science.

Annexe 3: Feasibility assessment of indices in focus countries

A3.1 Methodology

Selecting candidate volcanic unrest triggers

We select candidate volcanic unrest triggers based on current practices in detecting volcanic unrest, and emerging opportunities. The selection is based on consortium partner experience as a volcano observatory, individual consortium partner engagement with global volcano observatories through the World Organization of Volcano Observatories (WOVO) and Volcano Observatory Best Practice (VOBP) workshops, focus country visits, and the GAR15 report.

At the end of this Annex we provide a one-page reference list of the candidate triggers.

Evaluating volcanic unrest triggers

We evaluate candidate volcanic unrest triggers based on feasibility, objectivity, and ethical considerations, considering different geographic settings, levels of monitoring, and country arrangements. The shading of the 'answer' words indicates how the shading will be in the evaluation tables.

We evaluated select candidate triggers during a workshop on 19 October 2018 following the Understanding Risk Financing Pacific conference in Port Vila, Vanuatu, in partnership with representatives from Rabaul Volcano Observatory (PNG), Vanuatu Meteorology and Geohazards Department, and the Tonga Geosciences Service.

At the end of this Annex we provide a one-page reference list of the evaluation criteria.

Feasibility

In this report we evaluate the feasibility of candidate volcanic unrest triggers using the following questions. The shading corresponds to the cell shading used in the evaluation, and are designated such that green shading indicates yes/positive, amber shading indicates caution may be required, red shading indicates a potential serious problem, and black shading indicates a probable deal breaker. A slash indicates the question is not relevant.

A-C assume world-class monitoring capabilities and explores how the trigger would perform.

A. Given local volcanic and environmental factors, is the trigger possible for the volcano? *(Yes, Unlikely, No)*
B. What is the likelihood of false positives? *(Likely, Unlikely, Extremely unlikely)*
C. What is the likelihood of false negatives? *(Likely, Unlikely, Extremely unlikely)*

D-F considers whether trigger execution is possible given current resources and considers opportunities in the future.

D. Given available human, physical and/or institutional resources, is the trigger possible for the volcano *(Yes, Unlikely, No)*

E. If the trigger is currently not possible given human, physical and/or institutional resources, what is the likelihood of it being possible within the next 5 years? (*Planned and likely*, *Unplanned but possible*, *Unplanned and unlikely*, *Effective impossible*)
F. If the trigger is currently not possible given human, physical and/or institutional resources, what would the cost of implementation be? (*Minor*, *Moderate*, *Major*, *Effectively impossible*)

G-I considers trigger resilience.

G. If the trigger relies on an instrument(s), does the instrument(s) have reasonable and credible long-term maintenance plans and provisions in place should the instrument fail? (*Yes*, *No*)
H. If the trigger relies on an instrument(s), how resilient is the instrument(s) to volcanic activity? (*Resilient to all volcanic activity*, *Vulnerable in major eruption*, *Vulnerable in minor eruption*)
I. If the trigger relies on an instrument(s), how resilient is the instrument(s) to non-volcanic natural and societal hazards, including but not limited to earthquakes, tsunami, landslides, flooding, and vandalism? (*Resilient*, *Somewhat vulnerable*, *Vulnerable*)

Objectivity

The objective of candidate volcanic unrest triggers will be evaluated using the following question:

J. How objective is the unrest trigger? (*Entirely subjective*, *Mixed subjective and objective*, *Entirely objective*)
K. If the trigger depends on a volcano observatory, how independent is the volcano observatory from the policy holder? (*Controlled by policy holder*, *Independent during low level of activity but controlled during high levels of activity*, *Independent of policy holder*)
L. If the trigger is independent of a volcano observatory, how independent is the index? (*Dependent on subjective judgement of policy holder*, *Dependent on objective data controlled by policy holder*, *Independent of sovereign control*)

Ethical considerations

The ethical considerations of candidate volcanic unrest triggers will be evaluated using the following questions:

M. Can the trigger infringe on sovereignty? (*Major concern*, *Minor concern*, *Unlikely*)
N. Can the trigger be compromised or undercut by the policy holder? (*Major concern*, *Minor concern*, *Unlikely*)
O. Can the trigger be compromised or undercut by the policy underwriter? (*Major concern*, *Minor concern*, *Unlikely*)
P. Can the trigger lead to counterproductive behaviour that would negatively impact the local population? (*Major concern*, *Minor concern*, *Unlikely*)
Q. Can the trigger lead to counterproductive behaviour that would negatively impact the government? (*Major concern*, *Minor concern*, *Unlikely*)
R. Can the trigger lead to counterproductive behaviour that would negatively impact other actors? (*Major concern*, *Minor concern*, *Unlikely*)

Comments

- Evaluation criterion B (false positive) relates to false positives. As an example, if the sky is always blue the day before an eruption, but there are many blue-sky days without an eruption the following day, false positives would be evaluated as likely. A geophysical example could be a signal increase due to a regional earthquake swarm rather than seismic activity related to the volcano.
- Evaluation criterion C (false negative) relates to false negatives. As an example, if a cloud always covers the moon the day before an eruption, but there are many eruptions where a cloud did not

cover the moon the day before, false negatives would be evaluated as likely. An EO example could be a thermal anomaly not being picked up by a satellite.

- For evaluation criterion D, E, and F, human, physical and/or institutional resources may include but are not limited to staffing levels/expertise, available instrumentation, real-time data capacity, and real-time sharing of data with external parties.
- Evaluation criterion M concerns severity, specifically, whether if the candidate trigger was the parametric trigger, whether it would force behaviour that the country wouldn't otherwise take. As an example, in the 1990s in New Zealand during the Ruapehu 1995/96 eruptions, it was decided that the VAL would decrease if a series of parameters decreased below a certain point. One parameter remained elevated for months, and so while it was the judgement of the volcanologists that the volcano was at a lower VAL, they were unable to decrease the VAL in line with their professional judgement because of this pre-set criterion.

A3.2 Candidate volcanic unrest triggers

Below we consider possible unrest triggers with the aim of first supporting enhanced preparedness and second evacuation decisions. We stress that customization of the indices will be required for individual volcanoes. In some cases, logical groupings of volcanoes may be permissible (e.g. volcanoes with no monitoring located in a specific country).

In our evaluation we will consider the candidate triggers (presented in the next two sections) individually. In the future combining triggers (e.g. two of the following five must be present to trigger a payment) could be explored, but is considered out of scope for this project given time constraints.

Enhanced preparedness

Aim: Trigger payment in the early stages of volcanic unrest to increase monitoring capabilities and community preparedness. At frequently erupting volcanoes an escalation of volcanic activity can prompt the need of additional monitoring. This early injection of financing will decrease future scientific uncertainty and will help the community understand the situation, assisting further decision making.

Assistance with: Monitoring capabilities, include new instrumentation, additional personnel, helicopter or aircraft surveillance, and/or campaign data collection, and community preparedness measures.

Candidate triggers: Below we list candidate triggers that we will evaluate in the next sections. '*XX*' are values that would have be determined for the individual or group of volcanoes (e.g., volcanoes with no/limited/adequate instrumental monitoring, open vs closed system volcanoes).

