Volcanic Unrest and Pre-eruptive Processes: A Hazard and Risk Perspective

J. Gottsmann, J.-C. Komorowski and J. Barclay

Abstract

Volcanic unrest is complex and capable of producing multiple hazards that can be triggered by a number of different subsurface processes. Scientific interpretations of unrest data aim to better understand (i) the processes behind unrest and their associated surface signals, (ii) their future spatio-temporal evolution and (iii) their significance as precursors for future eruptive phenomena. In a societal context, additional preparatory or contingency actions might be needed because relationships between and among individuals and social groups will be perturbed and even changed in the presence of significant uncertainty. Here we analyse some key examples from three international and multidisciplinary projects (VUELCO, CASAVA and STREVA) where issues around the limits of volcanic knowledge impact on volcanic risk governance. We provide an overview of the regional and global context of volcanic unrest and highlight scientific and societal challenges with a geographical emphasis on the Caribbean and Latin America. We investigate why the forecasting of volcanic unrest evolution and the exploitability of unrest signals to forecast future eruptive behaviour and framing of response protocols is

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challenging, especially during protracted unrest. We explore limitations of current approaches to decision-making and provide suggestions for how future improvements can be made in the framework of holistic volcanic unrest risk governance. We investigate potential benefits arising from improved communication, and framing of warnings around decision-making timescales and hazard levels.

Resumen

La agitación volcánica es compleja y capaz de generar múltiples peligros que pueden ser desencadenados por un número diferente de procesos subsuperficiales. Las interpretaciones científicas sobre datos de agitación volcánica tienen como objetivo el mejor entendimiento de (i) los procesos detrás de la agitación volcánica y sus señales superficiales asociadas, (ii) su evolución espacial-temporal y (iii) su significado como precursores de fenómenos eruptivos a futuro. Dentro de un contexto social, acciones adicionales preparatorias o de contingencia podrían ser requeridas debido a que las relaciones entre individuos y dentro de grupos sociales serán perturbadas e inclusive modificadas ante la presencia de incertidumbre significativa. Aquí nosotros analizamos algunos ejemplos clave a partir de tres proyectos internacionales y multidisciplinarios (VUELCO, CASAVA y STREVA) en los cuales las cuestiones alrededor de los límites del conocimiento volcánico tienen impacto en la gestión pública del riesgo volcánico. Proveemos una perspectiva general del contexto regional y global de la agitación volcánica y sobresaltamos retos científicos y sociales con énfasis geográfico en el Caribe y América Latina. Investigamos porqué el pronóstico de la evolución en la agitación volcánica y el aprovechamiento de señales de agitación volcánica para el pronóstico de comportamiento eruptivo a futuro y el enmarque de protocolos de respuesta es un reto, especialmente durante periodos de agitación prolongada (años a décadas) en los que algunos retos surgen desde la utilización de señales de agitación para pronosticar la evolución de agitación a largo plazo y sus eventuales consecuencias. Exploramos las limitantes de actuales enfoques para la toma de decisiones y proveemos sugerencias acerca de cómo pueden hacerse reformas a futuro dentro del marco holístico de gobernabilidad ante el riesgo de agitación volcánica. Investigamos los potenciales beneficios que surgen por comunicación mejorada, y delimitando alertas alrededor de escalas de tiempo para la toma de decisiones y los niveles de alerta. Proponemos la necesidad de la cooperación a través de las fronteras científicas tradicionales, una valoración más amplia del riesgo natural y una mayor interacción de los sectores interesados.

1 Introduction

Volcanic unrest is a complex multi-hazard phenomenon of volcanism. Although it is fair to assume that probably all volcanic eruptions are preceded by some form of unrest, the cause and effect relationship between subsurface processes and resulting unrest signals (geophysical or geochemical data recorded at the ground surface, phenomenological observations) is unclear and surrounded by uncertainty (e.g., Wright and Pierson 1992). Unrest may, or may not lead to eruption in the short-term (days to months). If an eruption were to ensue it may involve the eruption of magma or may be non-magmatic and mainly driven by expanding steam and hot water (hydrothermal fluids) (Table 1). These conundrums contribute significant uncertainty to short-term hazard assessment and forecasting of volcanic activity and have profound impact on the management of unrest crises (e.g., Marzocchi and Woo 2007).

While institutional and individual decision-making in response to this unrest should promote the efficient and effective mitigation or management of risk, informed decision-making

Table 1 Summary of processes contributing to unrest signals in space and time, possible outcomes and hazards/impact of unrest

Nature of processes	Processes	Signals	Hazards/Impact	Unrest Outcome
Magmatic	Magma and/or melt and/or volatile migration (input, loss or ascent from reservoir), chemical differentiation, thermal convection, thermal perturbation (heating or cooling), pore fluid migration reservoir rejuvenation, crystallization and other phase changes	Seismicity, ground deformation, changes in potential fields, changes in gas and/or ground water chemistry, changes in heat flux, changes in volatile flux	Ground deformation, shaking and rupture and associated infrastructure damage; water table level changes; toxic gas emissions, contamination of ground water, atmosphere and crops; edifice destabilization; toxic gas emissions	Waning and return to background activity; eruptive activity (magmatic and/or phreatic)
Tectonic/gravitational	Faulting, changes in local/regional stress fields, edifice gravitational spreading, crustal loading, pore fluid migration			Waning and return to background activity; eruptive activity (magmatic and/or phreatic)
Hydrothermal	Fluid migration, phase changes, changes in temperature and/or pressure, chemical changes, pore pressure variations, porosity and permeability changes (sealing), host-rock alteration			Waning and return to background activity; phreatic eruptive activity

Processes can act individually, in unison or in any combination is fundamentally dependent on the early and reliable identification of changes in the subsurface dynamics of a volcano and their "correct" assessment as precursors to an impending eruption. However, uncertainties in identifying the causative processes of unrest impact significantly on the ability to "correctly" forecast the short-term evolution of unrest.

When a volcano evolves from dormancy through a phase of unrest, scientific interpretations of data generated by this unrest relate to (i) the processes behind unrest and their associated surface signals, (ii) their potential future spatio-temporal evolution (i.e., hydrothermal vs. phreatic vs. magmatic processes and their intensity) and (iii) their significance as precursors for future eruptive phenomena. Scientific interpretations framed towards the governance of and social responses to the risk implicit in the potential onset of an eruption focus on: (i) understanding the epistemic (relating to the limits of existing knowledge) and aleatoric (relating to the intrinsic variability of natural processes) uncertainties surrounding these data and their impact on decision making and emergency management, (ii) the communication of these uncertainties to emergency managers and the citizens at risk, and (iii) understanding how best to manage evolving crises through the use of forecasted scenarios.

2 Motivation

The analysis presented in this chapter synthesises wider results and experiences gained in three major research consortia with focus on volcanic hazards and risks: (1) The VUELCO project, (2) the CASAVA project, and (3) the STREVA project.

The European Commission funded VUELCO project (2011–2015; "Volcanic unrest in Europe and Latin America: Phenomenology, eruption precursors, hazard forecast, and risk mitigation; www.vuelco.net) focused on multi-disciplinary research on the origin, nature and significance of volcanic unrest and pre-eruptive processes from the scientific contributions generated by collaboration of ten partners in Europe and Latin America. Dissecting the science of monitoring data from unrest periods at six target volcanoes in Italy (Campi Flegrei caldera), Spain (Tenerife), the West Indies (Montserrat), Mexico (Popocatepetl) and Ecuador (Cotopaxi) the consortium created strategies for (1) enhanced monitoring capacity and value, (2) mechanistic data interpretation and (3) identification of eruption precursors and (4) crises stakeholder interaction during unrest.

The CASAVA project (2010–2014; Agence nationale de la recherche, France; *Understanding and assessing volcanic hazards, scenarios, and risks in the Lesser Antilles—implications for decision-making, crisis management, and pragmatic development;* https://sites.google.com/site/casavaanr/, last accessed 11-10-2016) implemented an original strategy of multi-disciplinary fundamental research on the quantitative assessment of volcanic risk for the Lesser Antilles region with emphasis on Guadeloupe and Martinique. The aim of the project was to improve the capacity to anticipate and manage volcanic risks in order to reduce reactive 'repairing' post-crisis solutions and promote the emergence of a society of proactive volcanic risk prevention in case of a future eruption. Part of this was achieved via a forensic analysis of past crises, described here.