I. Confirmation of visual observation of unusual activity
II. Increase from background to unrest VAL
III. Issuance of VAA from regional responsible VAAC
IV. *XX* earthquakes above *XX* magnitude within *XX* hours/days
V. RSAM above *XX* over *XX* hour/days at *XX* seismometer(s) within *XX* km of vent
VI. Ground-based detection of SO_2 or CO_2 gas above *XX* tons/day
VII. EO detection of SO_2 or CO_2 gas above *XX* tons/day
VIII. EO detection of thermal anomaly of *XX* degrees above XX over *XX* m^2
IX. EO detection of deformation of at least *XX* mm over *XX* km^2
X. Eruption of volcanic ash
XI. Increase of *XX%* of plume height, PDC runout or lava flow extent compared to that of the last *XX* years.

Comments

- Candidate trigger I (visual observation) could include but is not limited to reports from observatory staff or local lay observers, local leaders, pilots, members of the public, and webcam imagery. Unusual activity could include but is not limited to dying vegetation, appearance or change in behaviour of hot springs or fumaroles, hot ground, animals leaving area, and appearance of cracks.
- A further candidate trigger concerning detection of deformation through drone observations (using Structure-from-Motion data processing) was proposed at the workshop on 19 October by the representative from the Tonga Geological Services. We will consider this for the Tonga evaluation. It is not yet used routinely, to our knowledge, anywhere around the world.
- A concept we explored but have not included is an increase in vulnerability driven by people moving closer to the volcano, which could prompt the need of surveillance at a volcano that previously was not considered a priority for monitoring.

Evacuation support

Aim: Trigger payment to assist with pre-eruption evacuation in the interest of life-safety. This may be days, weeks, months, or even years into an eruption sequence, or before any eruptive products have reached the surface.

Assistance with: Evacuation support.

Candidate triggers: Below we list candidate triggers that we will evaluate in the next sections. '*XX*' are values that would have be determined for the individual or group of volcanoes (e.g., volcanoes with no/limited/adequate instrumental monitoring, open vs closed system volcanoes, mainland or island volcanoes).

XII. Declaration of a State of Emergency
XIII. Official evacuation of *XX* people called
XIV. Self-evacuation of *XX* people has occurred
XV. Official evacuation of *XX* people has occurred
XVI. Confirmed fatality outside of evacuated / limited access zone
XVII. VAL increase to *XX* level
XVIII. VUI increase to *XX* level
XIX. Volcano observatory information release forecasts with a likelihood of at last *XX*% an eruption of *XX* size within the next *XX* hours/days
XX. BET evaluation forecasts a likelihood of at last XX% an eruption of XX size within the next XX hours/days

Comments

- For candidate triggers XIII, XIV, and XV (various types of evacuations), the number will need to be carefully selected. We recommend consideration of percentage of exposed population, demographic trends, recognition of demographic trends, and other related factors.
- For candidate triggers XIII, XIV, XV, and XVI (various types of evacuations, fatality), we caution that the term evacuation will have to be carefully defined. In some contexts, an evacuation is equivalent to the establishment of an exclusion zone, while in other cases it may preclude people from living or sleeping within a zone but allows daytime (or other) entry for livelihood or economic reasons.

- Candidate trigger XVI (fatality) is motivated by that a fatality in a nominal 'safe' zone can quickly lead to the expansion of the evacuated / limited access zone.

A3.3 Evaluation of candidate volcanic unrest triggers

Enhanced preparedness candidate triggers

In this section we evaluate the enhanced preparedness candidate triggers. We provide comments on select evaluations after each table, but briefly make comments applicable to all volcanoes and countries:

- Candidate trigger III (Volcanic Ash Advisories issued by a Volcanic Ash Advisory Centre) is a communication tool developed to mitigate the risk of aircraft – ash encounters. It is not the mandate of the VAACs to monitor unrest, and non-ash volcanic hazards are not within their purview.
- Candidate trigger IV (earthquakes) requires a minimum of three seismometers near each volcano, although four seismometers is considered more reliable.

We first consider the case of a generic very well-monitored volcano by international standards to evaluate the candidate triggers in an ideal situation (Criteria A-C) and objectivity and ethical considerations (Criteria J, M-Q). We next evaluate the candidate triggers given the realities in each focus country (Criteria D, G-Q), subdividing as appropriate for the local context, and end with an evaluation of future opportunities (Criteria E-F) over a 5-year time frame.

Generic very-well monitored volcano

A generic very-well monitored volcano has, at a minimum, daily visual observations, a seismic network of four or more station, a gas monitoring network, ground deformation monitoring, and satellite data interpretation. The historic eruptive record is documented, and one or more geologic studies have characterised Holocene volcanic activity.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
A *(Phys. poss.)*											
B *(False positive)*											
C *(False negative)*											

Comments

- At a very-well monitored volcano, all the candidate triggers are possible, although most not definitive in isolation.

- Candidate triggers VII, VIII, and IX (satellite remote sensing) can easily miss the early stages of unrest due to time between images, pixel size, and cloud cover. Signal processing challenges can lead to misinterpretation of data, and anthropogenic sources in some areas can complicate signal interpretation.
- Candidate triggers X and XI (eruption of ash, increase reach of hazard footprints) are more suitable for volcanoes that are perpetually erupting, and so do not account for most volcanoes in the focus countries.

Objectivity and ethical considerations

Each focus country has different political and governing arrangements, and different challenges. We evaluate objectivity and ethical considerations broadly, and explain the rationale in the comments. These are not universal statements, and may be different in individual jurisdictions. We will comment on the independence of the observatories in the country sections.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
Objectivity											
J *(Objective)*											
Ethical considerations											
M *(Sovereignty)*											
N *(Undercut by PH)*											
O *(Undercut UW)*											
P *(Counter. local)*											
Q *(Counter. gov.)*											
R *(Counter. other)*											

Comments

- Criterion J (objectivity):
  - Candidate trigger I (visual observations) is by its nature subjective.
  - Candidate triggers II and III (Volcano Alert Level, Volcanic Ash Advisories issued by a Volcanic Ash Advisory Centre) do not follow a formula but rather rely on the interpretation, expert judgement, and synthesis of all the available data at the time the VAL or VAA is issued.
  - Candidate triggers X and XI (eruption of volcanic ash, increase of volcanic hazard extent) require an understanding of what is 'typical' activity at the volcano, which might not be formally defined.

- Criterion M (sovereignty): Candidate triggers III, VII, VIII, and XI (Volcanic Ash Advisories issued by a Volcanic Ash Advisory Centre, satellite observations) are issued or determined by a foreign entity. If these are used externally to the volcano observatories as a sole trigger, they could be in breach of the IAVCEI guidelines for professional interaction during volcanic crises[195] by which volcano observatories and their partners abide by.
- Criterion N and Q (undercut by policy holder, counterproductive behaviour by government): There could be an incentive for governments to not monitor certain volcanoes if it is deemed the cost of monitoring outweighs the potential payout. However, this is deemed unlikely, as it would be extremely controversial if revealed. The volcanology community has well-established the direct benefit towards saving lives that monitoring affords.
- Candidate trigger XI (EO deformation): InSAR requires sophisticated processing and expertise in interpretation. If this is not done properly there is a chance that either the policy holder (criterion N) or the underwriter (criterion O) could contest or offer a more suitable (for their needs) interpretation of the result.
- Criterion P (counterproductive behaviour by local population): Local populations could report false information to receive attention – there are anecdotal reports of such behaviour elsewhere in the world in disadvantaged communities who feel they only get attention if the local volcano is doing something. To our knowledge this has not happened in the focus countries.