The STREVA Project (2012–2018 funded by the UK Natural Environment and Economic and Social Research Councils; www.streva.ac.uk) was designed as a large interdisciplinary project to develop new means to understand how volcanic risk should be assessed and framed. It uses the 'forensic' interdisciplinary analysis of past volcanic eruptions in four settings to understand the key drivers of volcanic risk. The aim is to use this analysis to generate future plans that will reduce the negative consequences of future eruptions on populations and their assets. STREVA works closely with partners in the Caribbean, Ecuador and Colombia, focussing the forensic analysis on long-lived eruptions of Soufrière Hills Volcano (Montserrat) and Tungurahua (Ecuador) and shorter duration eruptions of La Soufrière (St. Vincent) and Nevado del Ruiz (Colombia). The focus of the 'forensic analysis' process in the STREVA project has been to understand the key drivers of risk and resilience during long-lived volcanic crises. Nonetheless the analysis of the initial phases of activity from these eruptions provide some insights into the acute uncertainties of unrest and the social, political and scientific consequences of that uncertainty.

3 Volcanic Unrest: Scientific and Social Context

Volcanic unrest can be defined in a scientific context: "The deviation from the background or baseline behaviour of a volcano towards a behaviour or state which is a cause for concern in the short-term (hours to few months) because it might prelude an eruption" (Phillipson et al. 2013). The term "eruption" in the context of a possible unrest outcome could either relate to a magmatic or non-magmatic (phreatic or hydrothermal) origin including the possible evolution from phreatic to magmatic activity or an alternation or mix between the two (e.g., Rouwet et al. 2014). In a social context, these concerns might necessitate additional preparatory or contingency actions in response to the unrest phenomena or the preparation for an eruption given that the organisation and preparedness of communities and those who manage them will be perturbed and even changed in the context of significant uncertainty (Barclay et al. 2008 and next section).

4 Challenges and Key Questions Relating to Volcanic Unrest

4.1 Wider Perspective

Whether or not unrest results in eruption, either of magmatic or non-magmatic origin, and whether (in hindsight) "correct" or "false" forecasts are issued to suggest there could be an imminent eruption are among the central questions that need answering as soon as unrest is detected.

The cost of scientific uncertainty regarding the causes and outcome of volcanic unrest may be substantial not only in terms of direct or indirect financial implications such as explored in Sect. 5, but also regarding knock-on (secondary) effects such as public trust in the accuracy or inaccuracy of scientific knowledge, public perception of the relationships between signals of unrest and volcanic risk and future public compliance with orders to evacuate or improve preparedness in the medium to long term.

A multitude of subsurface processes may contribute to unrest signals and some are summarised in Table 1. Not all processes are pre-eruptive and the challenge lies in deciphering the causes of unrest with a view to establish early on in a developing crises whether a volcanic system develops towards a state where an eruption may ensue. Whether or not unrest leads to eruption depends on many parameters. In general the main concern during volcanic unrest lies with the potential for a magmatic eruption. For this to occur magma must rise from depth and break through the surface. The dilemma for scientists is that magma movement does not create uniquely attributable unrest signals and does not necessarily lead to eruption (Table 1). For example, seismicity and ground uplift, both common indicator of unrest, may be induced by the replenishment of a magma reservoir, the ascent of magma towards the surface or the redistribution of aqueous fluids and fluid phase changes (see Salvage et al. 2017; Hickey et al. 2017; Mothes et al. 2017 for examples from VUELCO volcanoes). Similarly, an increase in the gas and heat flux (Christopher et al. 2015) at the surface may be induced by magmatic or hydrothermal processes and even tectonic stress changes have also been shown to trigger such behaviour (e.g., Hill et al. 1995). In fact, non-magmatic eruptions are associated with significant hazards and have or could have caused fatalities in the past such as for example Bandai in 1888 (Sekiya and Kikuchi

1890), Te Maari Tongariro in 2012 (e.g., Jolly et al. 2014) and recently at Ontake in 2014 (e.g., Maeno et al. 2016). Many unrest processes contribute to non-eruptive secondary hazards such as flank instability and collapse (e.g. Reid 2004).

4.2 Uncertain Causes and Uncertain Effects

Substantial uncertainties surround both the interpretation of the drivers of unrest and the assessment of the potential evolution and outcome of unrest. Critical questions include: Will an eruption ensue? If so, will it occur in the short-term (days to months) or long-term (years to decades)? What will be the nature and intensity of the eruption (magmatic vs. phreatic)?

In the case of magmatic unrest, magma ascent towards the surface can lead to a magmatic eruption with potential for the formation of lava flows, pyroclastic flows, lahars, ash-fall and ballistics. These processes impact the proximal (few tens to hundreds of meters), medial (kilometers) and distal (tens of kilometres or more) areas around the volcano. Conversely unrest driven by sub-surface hydrothermal activity may peak in a phreatic eruption and while impacted areas are rather proximal to the volcano, associated ballistics and dilute pyroclastic density currents triggered by laterally-directed explosions and emplacement of a debris avalanche from a partial edifice collapse can lead to an anomalously high loss of lives as recently shown by the September 27, 2014 Mount Ontake eruption, the deadliest eruption in more than 100 years in Japan (e.g. Maeno et al. 2016).

The challenge, however, is to identify and discriminate signals that are indicative of reactivation leading towards a major expulsion of magmatic material from those associated with a slight deviation from background levels and potential waning of unrest phenomena (Table 1).

The fundamental limitation for volcanologists is that it is not possible to directly observe causative processes at depth. Thus interpretations of these drivers rely on the secondary interpretation of observable signals associated with those processes (Salvage et al. 2017) or the reproduction of interpreted processes via laboratory experiments (Wadsworth et al. 2016). In addition, many volcanic processes are intrinsically non-linear and characterized by a chain-link reaction such that minor variations of some uncertain parameters might have ultimately significant consequences on the eruptive outcome. Such non-linear processes coupled with epistemic and aleatoric uncertainties are complex to understand and model. This chapter analyses some key examples across the three aforementioned projects where issues around the limits of volcanic knowledge exacerbated risk and makes suggestion for how future improvements can be made.

4.3 The Hazard and Risk Interface

Scientific Challenges

In the light of the above, from a scientific point of view the early identification of the cause of unrest and its likely outcome and evolution is pivotal for effective and efficient risk assessment, risk management and the design of mitigation efforts. In order to address the key scientific question of whether unrest is a prelude to imminent eruption or whether it will wane after some time without eruption several questions require answering first (note, that the list is not exhaustive):

- Is the anomalous behaviour unambiguously indicative for a change in the volcano's behaviour and for a deviation from its background state?
- How reliable is the assessment of unrest as a prelude to eruption, particularly in the absence of data on past events?

- What are the mechanistic processes at depth leading to observed unrest signals?
- Are monitoring signals indicative of magmatic, hydrothermal or tectonic unrest?
- Can the unrest be caused by perturbations and changes in the host-rock properties (e.g. porosity, permeability, mechanical properties) rather than by distinct endogenic processes of hydrothermal or magmatic origin?
- What are the uncertainties surrounding monitoring signals and inferred sub-surface processes (see Hickey et al. 2017 and Salvage et al. 2017)?
- Do secondary processes (e.g. hydrothermal system perturbation, meteorological forcing) modify primary signals from deeper-seated magmatic processes?
- What are the consequences of signal modification for the assessment of the process-to-signal-to-outcome causal link?
- Does one follow a deterministic or probabilistic approach for observations and forecasting (e.g., Hincks et al. 2014; Aspinall and Woo 2014; Rouwet et al. 2017)?
- What is the likelihood of a specific eruptive or non-eruptive scenario to manifest (e.g., Bartolini et al. 2017)?
- Which types of eruptions did the volcano produce in the past?
- If an eruption is to occur, what is its likely nature: magmatic, or phreatic or a mix?
- How much lead-time before eruption is there based on previous experience; how much lead-time is there in the absence of previous experience?
- Which eruptive or non-eruptive unrest episodes at analogue volcanoes can provide clues for the interpretation of signals and forecasting of unrest evolution and outcome (e.g., Sheldrake et al. 2016)?
- What is the likely size of the eruption and the associated hazards and risks and impacted area?
- What is the temporal evolution of eruptive intensity once the eruption has started? i.e., what is the likelihood that the eruption (a) will have its paroxysmal phase in the first 24 h of eruption (42% of eruptions do, according to Siebert et al. (2015)); or (b) will have a more progressive escalation over several months that will culminate in a paroxysm; or (c) will be characterised by peaks in activity separated by more or less long-lasting pauses or strong decline of activity preceding another rapid increase and peak of activity?

Societal Challenges

At the same time, the political, sociological, cultural and economic (grouped here under the term ‘societal’) implications from unrest need addressing in order to respond appropriately to the emerging natural hazard (Wynne 1992) Here we provide a (non-exhaustive) list of questions for risk managers and/or politicians in the context of risk governance during volcanic unrest:

- What is the best-practice to provide maximum response time, while minimizing vulnerability and optimizing the cost/benefit ratio (see Fig. 1) of mitigation actions in a developing unrest crises?
- What is the best practice to issue or raise an alert?
- When and how to decide to raise an alert and to take action?
- What are the potential (legal) consequences of a false positive or false negative (see Table 2 and Bretton et al. 2015)?
- What are the consequences of a true positive (Table 2)?
- What is the basis for raising an alarm: the outcomes of unrest (e.g., instability of buildings due to ground deformation or seismicity; toxic degassing and environmental contamination) or the potential for eruption?
- How to best disseminate what information on unrest and its potential consequences, when, and via which communication vehicle(s) to the public?

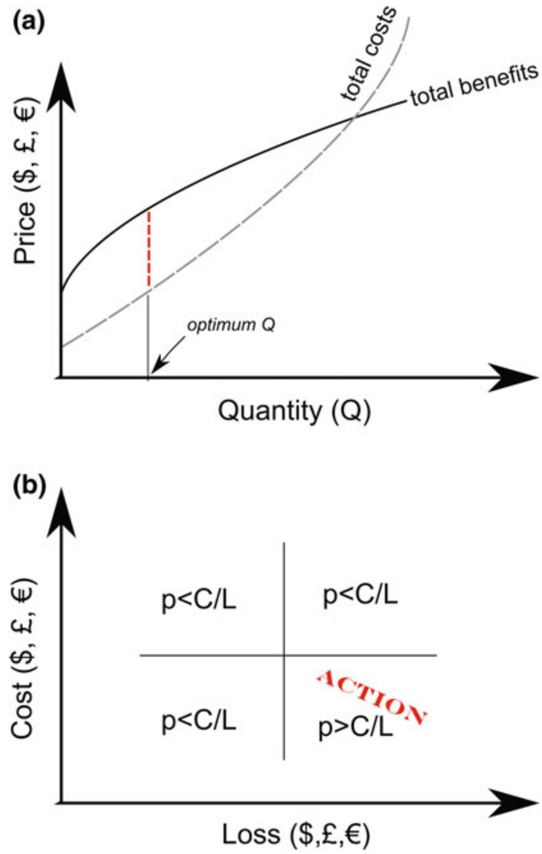

Fig. 1 Cost-benefit relationship as a tool for decision-making. **a** In the context of volcanic unrest risk management, actions of given quantity Q (for example, number of shelters or evacuees) are associated with costs in relation to their expected benefits (expressed by a financial value). An optimal relationship between costs of mitigation efforts and resultant benefits can be achieved when the difference between investment and benefit is greatest (shown by *stippled red line*). The example is based on concepts of capital management theory presented in Brealey et al. (2011). **b** Cost (C) versus loss (L) model for volcanic risk management (after Marzocchi and Woo 2007). If, in this decision-making framework, the expected expense (cost) for mitigation action is to be minimised, then action is required if the probability (*p*) of an adverse event to occur exceeds the ratio between the cost of the action and the expected loss (L/C). See discussion for a wider appraisal of the challenges arsing from such an analysis

Table 2 Concept of successful and unsuccessful forecasting

	Event forecast	Event not forecast
Event occurs	True positive	False negative (Type II error)
Event does not occur	False positive (Type I error)	True negative

- How to account for uncertainty and the diversity of expert opinions in deciding the alert level?
- In what context does this occur such as political pressures, concurrent natural or other hazards (pandemic, famine, cyclone, etc.)

4.4 Cost-Benefit Analysis (CBA)

In the previous paragraphs, several questions related to how to get both the scientific analysis ('what is going on?') and the societal response ('how to respond?') 'right'. One measure employed to quantify the economic consequences of action or no-action under imminent threat and a tool for informed institutional decision-making is the cost-benefit analysis (Marzocchi and Woo 2007) whereby one aims to find a good answer to the question: "Given an assessment of costs and benefits related to risk mitigation efforts, which actions should be recommended?" Figure 1 shows the concept of evaluating the optimum ratio between the cost and benefit of mitigation efforts and provides a cost-benefit matrix for the design of action plans in response to a future [short-term in context of this chapter) adverse event of given probability (p) (Brealey et al. 2011; Marzocchi and Woo 2007)]. A critical issue in CBA is the 'minimum value of a human life', which we will not discuss further here. The interested reader is referred to, for example, Woo (2015) for further details on this quantification. Another interesting point relates to what might be regarded as a 'cost' and a 'benefit' in a response to an unfolding unrest crisis with an uncertain outcome (see also Sect. 6).

5 Global and Regional Context of Volcanic Unrest

5.1 Unrest Durations and Characteristics

Phillipson et al. (2013) reviewed global unrest reports of the Smithsonian Institution Global Volcanism Program (GVP) between January 2000 and July 2011 to establish the nature and length of unrest activity, to test whether there are common temporal patterns in unrest indicators and to test whether there is a link between the length of inter-eruptive periods and unrest duration across different volcano types.

Using available formation on unrest at 228 volcanoes they defined unrest timelines to demonstrate how unrest evolved over time and highlight different classes of unrest including reawakening, pulsatory, prolonged, sporadic and intra-eruptive unrest (see Fig. 2 for an example from Cotopaxi volcano). Statistical analyses of the data indicate that pre-eruptive unrest (where there is a causal link between unrest and an eruption within the observation period) duration was different across different volcano types with 50% of stratovolcanoes erupting within one month of reported unrest. The median average

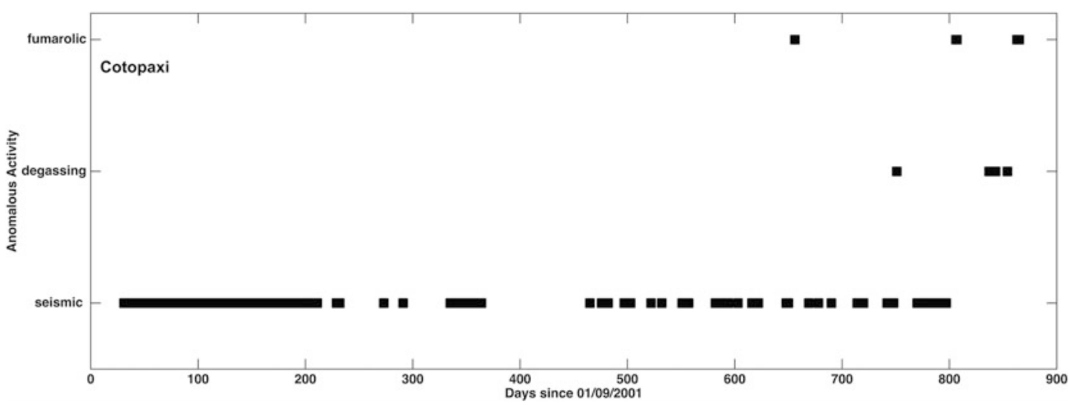

Fig. 2 Timeline of reported anomalous activity at Cotopaxi volcano (Ecuador) in 2001/2002. This period of pulsatory unrest lasted for more than 3 years with a heightened level of activity in 2001 and 2002. The unrest did not lead to an eruption in the short-term (weeks to months), but Cotopaxi entered an eruptive phase in August 2015 after a short-period of renewed unrest activity starting in April 2015 (see Mothes et al. 2017 for details). The data shown in the graph are from Phillipson et al. (2013)

duration of pre-eruptive unrest at large calderas was about two months, while at shield volcanoes a median average five months of unrest was reported before eruptive activity. The shortest median average duration is reported for complex volcanoes where eruptive unrest was short at only two days. Overall there appears to be only a very weak correlation between the length of the inter-eruptive period and pre-eruptive unrest duration. This may indicate that volcanoes with long periods of quiescence between eruptions will not necessarily undergo prolonged periods of unrest before their next eruption (Fig. 3). Phillipson et al. (2013) found statistically relevant information only from reports of anomalous seismic behaviour, most other monitoring signals are either not recorded or not reported as unrest criteria. The authors reported a noteworthy lack of geodetic data/information and in particular satellite remote sensing data in the available reports. Recently Biggs et al. (2014), addressed the latter and systematically analysed 198 volcanoes with more than 18 years of satellite remote sensing deformation data for their deformation behaviour. 54 volcanoes that showed deformation also erupted during the observation period. Their analysis does not imply any causal link, or even a temporal relationship between any specific eruptions and episodes of deformation and is hence not directly comparable to the causal and predictive analysis by Phillipson et al. (2013). However, given that 46% of deforming volcanoes erupted while 94% of non-deforming volcanoes did not erupt provides "strong evidential worth of using deformation data as a trait association with eruption" (Biggs et al. 2014).