Indonesia

The evaluation for Indonesia was done by the VIP team based on knowledge gathered during the country visit.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
No monitoring											
D *(Resources)*											
Limited monitoring											
D *(Resources)*											
Monitored											
D *(Resources)*											
All monitored volcanoes											
G *(Instr. plan)*											
H *(Instr. vol. resil.)*											
I *(Instr. haz. resil.)*											
Future opportunities											
E *(5 year)*											
F *(Impl. cost)*											

[195] IAVCEI Subcommittee for Crisis Protocols (1999) Professional conduct of scientists during volcanic crises. Bulletin of Volcanology 60: 323-334. doi: 10.1007/PL00008908

Comments

- CVGHM operates independently from the government in terms of volcano monitoring data interpretation.
- A major challenge for Indonesia is the number of volcanoes in their jurisdiction. CVGHM has ranked volcanoes into three groups based on threat assessment, and prioritise instrumenting volcanoes at higher threat levels.
- Candidate trigger IV (earthquake): CVGHM can locate earthquakes at well monitored volcanoes (e.g., Merapi), and at other volcanoes if magnitude large enough to be picked up as part of the national network.
- Candidate trigger V (RSAM): CVGHM automatically computes RSAM for one station at each of the most active volcanoes.
- Candidate trigger VI (gas): CVGHM has gas monitoring at some volcanoes (e.g., Merapi).
- Criterion G (instrument replacement): CVGHM has enough resources to source instrument replacements without relying on donors.
- Criterion I (instrument resilience to non-volcanic hazards): Earthquakes and tsunami can damage volcano monitoring instrumentation and networks.
- Future opportunities:
    - Candidate triggers IV and V (earthquakes, RSAM): The main obstacle is not cost in this case but rather data availability outside the observatory. Providing data in real-time would require major changes in how CVGHM operates, and development and maintenance of the service.
    - Candidate trigger VI (gas): The huge number of volcanoes make it unlikely and unplanned that there would be gas monitoring at all volcanoes within the next 5 years. The cost is estimated as moderate.
    - Candidate triggers VII, VIII, and IX (satellite remote sensing triggers): Cost here relates to creation of positions and training needed to undertake analysis at CVGHM. It is difficult to estimate how hard it is for CVGHM to create new positions.
    - The evaluation is not based on detailed costing, but rather judgment. A designation of moderate (orange) indicates there is more effort involved than minor (green).

Papua New Guinea

The evaluation for Papua New Guinea for criteria D, E, and F was done at the workshop on 19 October by the representative from RVO in partnership with the consortium. The remainder were done by the VIP team based on knowledge gathered during the country visit.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
No monitoring											
D *(Resources)*											
Limited monitoring - open system volcanoes											
D *(Resources)*											
Limited monitoring - closed system volcanoes											
D *(Resources)*											
Rabaul											
D *(Resources)*											
All monitored volcanoes											
G *(Instr. plan)*											
H *(Instr. vol. resil.)*											
I *(Instr. haz. resil.)*											
Future opportunities											
E *(5 year)*											
F *(Impl. cost)*											

Comments

- RVO operates independently from the government in terms of volcano monitoring data interpretation. However, RVO does not officially set the VAL – it advises the government on what the level should be. To date the government has always followed RVO's assessment in setting the VAL.
- Candidate trigger II (Volcano Alert Level):
    - It is unclear whether unmonitored volcanoes have a generic VAL system, as VALs are tailored to individual volcanoes. However, VAL systems for open system volcanoes are broadly similar, and VAL systems for closed system volcanoes are broadly similar. All VAL systems are a 1 to 4 scale.
    - RVO makes recommendations to the government as to what the VAL should be, but it is not the official decision maker (see Annexe 2). In practice the government follows RVO's recommendations.
- Candidate triggers X and XI (eruption of volcanic ash, increase of volcanic hazard extent): There are several volcanoes that are often continuously erupting. At these volcanoes, local observers would rapidly notify RVO if there is an increase in the intensity or severity of eruptions.
- Criterion G (instrument replacement): RVO is a resourceful observatory, but unfortunately, they do not have the financial support required to replace instruments as they fail. Monitoring equipment has been vandalised in the past – solar panels are an attractive resource.
- Future opportunities:
    - Candidate triggers I, X, and XI (visual, ash, and hazards): Webcams are desired, and the implementation cost is considered moderate.

- Candidate triggers IV and V (earthquakes and RSAM): RVO estimates that 2-3 more volcanoes still require instrumentation, although this number may be greater if all Holocene volcanoes are considered. The implementation cost is considered major.
- Candidate trigger VI (gas): One more volcano could feasibly be instrumented in the next five years, although the instrumentation cost is considered major.
- Candidate triggers VII, VIII, and IX (satellite remote sensing triggers): These would necessitate major implementation costs if the analysis was to be done by RVO.

Philippines

The evaluation for the Philippines was done by the VIP team based on knowledge gathered during the country visit.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
No monitoring											
D *(Resources)*											
Limited monitoring											
D *(Resources)*											
Monitored											
D *(Resources)*											
All monitored volcanoes											
G *(Instr. plan)*											
H *(Instr. vol. resil.)*											
I *(Instr. haz. resil.)*											
Future opportunities											
E *(5 year)*											
F *(Impl. cost)*											

Comments

- PHIVOLCS operates independently from the government in terms of volcano monitoring data interpretation.
- Candidate trigger IV (earthquake): PHIVOLCS can locate earthquakes at well monitored volcanoes (e.g., Taal), and at other volcanoes if magnitude large enough to be picked up as part of the national network.
- Candidate trigger V (RSAM): PHIVOLCS computes RSAM for a subset of volcanoes, and is deemed useful even at closed system volcanoes (e.g., Pinatubo 1991).
- Candidate trigger VI (gas): PHIVOLCS has gas monitoring at some volcanoes (e.g., Taal).
- Criterion G (instrument replacement): PHIVOLCS has enough resources to source instrument replacements without relying on donors.

- Criterion I (instrument resilience to non-volcanic hazards): Cyclones and earthquakes can damage volcano monitoring instrumentation and networks.
- Future opportunities:
  - Candidate triggers IV and V (earthquakes, RSAM): The main obstacle is not cost in this case but rather data availability outside the observatory. Providing data in real-time would require major changes in how PHIVOLCS operates, and development and maintenance of the service.
  - Candidate triggers VII, VIII, and IX (satellite remote sensing triggers): Cost here relates to creation of positions and training needed to undertake analysis at PHIVOLCS. It is difficult to estimate how hard it is for PHIVOLCS to create new positions.
  - The evaluation is not based on detailed costing, but rather judgment. A designation of moderate (orange) indicates there is more effort involved than minor (green).