It is important to note that exploitable records on volcanic unrest are limited and the available

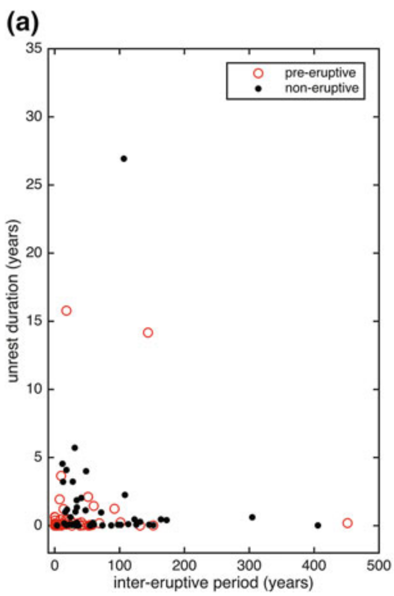

Fig. 3 Comparison between the inter-eruptive period (IEP) and unrest duration (UD) from the data set presented in Phillipson et al. (2013). **a** shows entire data set (n = 118) **b** shows a subset of the data for clarity of inter-eruptive periods <150 years. The *p*-values of the Pearson's correlation test are $p = 0.93$ for the entire data set, $p = 0.60$ for the subset of non-eruptive unrest (n = 58) and $p = 0.20$ for the subset of eruptive unrest (n = 60). The null hypothesis ("the UD is independent of the IEP") is hence statistically acceptable when considering the entire data set. Considering the subset of pre-eruptive unrest, however, the statistical tests do not provide enough evidence to fully accept the null hypothesis since the associated *p*-value of 0.20 might hint towards some weak correlation between the two variables

data sets are far from complete. Key issues are the lack of or poor instrumentation at most volcanoes, the lack of reporting by observers particularly if an unrest turns out to be minor and without immediate consequences, and the lack of integrating unrest data from satellite remote sensing. The GVP generally lacks the post-facto integration of unrest indicators from satellite-remote sensing data (e.g., Fournier et al. (2010) and Biggs et al. (2014) for deformation and Carn et al. (2011) for degassing). In this respect, it is vitally important to recognise and support initiatives to collate and exploit worldwide volcano monitoring data such as for example the WOVOdat project (Venezky and Newhall 2007). Only by significantly increasing the knowledge-base on the spatial and temporal evolution of the unrest-eruption relationship can we embark on statistically sound exploitations of the data with a potential to improve forecasting capabilities early on in developing unrest crises.

5.2 Socio-Economic Contexts

The Wider Perspective

Nowadays, about 800 million people live on or in direct vicinity of active volcanoes (Brown et al. 2015). The overwhelming majority of this population lives in low and middle income countries (countries with an annual gross national income per capita of less than US$12,700) including the focus area of the VUELCO, STREVA and CASAVA projects: the wider Latin American (LA) region extending from Mexico, through Central America and the Caribbean to South America. This region hosts about 330 Holocene volcanic centres compared to 84 in Europe and one quarter of the reported global fatalities attributed to volcanic events occurred there (Global Volcanism Program 2013).

Volcanic disasters are among the least audited of all natural disasters and therefore our knowledge on the impact of volcanic activity beyond claiming lives is largely incomplete (Benson 2006; Auker et al. 2013). Huge uncertainty surround estimates for indirect losses from for example disease or starvation as a result of volcanic activity. Beyond increased human vulnerability, the direct and indirect financial impacts from volcanic activity can be immense as demonstrated by the relatively small-scale eruption of Iceland's Eyjafjallajökull volcano in April 2010 and the associated air travel disruption. This eruption demonstrated the vulnerability of modern infrastructure to volcanic hazards on an unprecedented scale with losses to the aviation industry alone at a minimum of US$2.5 Billion (European Commission 2010).

Equally there are social, political and financial implications for "false positives" related to volcanic unrest. In these instances actions are taken in response to an imminent threat, which then did not manifest. In the case of volcanic unrest the imminent threat is generally defined as a volcanic eruption, although the multi-hazard nature of volcanic unrest (e.g., ground shaking, ground uplift or subsidence, ground rupture, ground instability, toxic gas emissions, contaminated water supplies) and possibly ensuing eruptive activity (magmatic vs. phreatomagmatic vs. phreatic) makes the definition of 'imminent threat' rather complex.

Although there is little systematic gathering and synthesis of data relating to financial or social losses associated with these episodes there are some well-documented analyses. Examples include:

(1) On Guadeloupe in the French West Indies a major evacuation over a period of 4 months in excess of 70,000 individuals was initiated in 1976, as a result of abnormal levels of volcanic seismicity and degassing (see also next section). The estimated cost of the unrest was about US$340 Million at the 1976 exchange rate (data compiled using Lepointe 1999; Tazieff 1980; Blérald 1986; Baunay 1998; Kokelaar 2002; Annen and Wagner 2003), which translates to more than US$ 1.2 Billion at the time of this writing (July 2016). At the time the cost equaled to ca. 60% of the Gross National Product of the Guadeloupe economy (Blérald 1986). 90% of these costs were incurred by the costs of the evacuation,

and the costs associated with the rehabilitation and salvage of the economy in Guadeloupe after the evacuation.

(2) Unrest at Rabaul volcano in Papua New Guinea (an LDC) between 1983 and 1985, had significant adverse implications for both the private and public sectors. Considerable economic costs were incurred, estimated at over US$22.2 Million at the 1984 rate of exchange although an eruption did not occur until 10 years later (Benson 2006).

(3) Evacuation and rehousing of 40,000 inhabitants of the Pozzuoli area in the Campi Flegrei volcanic area of Italy resulted as a response to intense seismicity and ground uplift in the early 1980s. Although decision-makers did not release notice that this was in part due to the threat from an imminent eruption (see also Sect. 4.3.2), it is true that the re-location of these inhabitants moved them from the area of highest threat in the event of an eruption. At the time there was no agreement amongst scientists as to the cause of the unrest (Barberi et al. 1984) and the scientific discussion as to the cause of these events is still ongoing more than 30 years after the crisis.

The following paragraphs focus on two examples of short-term and long-term volcanic unrest crises response and provide more detailed insights into the volcanic risk governance in two different jurisdictions.

Short-Term Crisis Example: The 1976–1977 La Soufrière of Guadeloupe Unrest

The unrest on Guadeloupe culminated in a series of explosive eruptions of hot gas, mud and rock (termed phreatic eruption) without the direct eruption of magma before waning in 1977 (Feuillard et al. 1983; Komorowski et al. 2005; Hincks et al. 2014). Fortunately no fatalities were caused by the activity. Had the unrest on Guadeloupe led to a magmatic eruption, then the cost of the unrest would have likely been negligible. Although the precautionary evacuation caused a substantial economic loss with severe social consequences, it is acknowledged that the "proportion of evacuees who would have owed their lives to the evacuation, had there been a major eruption, was substantial" (Woo 2008). The CASAVA project undertook an exhaustive hindsight analysis of the process of scientific decision-making for the unrest and eruptive crisis of 1976–1977 at La Soufrière de Guadeloupe. The crisis caused significant hardships and loss of livelihood for the evacuated population and the whole society in Guadeloupe as a result of controversial crisis management associated with a forecast of a major magmatic eruption that did not occur (false positive) (Feuillard et al. 1983; Fiske 1984; Komorowski et al. 2005; Hincks et al. 2014). Given the evidence of continued escalating pressurisation and the uncertain transition to a devastating magmatic eruption, authorities declared a 4-month evacuation of ca. 70,000 people on August 15, 1976 that provoked severe socio-economical consequences for months to years thereafter. This evacuation is still perceived as unnecessary and reflecting an exaggerated use of the "principle of precaution" on behalf of the government.

However, some level of risk governance (i.e. evacuation of the most exposed area) was justified in hindsight given the persistent ashfalls and environmental contamination from acid degassing as well as the hazards from a series of non-magmatic eruptions (e.g., pyroclastic flows from laterally directed explosions, partial edifice collapse, mudflows) (Komorowski et al. 2005; Hincks et al. 2014).

The (in hindsight) erroneous identification of the presence of '*fresh glass*' in the ejecta and its interpretation as evidence of the magmatic origin of the unrest and thus of its possible outcome, led to a major controversy amongst scientists that was widely echoed in the media. Lack of a comprehensive monitoring network prior to the crisis, limited knowledge of the eruptive history, and living memory of past devastating eruptions in the Lesser Antilles contributed to a high degree of scientific uncertainty and a publically-expressed lack of consensus and trust in available expertise. Consequently analysis, forecast, and crisis response were highly challenging for scientists and authorities in the context of escalating and fluctuating activity and societal pressure. The high uncertainty about a so-called "unequivocal" impending disaster fostered a binary zero-sum strongly opinionated approach in the scientific discourse. The public debate thus became polarized on issues of opposing "truths" served by contrasted scientific expertise rather than on how science could help constrain epistemic and aleatoric uncertainty and foster improved decision-making in the context of uncertainty (Komorowski et al. 2017). This situation acted as an ideal crucible to fuel a media-hyped controversy on the crisis and its management. A recent retrospective Bayesian Belief Network analysis of this crisis (Hincks et al. 2014) demonstrates that a formal evidential case could have been made to support the authorities' concerns about public safety and decision to evacuate in 1976.

As part of the CASAVA project we conducted focus group interviews, issued questionnaires, and ran role playing games with the population currently living in areas potentially threatened by renewed unrest and eruptive activity from La Soufrière, (be it magmatic or non-magmatic). We found that the current population's risk perception increases to a level of preparing to evacuate chiefly on the basis of the timing and nature of scientific information issued publically by the volcano observatory. This implies that the population is prone to self-evacuate ahead of any official evacuation order given by the authorities in charge of civil protection and crisis response.

Long-Term Crises Examples: Soufrière Hills (Montserrat) and Tungurahua (Ecuador)

The forensic analyses of the STREVA project have focussed on the integration of new social-science based understandings of population response and recovery with the scientific insights prompted by these long-lived eruptions. This has similarities with the 'FORIN' approach advocated by the International Program on Integrated Risk for Disaster Reduction (Burton 2010). In this description we focus particularly on the initial stages of the eruptions.

The long-lived volcanic crisis of the Soufrière Hills Volcano is probably one of the most written about volcanic eruptions, encompassing a wide variety of perspectives, scientific, social-scientific and personal, in that writing. As a consequence of the activity on the island of Montserrat a population of over 10,500 was reduced to just 2850 (the population has since risen to 4922 [2011 census], Hicks and Few 2015). At the onset of eruption (1995) an assessment of risk existed (Wadge and Isaacs 1988) but was not acted on or acknowledged by the authorities, and so preparedness was low, exacerbated by the recent passage of Hurricane Hugo (1989) which had caused 11 fatalities and rendered 3000 homeless. Governance on Montserrat was reforming in the wake of the economic and social crisis induced by the hurricane (Wilkinson 2015). The protracted uncertainty in the early stages of the eruption coupled with a lack of coherence in governance between the UK and local governments lead to the protracted evacuation of 1300 people in temporary public shelters, which suffered from overcrowding, lack of privacy, poor sanitation and lack of access to good nutrition. Ultimately, this led to a partial disregard for evacuation advice and a strong pulse of outwards migration. In the longer term, the long-lived volcanic eruption has acted to exaggerate pre-existing vulnerabilities in the local population (Hicks and Few 2015).

The early stages of the current Tungurahua (Ecuador) eruptive episode that started in 1999 typify a further challenge for the management of unrest prior to or between surface activity at the early stages of a volcanic crisis. Initially the local population were evacuated by a compulsory evacuation order but when the initial phases proceeded more slowly than had been expected by local authorities and communities, civil unrest and disturbance happened with the re-occupation by force and ultimately abandonment of the evacuation order. These arose from the acute economic and social pressures visited on the population by the evacuation (Mothes et al. 2015). Subsequently, the response of the monitoring organisation to these pressures represents a new archetype for collaborative monitoring and management of restive volcanoes (Mothes et al. 2015; Stone et al. 2014). The growth of trust, and attempts to maximise resilience in the face of repeated unrest episodes provides strong evidence for collaborative approaches to risk management (Few et al. 2017). Nonetheless tensions still exist, largely arising from our current incapacity to predict the intensity or magnitude of eruptions from signals relating to new unrest. There can be problems in this risk system implicit in anticipating the 'maximum expected' outcome from unrest.

6 Discussion

6.1 The Caveats of Volcanic Unrest Response

Managing volcanic unrest episodes is extremely complex and challenging due to the multi-hazard nature of unrest. The risks to be assessed and mitigated include both those associated with the unrest itself as well as those from the potential future eruptive activity. Whilst ground deformation, seismicity, thermal flux or anomalous degassing are indicators of possible future activity these phenomena also pose significant immediate threats to population, infrastructure and other assets in affected areas during the unrest.

From a scientific point of view, hazard assessment relating to eruptive activity has made considerable progress in recent years partly through the deployment of increasingly powerful computational models and simulation capabilities (e.g., Esposti Ongaro et al. 2007; Manville et al. 2013) as well as through advances in the development of probabilistic eruption forecasting tools (e.g., Marzocchi et al. 2008; Aspinall 2006; Aspinall and Woo 2014) and improvements to fundamental understandings of the root drivers of changing activity (e.g., Cashman and Sparks 2013).

Despite these crucial advances for short-term eruption forecasting, the knowledge-base on volcanic unrest, its significance as an eruption precursor, its exploitability regarding forecasting of potential eruptive behaviours and framing of response protocols (e.g., CBA) remains weak for a number of reasons:

(1) The scientific interpretation of volcanic unrest is surrounded by substantial uncertainty, ambiguity and ignorance (Stirling 2010) regarding causes and eventual outcome. Since the contributing subsurface processes cannot be directly observed, volcanic unrest is likely among the least understood phenomena in volcanology for a variety of reasons:

(i) Incomplete knowledge of the mechanistic processes and their dynamic behaviour over time within a magma reservoir and its surroundings (host-rock, hydrothermal system, meteoric recharge, local and regional structural context) that trigger the geophysical, geochemical and geodetic signals recorded at the surface during unrest periods (Table 1).

(ii) Consequently, the interpretation, of the departure of monitoring signals from a long-term baseline level or in the absence of baseline data a crescendo or decrescendo of signals collected during periods of unrest are often ambiguous or non-unique. While this can in practice be addressed in models through epistemic and aleatoric uncertainties, ambiguities in the interpretation will remain.

(2) Ambiguity, uncertainty and ignorance (Stirling 2010) have impact on probabilistic forecasting of duration, spatio-temporal evolution, causal relationship between sequential events and outcomes of unrest episodes (see Sandri et al. 2017) and on remedial actions to mitigate current and future adverse effects. Uncertainties in the decision-making process may give rise to "false alerts" (i.e., false positives; see Table 2) and actions by civil protection with adverse impacts on the compliance of affected communities in future unrest events.

(3) Lack of globally accepted and standardised approach for the terminology, methodology,

criteria, protocols and best practice employed to evaluate and respond to volcanic unrest by different stakeholders such as academia, volcano observatories and the Civil Protection Agencies. This absence of commonly recognised standards can result in the critical issue of managerial risk vulnerability (i.e., standard equivocality' after Bretton et al. 2015). It also often impacts negatively on the effectiveness of communication between stakeholders, hinders or delays effective and efficient decision-making processes and hampers the dialogue among members of scientific, governmental and civil communities (De la Cruz-Reyna and Tilling 2008). However, it is important to note that internationally-defined standards should not be rigidly imposed irrespective of local, cultural, political and social practices (e.g., Bretton et al. 2015; IAVCEI 2016).

(4) Globally, there is no commonly accepted and standardised denominator between those that provide and those that receive scientific advice regarding the level of appropriate scientific complexity to be considered. This may hamper a wider discourse on scientific and technological advances in the quantification of unrest phenomena and resultant uncertainties with other stakeholders. From the scientist's perspective this may generate the notion that the public, administrators, mass media and governmental entities do not appreciate the "excellence of the science" behind unrest characterisation and use the inherent uncertainty as a rationale to go into denial over the hazards posed during unrest. From a sociological point of view, however, decision-making apparently prompted solely by the present or likely volcanic hazards, does not account for local context and can result in a lack of trust in either scientific expertise or government representatives, (Johnson 1987; Haynes et al. 2008; Christie et al. 2015; Komorowski et al. 2017).