Tonga

The evaluation for Tonga was done at the workshop on 19 October by the representative from TGS in partnership with the consortium. Criteria E and F were not evaluated for candidate triggers I, III or VII by the TGS representative, and so were done by the VIP team based on knowledge gathered during the country visit. When considering future opportunities, the TGS representative did not want to designate anything 'effectively impossible' and so that is not assigned here.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
Terrestrial (all islands)											
D *(Resources)*	[green]	[black]	[green]	[black]	[black]	[black]	[green]	[green]	[green]	[black]	[black]
Submarine											
D *(Resources)*	[green]	[black]	[black]	[black]	[black]	[black]	[black]	[black]	[black]	[black]	[black]
Future opportunities											
E *(5 year)*	[orange]	[orange]	[diagonal line]	[red]	[orange]	[red]	[diagonal line]	[diagonal line]	[diagonal line]	[diagonal line]	[diagonal line]
F *(Impl. cost)*	[green]	[orange]	[diagonal line]	[red]	[green]	[orange]	[orange]	[orange]	[orange]	[diagonal line]	[diagonal line]

Comments

- TGS and Tonga has little experience with monitoring and managing volcanic crises, and to date has relied on international partners to provide expert advice.
- Candidate trigger II (Volcano Alert Level): Tonga does not have a VAL system.
- Candidate triggers IV and V (earthquakes, RSAM): The national seismic network is inappropriate for detecting volcanic unrest, and there is no other ground-based instrumentation nationally.

- Criterion D for submarine (current resources): It is very challenging to monitor submarine volcanoes; monitoring generally is only possible once the eruption is underway (if it reaches the surface).
- Future opportunities:
  - Candidate trigger II (Volcano Alert Level): While there are no instrumental costs required to develop a VAL system, global experience shows it takes 1-3 years to develop a fit-for-purpose VAL system for a country, and resources are required to socialise it, provide training to those assigning it, and implementing it into the national framework.
  - Candidate triggers IV and V (earthquakes, RSAM): Tonga is upgrading its national seismic network within the next few years, but it will not have the capability to locate earthquakes underneath specific volcanoes. However, with training RSAM can be computed using the upgraded network.
  - Candidate trigger VI (gas): The major barrier is acquiring enough instruments for monitoring, and capacity building for data processing and interpretation.
  - Candidate triggers VI, VII, and VIII (satellite remote sensing triggers): These would necessitate major implementation costs if the analysis was to be done by TGS.
  - TGS is planning on acquiring a drone, which would provide the ability make visual observations and detect deformation, the latter through repeat flights using Structure-from-Motion data processing to create high precision digital elevation models. The training costs are deemed minor.

Vanuatu

The evaluation for Vanuatu for criterion D was done at the workshop on 19 October by the representative from VMGD in partnership with the consortium. The remainder were done by the VIP team based on knowledge gained from working in close partnership with VMGD over the past 6 years.

Trigger → **Criterion ↓**	**I** *Vis*	**II** *VAL*	**III** *VAA*	**IV** *EQ*	**V** *RSAM*	**VI** *Gas*	**VII** *EO Gas*	**VIII** *EO Ther.*	**IX** *EO Def.*	**X** *Ash*	**XI** *Haz.*
No monitoring											
D *(Resources)*											
Monitored											
D *(Resources)*											
G *(Instr. plan)*											
H *(Instr. vol. resil.)*											
I *(Instr. haz. resil.)*											
Future opportunities											
E *(5 year)*											
F *(Impl. cost)*											

Comments

- VMGD is independent from the government at low levels of unrest. Government pressure may intensify as unrest, uncertainty, and eruptive activity increases.
- Candidate triggers X and XI (eruption of volcanic ash, increase of volcanic hazard extent): There are several volcanoes that are often continuously erupting. However, observations are linked to other actions (such as setting VAL), and so VMGD felt these are too closely linked to other candidate triggers to be independent triggers.
- Candidate triggers VII and VIII (gas and thermal satellite remote sensing triggers): VMGD monitors processed freely available products.
- Candidate trigger XI (deformation satellite remote sensing trigger): VMGD relies on GNS Science, New Zealand, for the processing and interpretation of InSAR imagery. This is undertaken on request rather than in a routine manner.
- Criterion D for unmonitored volcanoes (current resources):
  - Candidate trigger I (visual): VMGD currently advises community leaders on what to look out for.
  - Candidate trigger II (Volcano Alert Level): At unmonitored volcanoes, the VAL is set based on visual observations by VMGD volcanologists, and so requires resources to visit the volcano.
  - Candidate trigger III (Volcanic Ash Advisories issued by a Volcanic Ash Advisory Centre): The Wellington VAAC calls VMGD to check the situation on the ground before they issue a VAA. There is good communication between the Wellington VAAC and VMGD. VAAs can be false alarms (false positives).
  - Candidate trigger IV (earthquakes): Seismicity near dormant volcanoes (i.e., no record of historic activity) is not investigated – reports of unusual visual activity prompts investigation. However, if an earthquake happens near a historically active volcano there will be an investigation even without reports of unusual activity.
  - In general, if there is activity, extra monitoring resources are deployed.
- Criterion D for monitored volcanoes (current resources):
  - Candidate trigger I (visual): If unusual activity is reported by the community, VMGD generally investigates, and request for additional monitoring instrumentation.
  - Candidate trigger II (Volcano Alert Level): The VAL system works well.
  - Candidate trigger III (Volcanic Ash Advisories issued by a Volcanic Ash Advisory Centre): In general, a VAA is issued by the Wellington VAAC after one of the other candidate triggers has occurred. A VAA can be viewed as a confirmation of change.
  - Candidate trigger V (RSAM): At some volcanoes RSAM can be used as eruption confirmation. However, it is challenging to determine in advance what the specific RSAM value will be – it's interpreted in context.
  - In general, if there is activity, extra monitoring resources are deployed.
- Criterion I (instrument resilience to non-volcanic hazards): Cyclone Pam destroyed volcano monitoring instrumentation.
- Future opportunities:

- Candidate triggers VI, VII, VIII, and IX (gas, satellite remote sensing triggers): Cost here relates to creation of positions and training needed to undertake analysis at VMGD.
- Candidate triggers IV and V (earthquakes, RSAM): A pool of deployable equipment (e.g., 3 seismometers and telemetry kit for cell phone towers) would be greatly beneficial.
- The Vanuatu – PNG – Tonga seismic network provides opportunities for capacity building and networking of staff.

Evacuation assistance

We first consider the case of a generic very well-monitored volcano by international standards to evaluate the candidate triggers in an ideal situation (Criteria A-C). We next evaluate the candidate indices given the realities in each focus country (Criterion D), subdividing as appropriate for the local context.

We provide comments on select evaluations after each table. We will consider future opportunities for each country in the comment section.

As the instrumental and other monitoring data, if any, used in these triggers are the same as for enhanced monitoring candidate triggers, refer to the enhanced monitoring trigger evaluation for index resilience (Criteria G-I) and future opportunities (Criteria E and F).

Generic very-well monitored volcano

In the table below, we evaluate the candidate indices for a generic very-well monitored volcano. We note it is nearly impossible in retrospect to honestly evaluate 'the volcano didn't erupt, and so we should not have evacuated', as volcanoes are highly complex and change trajectories often.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
A *(Physically possible)*									
B *(False positive)*									
C *(False negative)*									

Comments

- Candidate trigger XIII (evacuation called): An evacuation call has very different financial implications for the movement of people if they are evacuating via land routes or if it is an evacuation of an entire island.
- Candidate trigger XV (evacuation occurred): This trigger necessitates that an evacuation has already occurred.
- Candidate trigger XVI (fatality): While deaths do occur within evacuated or exclusion zones, many successful and necessary evacuations do not have fatality associated with them. However, a

fatality can prompt the population to take the evacuation more seriously, or can prompt local authorities to extend the evacuated area.

- Candidate trigger XVIII (Volcano Unrest Index): The VUI is not used operationally anywhere in the world. It was developed in New Zealand for caldera systems, and faced considerable resistance by the New Zealand volcano monitoring team when there was an attempt to assign thresholds at other New Zealand volcanoes. Thresholds are best set using a comprehensive data-rich record covering the span of expected activity, a record that is unavailable at most volcanoes.
- Candidate trigger XIX (volcano observatory probabilistic forecast): Most volcano observatories do not routinely issue numerically precise forecasts of future activity.
- Candidate trigger XX (Bayesian Event Tree forecast): Few volcanoes globally have tested and validated BET forecasts.

Objectivity and ethical considerations

Each focus country has different political and governing arrangements, and different challenges. We evaluate objectivity and ethical considerations broadly and explain the rationale in the comments. These are not universal statements and may be different in individual jurisdictions. We will comment on the independence of the observatories in the country sections.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
Objectivity									
J *(Objective)*									
Ethical considerations									
M *(Sovereignty)*									
N *(Undercut by PH)*									
O *(Undercut UW)*									
P *(Counter. local)*									
Q *(Counter. gov.)*									
R *(Counter. other)*									

Comments

- Criterion J (objectivity):
  - Candidate trigger XVII (Volcano Alert Level) is not designated following a formula but rather relies on the interpretation, expert judgement, and synthesis of all the available data at the time the VAL is issued.
  - Candidate triggers XVIII (Volcano Unrest Index) requires many different thresholds to be set in advance. This would most likely rely on subjective expert judgement, at the record isn't long enough for statistical designation.

  - Candidate trigger XIX (volcano observatory probabilistic forecast): In the instances that an observatory has issued a probabilistic statement, the forecasts generally depend on event trees populated using expert judgement.
- Criterion M (sovereignty): Candidate trigger XX (Bayesian Event Tree forecast) would be issued or determined by an independent. If these are used as a sole trigger, they could be in breach of the IAVCEI guidelines for professional interaction during volcanic crises[196] by which volcano observatories and their partners abide by.
- Criteria N and Q (undercut by policy holder, counterproductive behaviour by government):
  - Candidate triggers XII, XIII, XV (State of Emergency, official evacuations): Globally, there have been instances where evacuations have been called to remove a problematic community from its local. However, this is deemed unlikely, as it would be extremely controversial if revealed, and could have diplomatic repercussions.
  - Candidate trigger XVI (reported fatality): It is unlikely that a government would *only* take evacuative actions if there was a fatality rather than undertake preventative measures beforehand if a situation is serious enough.
  - Candidate trigger XVIII (Volcano Alert Level): In tense situations, governments sometimes exert pressure on a volcano observatory to designate a high VAL, often to justify their actions. How likely this is will depend on the independence of the volcano observatory.
- Criterion O (undercut by policy holder): Unless very clearly defined, a policy holder could dispute the legitimacy of a called evacuation (candidate trigger XIII) or a volcano observatory forecast (candidate trigger XVIII), or dispute reports of self-evacuations (candidate trigger XIV) or fatalities (candidate trigger XVI).
- Criterion P (counterproductive behaviour by local population): A local population could self-evacuate if they thought it would mean they would receive lots of money, but this is considered extremely unlikely as evacuation is generally not supported unless necessary, and the population may not believe they would get any money the central government has received.

Indonesia

The evaluation for Indonesia was done by the VIP team based on knowledge gathered during the country visit.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
No monitoring									
D *(Resources)*									
Limited monitoring									
D *(Resources)*									
Monitoring									
D *(Resources)*									

[196] IAVCEI Subcommittee for Crisis Protocols (1999) Professional conduct of scientists during volcanic crises. Bulletin of Volcanology, 60: 323-334.

Comments

- Candidate trigger XV (evacuation occurred): Indonesia has successfully evacuated tens of thousands of people in a short amount of time many times in the last several decades.
- Candidate trigger XVII (Volcano Alert Level): In Indonesia, evacuation decisions are hardwired into the VAL system. These decisions are made in advance with authorities in charge of evacuations.
- Candidate triggers XVIII, XIX, XX (Volcano Unrest Level, volcano observatory forecast, Bayesian Event Tree forecast): At volcanoes with no monitoring, this is currently effectively impossible at monitoring data streams and an appreciation of past activity is required for these to be credible products.
- Candidate trigger XIX (volcano observatory forecast): Indonesia has utilised a Bayesian Event Tree approach to manage volcanic crisis, including the well-documented example of Sinabung – a volcano with limited monitoring[197]. The BET framework evolved over the course of the crisis and was not fixed beforehand. We are not aware of the outcomes of the BETs being formally published during a crisis.
- Future opportunities
  - Candidate triggers XVIII, XIX, XX (Volcano Unrest Level, volcano observatory forecast, Bayesian Event Tree forecast): Increasing the number of monitored volcanoes, increasing the diversity of monitoring methods, increasing the longevity of monitoring baseline data, and improving knowledge of the historical and geological eruptive record through scientific studies will make the development of tools like BETs and possibly VUI more likely.

Papua New Guinea

The evaluation for Papua New Guinea was done by the VIP team based on knowledge gathered during the country visit.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
No monitoring - island									
D *(Resources)*									
No monitoring - terrestrial									
D *(Resources)*									
Limited monitoring – open vent system									
D *(Resources)*									
Limited monitoring – closed vent system									
D *(Resources)*									
Rabaul									
D *(Resources)*									

[197] Wright, H.M.N., Pallister, J.S., McCausland, W.A., Griswold, J.P., Andreastuti, S., Budianto, A., Primulyana, S., Gunawan, H., 2013 VDAP team & CVGHM event tree team (in press) Construction of probabilistic event trees for eruption forecasting at Sinabung volcano, Indonesia 2013–14. Journal of Volcanology and Geothermal Research.

Comments

- Candidate trigger XV (evacuation occurred): This trigger is possible, but is not helpful in the case of island evacuations, regardless of volcano type. It is expensive to evacuate islands.
- Future opportunities
  - Candidate triggers XVIII, XIX, XX (Volcano Unrest Level, volcano observatory forecast, Bayesian Event Tree forecast): Increasing the number of monitored volcanoes, increasing the diversity of monitoring methods, increasing the longevity of monitoring baseline data, and improving knowledge of the historical and geological eruptive record through scientific studies will make the development of tools like BETs and possibly VUI more likely.