6.2 Some Ways Forward

The issues identified above can contribute less optimal unrest response and risk mitigation actions. Although there are other strong contributors to societal vulnerability, we have shown that scientific uncertainty combined with a lack of social awareness and preparedness does act to increase the vulnerability of a society to hazardous unrest phenomena with possibly adverse outcomes. Here, we propose future avenues which can form part of a Risk Governance Framework (IGRC 2017; Fig. 4) including research that could gather critical evidence for some of the key drivers of decisions that result in adverse outcomes for affected populations in the face of an unrest crisis. Such research could also contribute to the analysis of and identification of key targets for future research in volcanology and the social sciences.

(a) Cost-Benefit Analysis

CBA, where the economic impacts of different decisions are quantified, can be difficult at the unrest hazard and risk interface. The case studies presented here demonstrate that intangible assets such as social and cultural cohesion and capital as well as trust (in the context of CBA analysis this would be intentional trust in the sense of Dasgupta (1988); i.e., the subjective probability assigned to compassionate action by an individual or a group of individuals) between different stakeholders can have a strong impact on individual and institutional vulnerabilities during crises.

Analyses that include a wider range of definitions and types of 'costs' and 'benefits' of mitigation efforts (e.g. loss of empowerment, a loss of cultural identity or cultural references), informed by past experiences would facilitate a discourse between different stakeholders. This would entail the need to attribute a financial value to, for example, mental well-being, social networks and cohesions and would necessarily trigger a wider discourse of the impacts of decision-making beyond the avoidance of 'cost

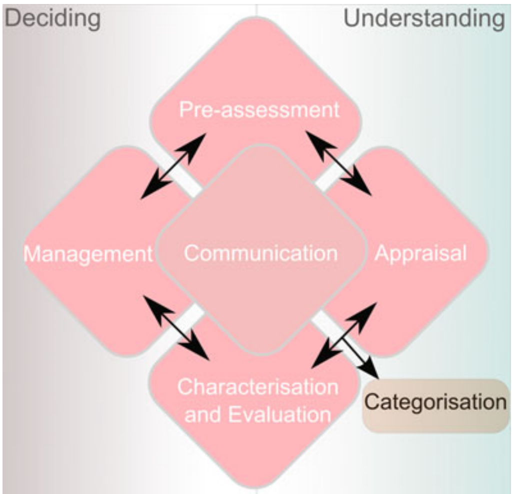

Fig. 4 The *International Risk Governance Council* (IRGC 2017) Risk Governance Framework adapted for the specific case of volcanic unrest. *Hazard and Risk Pre-assessment*—"peacetime framing" the hazard and risk in order to provide a structured definition of the baseline behaviour of the volcano and its consequences, of how the hazard and risk are framed by different stakeholders, of how the risk may best be handled, and of the thresholds to be met or exceeded to declare a state of unrest. *Hazard and Risk Appraisal*—combining a scientific risk assessment of the current unrest hazards (using for example a rating scheme of unrest intensity, e.g., Potter et al. 2015) and its probability with a systematic concern assessment (of public concerns and perceptions) to provide the knowledge base for subsequent decisions in an emerging unrest crises. *Risk Characterisation and Evaluation*—in which the scientific data and a thorough understanding of societal values affected by the risk are used to evaluate the risk as acceptable, tolerable (requiring mitigation), or intolerable (unacceptable). *Risk Management*—the actions and remedies needed to avoid, reduce transfer or retain the unrest risk and risks from probable unrest outcomes. *Risk Communication*—how stakeholders and civil society understand the unrest risk and participate in the risk governance process. *Risk Categorisation and Evaluation*—categorising the knowledge about the cause-effect relationships as either simple, complex, uncertain or ambiguous. In the context of volcanic unrest this may include the categorisation of the outcome of unrest and probable future eruptive activity

to lives'. Ideally this discourse would be framed during 'peace-time' (i.e. not in response to an unfolding unrest crisis) and involve participation from a wide spectrum of scientific and societal stakeholders. The necessity to move beyond circumscribed appraisal methods such as the CBA is also evident from the response to protracted (several years or decades) unrest requiring an above back-ground level of long-term vigilance (e.g. yellow/vigilance level for La Soufrière of Guadeloupe since 1999, Komorowski et al. 2005; OVSG-IPGP 1999–2016 or at the Campi Flegrei caldera since 1969; Ricci et al. 2013). In such cases there are obvious long-term strategies that could be developed to improve social well-being and economic development (e.g. developing resilient critical infrastructures such as roads, bridges, public electrical water and sewer systems and communications networks) that would significantly enhance the quality of life for years of "peace time" from the volcano while ensuring a more efficient crisis response and recovery should the volcano erupt and impact the society.

(b) Improved communication

Open and multi-directional communication processes are of paramount importance in fostering the development of a shared representation and understanding among all stakeholders of the nature, magnitude, dynamics, and societal and environmental consequences of unrest and its potential eruptive outcome on multiple spatio-temporal scales (e.g. Barclay et al. 2008, 2015; Komorowski et al. 2017). While communicating this information in a timely and comprehensible format is challenging, the evidence presented here suggests that a continuous discourse is needed between different stakeholders ideally both before, during and after an unrest situation. The case studies presented here demonstrate that part of this discourse should involve a discussion about the appropriate scientific complexity in the communication between scientific and non-scientific stakeholders is essential, so that the information exchange is 'useful, usable and used' (Aitsi-Selmi et al. 2016) and fit for the decision-making purpose to which it is intended (Fischhoff 2013). Wider discourse could for example include regular information bulletins from monitoring agents to the civil society and authorities, the development of scenario-based approaches in simulation exercises involving the civil society and the wider appraisal of less tangible 'assets' (i.e., live stock or cultural capital) in risk governance efforts.

Dialogues between those responsible for monitoring hazards and those responsible for managing risk, as well as the communities at risk cannot only help to understand the most important aspects of scientific information to convey but could also lead to an improved understanding of the context into which emergency response actions must be made (e.g. Christie et al. 2015), and encourage citizens at risk to act on advice. In particular more systematic studies that analyse the effectiveness of different techniques and strategies in achieving these goals would be very useful (see Fearnley et al. 2017 for a recent compilation). These efforts should help address reluctance by the public to follow emergency-response advice in an emerging unrest crises.

(c) Wider natural risk appraisal

In a similar vein, the implementation of advice on volcanic risk could be more effective if it is considered in the context of other natural risks and social challenges (e.g., Wilkinson et al. 2016). By definition the onset of a volcanic eruption involves the anticipation of impacts from multiple hazards but the risk associated with volcanic hazards are often considered in isolation, and as a low probability, high consequence hazard, ignored in advance of an unrest crisis. This lack of dialogue and preparation has been identified above as a strong contributor to tensions during unrest crises. Volcanic regions only very rarely suffer solely from the impacts of a single natural hazard (e.g. volcanic small-island developing states discussed in Wilkinson et al. 2016; Komorowski et al. 2017). Therefore methods that consider the multi-hazard context more clearly may ultimately help communities at risk cope with uncertainty in face of volcanic hazards. This may be particularly the case, if they are able to identify 'co-benefits' during volcano "peace time" where preparedness or mitigation measures yield benefits for more than one hazard scenario (Wilkinson et al. 2016). This improvement of social well-being is likely to allow the society to take better decisions when times of impeding adversity arise.

(d) Framing of warnings around decision-making timescales and hazard level

Typically changes in alert levels are strongly tied to pre-determined changes in geophysical and geochemical signals or phenomenological observations and have carefully worked out associated actions. In our case studies, difficulties have arisen when the time-scale over which mitigating actions can be taken is much shorter than needed to implement mitigating actions such as evacuation or much longer than the timescale over which unrest or new eruptive activity impacts on the population at risk. In the case of the former, lives or assets may be put at risk and in the case of the latter, possessions and livelihoods can be negatively impacted with repercussions on trust and political stability. Managing decade or longer periods of protracted moderate-level unrest amid significant epistemic and aleatoric uncertainty on its outcome constitutes major challenges for scientists, authorities, the population, and the media.

The development of novel probabilistic formalism for decision-making could help reduce scientific uncertainty and better assist public officials in making urgent evacuation decisions and policy choices should the current and ongoing unrest lead to renewed eruptive activity. To improve decision-making around changing alert or hazard levels, improved modelling efforts of the time-scales and pathways of population mobilisation or actions (both as forward modelling and as analysis of past events) and better understanding of the consequences of protracted unrest or eruptive activity on the vulnerabilities of affected populations (e.g. Few et al. 2017) could improve choices to be made in responding to changing or escalating activity as well as chain-link scenarios.