Philippines

The evaluation for the Philippines was done by the VIP team based on knowledge gathered during the country visit.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
No monitoring									
D *(Resources)*									
Limited monitoring									
D *(Resources)*									
Monitoring									
D *(Resources)*									

Comments

- Candidate trigger XVII (Volcano Alert Level): In the Philippines, evacuation decisions are hardwired into the VAL system. These decisions are made in advance with authorities in charge of evacuations, and are customised for each volcano based on past and anticipated volcanic activity.
- Future opportunities
  - Candidate triggers XVIII, XIX, XX (Volcano Unrest Level, volcano observatory forecast, Bayesian Event Tree forecast): Increasing the number of monitored volcanoes, increasing the diversity of monitoring methods, increasing the longevity of monitoring baseline data, and improving knowledge of the historical and geological eruptive record through scientific studies will make the development of tools like BETs and possibly VUI more likely.

Tonga

The evaluation for Tonga was done at the workshop on 19 October by the representative from TGS in partnership with the consortium.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
No monitoring - island									
D *(Resources)*									
No monitoring - submarine									
D *(Resources)*									

Comments

- Candidate trigger XV (evacuation occurred): This trigger is possible, but is not helpful in the case of island evacuations. It is expensive to evacuate islands.
- Candidate trigger XVII (Volcano Alert Level): Tonga does not have a VAL system.
- Future opportunities
  - Candidate trigger XVII (Volcano Alert Level): While there are no instrumental costs required to develop a VAL system, global experience shows it takes 1-3 years to develop a fit-for-purpose VAL system for a country, and resources are required to socialise it, provide training to those assigning it, and implementing it into the national framework.
  - There is little understanding of past eruptive volcanic activity in Tonga. Geological studies would greatly advance knowledge of volcanic activity and help with interpreting data in future responses.

Vanuatu

The evaluation for Vanuatu was done by the VIP team based on knowledge gained from working in close partnership with VMGD over the past 6 years.

Trigger → **Criterion ↓**	**XII** *SOE*	**XIII** *Evac. called*	**XIV** *Self-evac.*	**XV** *Evac. occ.*	**XVI** *Fat.*	**XVII** *VAL*	**XVIII** *VUI*	**XIX** *VO fore.*	**XX** *BET fore.*
No monitoring - terrestrial									
D *(Resources)*									
No monitoring - island									
D *(Resources)*									
Monitoring – terrestrial									
D *(Resources)*									
Monitoring – island									
D *(Resources)*									

Comments

- Candidate trigger XV (evacuation occurred): This trigger is possible but is not helpful in the case of island evacuations. It is expensive to evacuate islands.
- Candidate trigger XV (evacuation occurred): Small scale on-island evacuations (for example, evacuating people from one part of Ambrym to another) that do not involve evacuation of the island may be more appropriate considered terrestrial evacuations.
- Future opportunities
  - Candidate triggers XVIII, XIX, XX (Volcano Unrest Level, volcano observatory forecast, Bayesian Event Tree forecast): Increasing the number of monitored volcanoes, increasing the diversity of monitoring methods, increasing the longevity of monitoring baseline data, and improving knowledge of the historical and geological eruptive record through scientific studies will make the development of tools like BETs and possibly VUI more likely.

A3.4 Reference page: Evaluation criteria

Trigger performance assuming world-class monitoring

A. Given local volcanic and environmental factors, is the trigger possible for the volcano? *(Yes, Unlikely, No)*
B. What is the likelihood of false positives? *(Likely, Unlikely, Extremely unlikely)*
C. What is the likelihood of false negatives? *(Likely, Unlikely, Extremely unlikely)*

Current resources

D. Given available human, physical and/or institutional resources, is the trigger possible for the volcano *(Yes, Unlikely, No)*

Future opportunities

E. If the trigger is currently not possible given human, physical and/or institutional resources, what is the likelihood of it being possible within the next 5 years? *(Planned and likely, Unplanned but possible, Unplanned and unlikely, Effective impossible)*
F. If the trigger is currently not possible given human, physical and/or institutional resources, what would the cost of implementation be? *(Minor, Moderate, Major, Effectively impossible)*

Trigger resilience

G. If the trigger relies on an instrument(s), does the instrument(s) have reasonable and credible long-term maintenance plans and provisions in place should the instrument fail? *(Yes, No)*
H. If the trigger relies on an instrument(s), how resilient is the instrument(s) to volcanic activity? *(Resilient to all volcanic activity, Vulnerable in major eruption, Vulnerable in minor eruption)*
I. If the trigger relies on an instrument(s), how resilient is the instrument(s) to non-volcanic natural and societal hazards, including but not limited to earthquakes, tsunami, landslides, flooding, and vandalism? *(Resilient, Somewhat vulnerable, Vulnerable)*

Objectivity

J. How objective is the unrest trigger? *(Entirely subjective, Mixed subjective and objective, Entirely objective)*
K. If the trigger depends on a volcano observatory, how independent is the volcano observatory from the policy holder? *(Controlled by policy holder, Independent during low level of activity but controlled during high levels of activity, Independent of policy holder)*
L. If the trigger is independent of a volcano observatory, how independent is the index? *(Dependent on subjective judgement of policy holder, Dependent on objective data controlled by policy holder, Independent of sovereign control)*

Ethical considerations

M. Can the trigger infringe on sovereignty? *(Major concern, Minor concern, Unlikely)*
N. Can the trigger be compromised or undercut by the policy holder? *(Major concern, Minor concern, Unlikely)*
O. Can the trigger be compromised or undercut by the policy underwriter? *(Major concern, Minor concern, Unlikely)*
P. Can the trigger lead to counterproductive behaviour that would negatively impact the local population? *(Major concern, Minor concern, Unlikely)*
Q. Can the trigger lead to counterproductive behaviour that would negatively impact the government? *(Major concern, Minor concern, Unlikely)*
R. Can the trigger lead to counterproductive behaviour that would negatively impact other actors? *(Major concern, Minor concern, Unlikely)*

A slash indicates the question is not relevant.

A3.5 Reference page: Candidate triggers

Enhanced preparedness

Aim: Trigger payment in the early stages of volcanic unrest to increase monitoring capabilities and community preparedness. At frequently erupting volcanoes an escalation of volcanic activity can prompt the need of additional monitoring. This early injection of financing will decrease future scientific uncertainty and will help the community understand the situation, assisting further decision making.

Assistance with*:* Monitoring capabilities, include new instrumentation, additional personnel, helicopter or aircraft surveillance, and/or campaign data collection, and community preparedness measures.

Candidate triggers: Below we list candidate triggers that we will evaluate in the next sections. '*XX*' are values that would have be determined for the individual or group of volcanoes (e.g., volcanoes with no/limited/adequate instrumental monitoring, open vs closed system volcanoes).

I. Confirmation of visual observation of unusual activity
II. Increase from background to unrest VAL
III. Issuance of VAA from regional responsible VAAC
IV. *XX* earthquakes above *XX* magnitude within *XX* hours/days
V. RSAM above *XX* over *XX* hour/days at *XX* seismometer(s) within *XX* km of vent
VI. Ground-based detection of SO_2 or CO_2 gas above *XX* tons/day
VII. EO detection of SO_2 or CO_2 gas above *XX* tons/day
VIII. EO detection of thermal anomaly of *XX* degrees above XX over *XX* m^2
IX. EO detection of deformation of at least *XX* mm over *XX* km^2
X. Eruption of volcanic ash
XI. Increase of *XX%* of plume height, PDC runout or lava flow extent compared to that of the last *XX* years.