Further, focussing on the time-scales associated with the *responses* to unrest (from the time taken to mobilise populations in an acute emergency, to the time-limits of tolerability of evacuation processes and finally the time-scales over which services and livelihoods deteriorate in response to protracted unrest) could provide important indicators for the time-scales over which alert levels (and attendant actions) need attention. In turn this perspective could inform scientific targets for improved forecasting, with strong effort expended to reduce uncertainty over time intervals that match those most critical to effective societal action.

7 Conclusions

We have identified a number of scientific and sociological problems surrounding volcanic unrest and have highlighted key aspects of risk governance at the interface between scientists, emergency managers and wider societal stakeholders. We have in particular focussed on the issue of scientific uncertainty and its impact on preparatory or contingency actions that might be needed because relationships between and among individuals and social groups will be perturbed or even changed. Especially, during periods of protracted unrest (years to decades) challenges arise from the exploitability of unrest signals to forecast long-term unrest evolution and its eventual outcome. This impacts directly on establishing the probability for and the timing and type of future eruptive behaviour as well as the definition of appropriate response protocols. To improve communication and trust between stakeholders as well as the framing of warnings around decision-making timescales and hazard levels of unrest, we propose that bridging across traditional scientific boundaries, wider natural risk appraisal and broader stakeholder interaction is needed.

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References

Aitsi-Selmi A, Blanchard K, Murray V (2016) Ensuring science is useful, usable and used in global disaster risk reduction and sustainable development: a view through the Sendai Framework lens. Palgrave Commun (2) doi:10.1057/palcomms.2016.16

Annen C, Wagner J-J (2003) The impact of volcanic eruptions during the 1990s. Nat Hazards Rev 4:169–175

Aspinall WP (2006) Structured elicitation of expert judgment for probabilistic hazard and risk assessment in volcanic eruptions. In: Mader HM, Coles SG, Connor CB, Connor LJ (eds) Statistics in volcanology. The geological society for IAVCEI, 15–30

Aspinall WP, Woo G (2014) Santorini unrest 2011–2012: an immediate Bayesian belief network analysis of eruption scenario probabilities for urgent decision support under uncertainty. J Appl Volcanol 3:12

Auker MR, Sparks RSJ, Siebert L, Crossweller S, Ewert J (2013) A statistical analysis of the global historical volcanic fatalities record. J Appl Volcanol 2:2

Barclay J, Haynes K, Mitchell T, Solana C, Teeuw R, Darnell A, Crosweller HS, Cole P, Pyle DM, Lowe C, Fearnley C, Kelman I (2008) Framing volcanic risk within disaster risk reduction: finding ways for the social and physical sciences to work together. In: Liverman DGE, Pereria CPG, Marker B (eds) Communicating environmental geoscience. Geological Society Special Publication, 305

Barclay J, Haynes K, Houghton BF, Johnston DM (2015) Social processes in volcanic risk reduction. In: Sigurdsson H et al (eds) Encyclopaedia of volcanology, 2nd edn. Elsevier, Amsterdam.

Barberi F, Corrado G, Innocenti F, Luongo G (1984) Phlegraean Fields 1982–1984: brief chronicle of a volcano emergency in a densely populated area. Bull Volcanol 47:175–185

Bartolini S, Marti J, Sobradelo R, Becerril L (2017) Probabilistic e-tools for hazard assessment and risk management. Adv Volcanol 1–15

Baunay Y (1998) Gestion des risques et des crises: l'exemple de deux crises d'origines volcaniques dans les Caraïbes: Montserrat 1995–1998 et la Guadeloupe 1976–1977. Mémoire de Maîtrise de Géographie, Université de Paris 1, Panthéon-Sorbonne, Paris, unpublished, 164 pp.

Biggs J, Ebmeier SK, Aspinall WP, Lu Z, Pritchard ME, Sparks RSJ, Mather TA (2014) Global link between deformation and volcanic eruption quantified by satellite imagery: Nat Commun 5

Blérald APh (1986) Histoire éruptive de la Guadeloupe et de la Martinique du XVIIème siècle à nos jours, Editions Karthala, Paris, 336 p

Benson C (2006) Volcanoes and the economy. In: Marti J, Ernst GGJ (eds) Volcanoes and the environment. Cambridge University Press, pp 440–467.

Brealey R, Myers S, Allen F (2011) Principles of corporate finance. McGraw, 872 p

Bretton R, Gottsmann J, Aspinall WP, Christie R (2015) Implications of legal scrutiny processes (including the L'Aquila trial and other recent court cases) for future volcanic risk governance. J Appl Volcanol 4:18

Brown SK, Auker MR, Sparks RSJ (2015) Populations around Holocene volcanoes and development of a population exposure index. In: Loughlin SC et al (eds) Global volcanic hazards and risk 'populations around volcanoes and the development of a population exposure index. Cambridge

Burton I (2010) Forensic disaster investigations in depth: a new case study model. Environ Mag 52(5):36–41

Cashman KV, Sparks RSJ (2013) How volcanoes work: a 25 year perspective. Geol Soc Am Bull. doi:10.1130/b30720.1

Carn SA, Froyd KD, Anderson BE, Wennberg P, Crounse J, Spencer K, Dibb JE, Krotkov NA, Browell EV, Hair JW, Diskin G, Sachse G, Vay SA (2011) In situ measurements of tropospheric volcanic plumes in Ecuador and Colombia during TC4. J Geophys Res Atmos, 116

Christie R, Cooke O, Gottsmann J (2015) Fearing the knock on the door: critical security studies insights into limited cooperation with disaster management regimes. J Appl Volcanol 4:19

Christopher TE, Blundy J, Cashman K, Cole P, Edmonds M, Smith PJ, Sparks RSJ, Stinton A (2015) Crustal-scale degassing due to magma system destabilization and magma-gas decoupling at Soufrière Hills Volcano, Montserrat: Geochemistry. Geophys Geosyst 16(9):2797–2811

Dasgupta P (1988) Trust as a commodity. In: Gambetta D (ed) Trust: making and breaking of cooperative relations. Blackwell, Oxford, 49–72

De la Cruz-Reyna S, Tilling RI (2008) Scientific and public responses to the ongoing volcanic crisis at Popocatépetl Volcano, Mexico: importance of an effective hazards-warning system. J Volcanol Geotherm Res 170:121–134

Esposti Ongaro T, Cavazzoni C, Erbacci G, Neri A, Salvetti MV (2007) A parallel multiphase flow code for the 3D simulation of volcanic explosive eruptions. Parallel Comput 33:541–560

European Commission (2010) Press Release 27. April, 2010). http://ec.europa.eu/commission_2010-2014/kallas/headlines/news/2010/04/doc/information_note_volcano_crisis.pdf

Fearnley C, Bird D, Haynes K, Jolly G, McGuire B (eds) (2017) Observing the volcano world: volcano crisis communication. Advances in volcanology, IAVCEI. Springer, Berlin, 350 p

Feuillard M, Allegre CJ, Brandeis G, Gaulon R, Le Mouel JL, Mercier JC, Pozzi JP, Semet MP (1983) The 1975–1977 crisis of La Soufrière de Guadeloupe (FWI): a still-born magmatic eruption. J Volcanol Geotherm Res 16:317–334

Few R, Armijos T, Barclay J (2017) Living with Volcan Tungurahua: the dynamics of vulnerability during prolonged volcanic activity. Geoforum 80:72–81

Fischhoff B (2013) The sciences of science communication. In: Proceedings of the National Academy of Sciences of the United States of America, 110 (Supplement 3), 14033–14039. doi:10.1073/pnas.1213273110

Fiske R (1984) Volcanologists, journalists, and the concerned local public: a tale of two crises in the eastern Caribbean. In: Boyd F (ed) Explosive volcanism: inception, evolution and hazards. Studies in geophysics. National Academy Press, Washington DC, pp 170–176

Fournier TJ, Pritchard ME, Riddick SN (2010) Duration, magnitude, and frequency of subaerial volcano deformation events: new results from Latin America using InSAR and a global synthesis. Geochem Geophys Geosyst 11:Q01003. doi:10.01029/02009GC002558

Global Volcanism Program (2013) Volcanoes of the World, v. 4.5.5. In: Venzke E (ed) Smithsonian Institution. Downloaded 04 May 2017. http://dx.doi.org/10.5479/si.GVP.VOTW4-2013

Haynes K, Barclay J, Pidgeon NF (2008) The issue of trust and its influence on risk communication during a volcanic crisis. Bull Volcanol 70:605–621

Hicks A, Few R (2015) Trajectories of social vulnerabiltiy during the Soufriere Hills volcanic crisis. J Appl Volcanol 4:10

Hill DP, Johnston MJS, Langbein JO, Bilham R (1995) Response of Long Valley caldera to the Mw = 7.3 Landers, California, Earthquake. J Geophys Res 100 (B7):12985–13005

Hickey J, Gottsmann J, Mothes P, Odbert HM, Prutkin I, Vajda P (2017) The ups and downs of volcanic unrest: insights from integrated geodesy and numerical modelling. Adv Volcanol 1–17

Hincks T, Komorowski J-C, Sparks RSJ, Aspinall WP (2014) Retrospective analysis of uncertain eruption precursors at La Soufrière volcano, Guadeloupe, 1975–77: volcanic hazard assessment using a Bayesian Belief Network approach. J Appl Volcanol 3:3

IAVCEI task force on crises protocols (2016) Toward IAVCEI guidelines on the roles and responsibilities of scientists involved in volcanic hazard evaluation, risk mitigation, and crisis response. Bull Volcanol 8(31). doi:10.1007/s00445-00016-01021-00448

IRGC (2017) https://www.irgc.org/risk-governance/irgc-risk-governance-framework/. Last accessed 05/02/2017.