Evacuation support

Aim: Trigger payment to assist with pre-eruption evacuation in the interest of life-safety. This may be days, weeks, months, or even years into an eruption sequence, or before any eruptive products have reached the surface.

Assistance with*:* Evacuation support.

Candidate triggers: Below we list candidate triggers that we will evaluate in the next sections. '*XX*' are values that would have be determined for the individual or group of volcanoes (e.g., volcanoes with no/limited/adequate instrumental monitoring, open vs closed system volcanoes, mainland or island volcanoes).

XII. Declaration of a State of Emergency
XIII. Official evacuation of *XX* people called
XIV. Self-evacuation of *XX* people has occurred
XV. Official evacuation of *XX* people has occurred
XVI. Confirmed fatality outside of evacuated / limited access zone
XVII. VAL increase to *XX* level
XVIII. VUI increase to *XX* level
XIX. Volcano observatory information release forecasts with a likelihood of at last *XX*% an eruption of *XX* size within the next *XX* hours/days
XX. BET evaluation forecasts a likelihood of at last XX% an eruption of XX size within the next XX hours/days

Annexe 4: Underwriting model

The underwriting model comprises one data input file covering all five focus countries, and individual model files for each country. The model files require the monte carlo simulation software programme ‘@Risk’ to function as designed; relatively minor adjustments can be made to accommodate other monte carlo simulation software.

All files have a ‘Notes’ tab which provides detailed information on each of the other tabs in each file. These notes are repeated below, with the addition of a short narrative description where appropriate to provide greater information about the overall modelling approach and data sources.

Data Input File

VIP_UnrestProductModel_PrepData_181220.xlsx

The following table reproduces the ‘Notes’ tab in the above-referenced file. As described in the main text, assumptions have been made in order to demonstrate how the model works and to provide some quantification of the risk.

The ‘structuring inputs’ described in #1 below have been estimated based on the project team’s knowledge and information gathered during the project, but not in consultation with any officials from the five focus countries. Under ‘live’ conditions, these selections would be made by the client country as part of the policy customisation.

The probability fields have been estimated **FOR ILLUSTRATIVE PURPOSES ONLY**. The main text provides substantial discussion on the issue of assigning probabilities to VAL movements and evacuation calls, given the short historical record, impossibility of modelling and subjective nature of the indices. Specific notes on our approach in the delivered dataset are provided below:

- VAL movement probabilities are unconstrained, but have been set at levels which we feel appropriate for illustrative purposes and to contribute to initial quantification of risk profiles for the potential coverage.
- Total evacuation probabilities at the country level are constrained by the historical data, which we treat as effectively complete for the past 50 years (noting that we have used older data for Tonga which has had no evacuations in the past 50 years). There is no valid guidance for assigning probabilities at the individual volcano level, so we have assigned the same probabilities for many volcanoes and only deviate from the ‘default’ values where we have specific information of relatively higher, or lower, unrest potential. The ‘default’ probabilities were established such that the overall probability of evacuation for a given country in the model matched the historical rate, and any adjustments to those defaults had to balance out such that the overall probability remained the same.

1	**Structuring Input (these will be selected by the client country during coverage structuring)**
1a	Columns B-E are derived from the 'VolDat_***' tab for each country, see descriptions below
1b	Early Trigger Pay-out Amount - 'Fixed' or 'Variable' - selection of whether the amount of the early trigger pay-out amount is a fixed dollar amount or an amount varying with PEI of the volcano at which the trigger occurs
1c	Early Trigger Pay-out Amount Scalar - percentage of the full 'main trigger' amount for that volcano that will be paid out for an early VAL movement trigger, if 'Variable' is selected in 1b
1d	Fixed Early Trigger Pay-out Amount - the fixed amount of the early VAL movement trigger pay-out, if 'Fixed' is selected in 1b
1e	Higher Evac Cost Multiplier - this is the multiplier for high-cost evacuations, and is expressed as an additional percentage of a normal evacuation pay-out at that volcano that would be paid for an evacuation call trigger - for those volcanoes which are flagged as having high evacuation costs in 4a
1f	Dollar Value per PEI Unit - this is the conversion from PEI units to pay-out amount for an evacuation call, in USD. Core assumption is that there is a 1:1 relationship between evacuation size and PEI for a 'full' evacuation, meaning that the dollar value per PEI unit is effectively the per-person cost of evacuation
1g	Coverage Limit - this is the total amount that the policy will pay in any one policy period. Ultimately this will be selected by a client country, but notes on assumptions for modelling purposes are provided
1h	Deductible - this is the total amount of calculated pay-outs which are retained by the insured. Ultimately this will be selected by a client country, but notes on assumptions for modelling purposes are provided. A deductible is not necessary but is usual
VolDat_* **	Tab for each of the five focus countries
2	**PEI**
2a	PEI is from the VIP database as per current version. RoundedPEI is PEI rounded up to the nearest 1,000
2b	High PEI flag is for volcanoes with higher than 1 SD above the average PEI for that country. This is used as a means of selecting volcanoes which require special attention due to their 'severity' impact on the risk profiling
3	**High evacuation and / or unrest rates**
3a	Volcanoes in the Case Study list are selected for special attention as these were identified as having high unrest and / or evacuation rates and therefore have a high 'frequency' impact on risk profiling
4	**High Evacuation Cost Status**
4a	Flagged volcanoes are moved out of the main group and receive specific attention as they attract the Higher Evac Cost Multiplier and therefore have high 'severity' impact on the risk profiling
5	**VAL Status**
5a	Flagged volcanoes have non-background VAL and are treated separately for analytical purposes
5b	Source of current VAL information:

	Indonesia: https://magma.vsi.esdm.go.id/ (as of 14-Nov-18, 2130UTC). Note: "Bromo" on the map on this website refers to Tengger Caldera in the VOTW catalogue; "Rokatendu" refers to Paluweh; and "ili Lewotolok" refers to Lewotolo
	PNG: No current information available publicly
	Philippines: https://www.phivolcs.dost.gov.ph/index.php/volcano-hazard/volcano-bulletins3 (as of 14-Nov-18, 2200UTC). It is presumed that bulletins are being issued for all volcanoes which are or have recently been above background level of activity - all bulletins have alert level stated. Note that the Bulusan bulletin states that as of 22 October 2018, the VAL there has reverted to 0 (No Alert, i.e. background)
	Tonga: No VAL system in place
	Vanuatu: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/current-volcanic-activity (as of 14-Nov-18, 2200UTC). It is presumed that bulletins on this site include all those volcanoes which are currently above background levels of activity. "Vanua Lava Volcano" refers to Suretamatai
6	**List construction**
6a	Column K lists the volcanoes which have non-background VAL, Column L lists any volcano that is otherwise flagged for special attention (but is NOT in Column K), and Column M lists all the remaining volcanoes (the "Main Group")
6b	Column O is cut/paste as values from Column K then sort alphabetically, and Column P brings in the PEI for the listed volcanoes. Columns R & S do the same for Column L volcanoes, and Columns U &V do the same for Column M volcanoes
6c	These column pairs are imported as values into the 'Probs_***' tab as described below
Probs_* **	Tab for each of the five focus countries
7	**Historical Notes**
7a	These historical notes are taken from the 'HistoricalData' tab and are included in each country tab for ease of reference. The description of this tab is as follows: This sheet contains data from the main project database on historical evacuation event rates, which can provide a constraint on probability estimation or evacuations at the national level. As noted in the Component 2 Technical Report, VAL movements are not routinely reported by VOs or any other national authorities - they are, to a variable and uncertain extent, captured within the Monthly Bulletin of the Smithsonian Institution's Global Volcanism Program, but sufficient resources will be required to extract that information on a systematic basis.
7b	Row 2 provides available historical information regarding unrest episodes, VAL movements, and current VAL status, to inform the estimation of probabilities for all relevant volcanoes for the early VAL movement trigger occurrence
7c	Row 3 provides available historical information regarding evacuations, to inform the estimation of probabilities for the main evacuation call trigger
8	**Summary**
8a	In rows 7-9, each of the probability estimates, Prob 1, Prob 2 and Prob 3 are summed for all volcanoes and then multiplied by the number of volcanoes to get the total number of triggers of each type expected for that country. Row 10 sums Prob 2 and Prob 3 to give the overall evacuation rate. Rows 7 and 10 can be compared with the equivalent rates deduced from history
9	**Probability assignment**
9a	For the purposes of assignment of probabilities (Prob 1, Prob 2 and Prob 3), the three groups of volcanoes listed in Columns O, R and U in the VolDat_*** tab are separated

9b	The Main Group is treated as one set, with the number of volcanoes in the group and the average PEI of the group listed and then all three probability assigned - this probability is for any individual volcano in the group, and will effectively be assigned to every volcano in the group during the risk profiling
9c	The second group comprises those volcanoes already in unrest - all are listed, with PEI and high evacuation cost flag, and each is assigned Prob 3 separately. This analysis preparation is for a policy formulation that does not allow for a volcano already in unrest (i.e. higher than background VAL) to have an early trigger, so Prob 1 and Prob 2 do not apply
9d	The third group comprises the other volcanoes which require special attention - all are listed, with PEI and high evacuation cost flag, and each is assigned all three probabilities separately
9e	Prob 2 is always a conditional probability, only applying if an upward VAL movement from background occurs first
9f	This sheet is used as the input dataset for each country for the risk profile modelling
10	**Pending issues**
10a	Partial evacuations' need to be defined as they will need to be recognised in the reporting of the evacuation call trigger, so that partial evacuations do not trigger the full pay-out (as we know the PEI to evacuation size relationship works only for 'full' evacuations). At present the probability assumption is for a full evacuation call only

Model files

*VIP_UnrestProductModel_***_181220.xlsx*

The following table reproduces the 'Notes' tab in the above-referenced files (the 'Notes' tab is the same in all versions). There is one model file for each country, and each contains both the model itself and the results for the last run completed; this last run is that from which the results are summarised and illustrated in the main text.

All model runs use 100,000 simulations. Exceedance probability curves are less and less smooth the fewer volcanoes there are in the country. This is a result of the binary nature of the triggers, and more simulations does not improve the smoothness of the EP curves.

The Indonesia model file should be used as a base as it has the most volcanoes in unrest and in the special attention group, and these required number of rows is easy to edit down, but hard to add back in.

1	**Input Data**
1a	For a given country, row 3 of the Input Data sheet is taken from the 'StructuringInput' tab of the 'PrepData' workbook
1b	The remainder of the data in the Input Data Sheet is taken from the relevant 'Probs_***' tab
1c	The number of rows in the 'In Unrest' and 'Individual Consideration' groups varies between countries and this and the 'Calcs' tab need to have rows added or removed in these two sections to function correctly
Calcs Tab	
2	**Trigger generator (columns C to E)**
2a	A random number generator is used at every volcano to capture the binary nature of triggers occurring, so if the random number is lower than the trigger probability threshold, a trigger occurs in that simulation for that volcano
2b	For the 'Main Group' of volcanoes, triggers are logged individually and then summed (see 'MainGroupSims' tab)
2c	This approach produces the variability in annual outcomes which results from independent binary triggers being aggregated
3	**Pay-out 1 - for VAL movement (Column F)**
3a	If InputData cell C3 is 'Variable' then calculation is [Trig1 * PEI * Early Trigger Pay-out Amount Scalar * Dollar Value per PEI Unit]
3b	If InputData cell C3 is 'Fixed' then calculation is [Trig1 * Fixed Early Trigger Pay-out Amount]
4	**Pay-out 2 - for evacuation call after VAL movement (Column G)**
4a	Calculation is [Trig2 * PEI * Dollar Value per PEI Unit] * [1 + (Higher Evac Cost Multiplier * Higher Evac Cost Flag)]
5	**Pay-out 3 - for evacuation at volcanoes already in unrest or where there is no prior unrest (Column H)**
5a	Calculation is [Trig3 * PEI * Dollar Value per PEI Unit] * [1 + (Higher Evac Cost Multiplier * Higher Evac Cost Flag)]
6	**Total pay-out (Column I)**
6a	Total pay-out for each simulated year is calculated for each volcano or group of volcanoes by summing the three pay-out types described in 3, 4 & 5 above. These totals are then aggregated to the country level (cell I4)
6b	Recalc of the sheet (F9) will change all the random numbers and therefore the pay-out amount. This workbook is set up to run monte-carlo simulations via the software @Risk, which effectively recalculates a large number of times and collates the results
6c	Cells I2 and I3 have functions which are used by @Risk when running monte carlo simulations
6d	Any #N/A values in column I must be edited out for the total to work
7	**Results**
7a	Using @Risk, 100,000 years of triggers is simulated to generate a representative range of annual outcomes in terms of total pay-out. Simulation runs can be increased, but Column F must be copied downwards to match the number of records in Column A

7b	Results from simulations are pasted into Column A and can be sorted largest first (not necessary for other calculations or plotting). These are gross results, also known as 'Ground-up Losses'
7c	Column F provide the annual results after application of the Deductible and Coverage Limit taken from the InputData tab (known as the net result)
7d	Cells K1:M14 provides as summary of the results suitable for use as a table of results
8	**EP Curves**
8a	Once results are in place for a simulation, two exceedance probability curves are produced, one for gross pay-outs and one for net pay-outs. Three versions are provided, the only difference being the range of return periods show on each (250yr, 1,000yr and 10,000yr)
9	**MainGroupSims**
9a	Columns B to D complete the allocation of trigger / no trigger to each of the individual volcanoes in the main group - they all use the same probability but as they have different random numbers, they each act independently for trigger purposes.
9b	The number of rows starting at row 5 needs to equal the number of volcanoes in the main group - rows should be added or deleted to achieve this
9c	Row 3 aggregates all the individual triggers to give the total number of each trigger for each simulation - which is then used in the 'Calcs' sheet to calculate the pay-out for that simulation for the main group
9d	Because triggers are random, we can use the average PEI for the main group to calculate pay-outs, rather then needing to do it for every volcano in the main group individually
9e	Checks are provided when using @Risk to ensure that the probabilities for both the group as a whole and for individual volcano(es) within the group are consistent between the input value and the set of simulations