Johnson BB (1987) Accounting for the social context of risk communication. Sci Technol Stud, 103–111

Jolly AD, Jousset P, Lyons JJ, Carniel R, Fournier N, Fry B, Miller C (2014) Seismo-acoustic evidence for an avalanche driven phreatic eruption through a beheaded hydrothermal system: an example from the 2012 Tongariro eruption. J Volcanol Geotherm Res 286:331–347

Kokelaar BP (2002) Setting, chronology and consequences of the eruption of Soufrière Hills Volcano, Montserrat (1995–1999). In: Druitt TH, Kokelaar BP (eds) The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, vol 21. Geological Society, London, Memoirs, pp 1–44

Komorowski J-C, Boudon G, Semet M, Beauducel F, Anténor-Habazac C, Bazin S, Hammouya G (2005) Guadeloupe. In: Lindsay JM, Robertson REA, Shepherd JB, Ali S (eds) Volcanic Atlas of the Lesser Antilles, Seismic Research Unit, The University of the West Indies, Trinidad and Tobago, WI, 65-102

Komorowski J-C, Morin J, Jenkins S, Kelman I (2017) Challenges of volcanic crises on small islands states. In: Fearnley C, Bird D, Haynes K, Jolly G, McGuire B (eds) Observing the volcano world: volcano crisis communication', Advances in Volcanology, IAVCEI, Springer, Berlin, pp 1–18. doi:10.1007/11157_2015_15

Lepointe E (1999) Le réveil du volcan de la Soufrière en 1976: la population guadeloupéenne à l'épreuve du danger. In: Yacou A (ed) Les catastrophes naturelles aux Antilles – D'une Soufrière à l'autre. CERC Université Antilles et de la Guyane, Editions Karthala, Paris, pp 15–71

Maeno F, Nakada S, Oikawa T, Yoshimoto M, Komori J, Ishizuka Y (2016) Reconstruction of a phreatic eruption on 27 September 2014 at Ontake volcano, central Japan, based on proximal pyroclastic density current and fallout deposits. Earth, Planets and Space 68:82

Manville V, Major JJ, Fagents SA (2013) Modeling lahar behavior and hazards. In: Fagents S, Gregg T, Lopes R (eds) Modeling volcanic processes: the physics and mathematics of volcanism. Cambridge University Press, pp 300–330

Marzocchi W, Woo G (2007) Probabilistic eruption forecasting and the call for an evacuation. Geophys Res. Lett 34:L22310. doi:10.21029/22007GL031922

Marzocchi W, Sandri L, Selva J (2008) BET_EF: a probabilistic tool for long- and short-term eruption forecasting. Bull Volc 70:623–632

Mothes P, Yepes HA, Hall ML, Ramon PA, Steele AL, Ruiz MC (2015) The scientific-community interface over the 15 year eruptive episode of the Tungurahua Volcano, Ecuador. J Appl Volcanol 4:9

Mothes P, Ruiz MC, Viracucha EG, Ramón PA, Hernández S, Hidalgo S, Bernard B, Gaunt EH, Jarrín P, Yépez MA, Espín PA (2017) Geophysical footprints of Cotopaxi´s unrest and minor eruptions in 2015: an opportunity to test scientific and community preparedness. Adv Volcanol 1–30

OVSG-IPGP (1999–2013) Bulletin mensuel de l'activité volcanique et sismique de Guadeloupe. Monthly public report, Observatoire Volcanologique et Sismologique de Guadeloupe - Institut de Physique du Globe de Paris, Gourbeyre (ISSN 1622-4523). http://www.ipgp.fr/fr/ovsg/bulletins-mensuels-de-lovsg. Last accessed 11-10-2016

Phillipson G, Sobradelo R, Gottsmann J (2013) Global volcanic unrest in the 21st century: an analysis of the first decade. J Volcanol Geotherm Res 264:183–196

Potter S, Scott B, Jolly G, Neall V, Johnston D (2015) Introducing the volcanic unrest index (VUI): a tool to quantify and communicate the intensity of volcanic unrest. Bull Volcanol 77:1–15

Reid ME (2004) Massive collapse of volcano edifices triggered by hydrothermal pressurization. Geology 32:373–376

Ricci T, Barberi F, Davis MS, Isaia R, Nave R (2013) Volcanic risk perception in the Campi Flegrei area. J Volcanol Geoth Res 254:118–130

Rouwet D, Sandri L, Marzocchi W, Gottsmann J, Selva J, Tonini R, Papale P (2014) Recognizing and tracking volcanic hazards related to non-magmatic unrest: a review. J Appl Volcanol 3:17

Rouwet D, Constantinescu R, Sandri L (2017) Deterministic versus probabilistic volcano monitoring: not "or" but "and". Adv Volcanol. doi:10.1007/11157_2017_8

Sandri L, Tonini R, Rouwet D, Constantinescu R, Mendoza-Rosas AT, Andrade D, Bernard B (2017) The need to quantify hazard related to non-magmatic unrest: from BET_EF to BET_UNREST. Adv Volcanol. doi:10.1007/11157_12017_11159

Salvage RO, Karl S, Neuberg J (2017) Volcano seismology: detecting unrest in wiggly lines. Adv Volcanol 1–17

Sekiya S, Kikuchi Y (1890) The eruption of Bandai-san. Tokyo Imp Univ Coll Sci J 3:91–172

Sheldrake TE, Sparks RSJ, Cashman KV, Wadge G, Aspinall WP (2016) Similarities and differences in the historical records of lava dome-building volcanoes: Implications for understanding magmatic processes and eruption forecasting. Earth Sci Rev 160:240–263

Siebert L, Cottrell E, Venzke E, Andrews B (2015) Earth's volcanoes and their eruptions: an overview. In: Sigurdsson H et al (eds) The encyclopedia of volcanoes, 2nd edn. Elsevier, Amsterdam. http://dx.doi.org/10.1016/B978-0-12-385938-9.00012-2

Stone J, Barclay J, Simmons P, Cole PD, Loughlin SC, Ramon P, Mothes P (2014) Risk reduction through community-based monitoring: the vigías of Tungurahua. Ecuador. J. Appl. Volcanol. 3:11

Stirling A (2010) Keep it complex. Nature 468:1029–1031

Tazieff H (1980) About the Soufrière of Guadeloupe. J Volcanol Geotherm Res 8:3–6

Venezky D, Newhall C (2007) "WOVOdat Design Document; The Schema, Table Descriptions, and Create Table Statements for the Database of Worldwide Volcanic Unrest (WOVOdat Version 1.0)." U.S. Geological Survey Open-File Report, 184.

Woo G (2008) Probabilistic criteria for volcano evacuation decisions. Nat Hazards 45(1):87–97

Woo G (2015) Cost-Benefit analysis is volcanic risk. In: Papale P (ed) Volcanic Hazards, Risks and Disasters. Springer, pp 289–300. https://www.elsevier.com/books/volcanic-hazards-risks-and-disasters/papale/978-0-12-396453-3

Wadge G, Isaacs MC (1988) Mapping the volcanic hazards from Soufriere Hills Volcano, Montserrat, West Indies using an image processor. J Geol Soc 145(4):541–551
Wadsworth FB, Vasseur J, Scheu B, Kendrick JE, Lavallée Y, Dingwell DB (2016) Universal scaling of fluid permeability during volcanic welding and sediment diagenesis. Geology 44(3):219–222
Wilkinson E (2015) Beyond the volcanic crisis: co-governance of risk in Montserrat. J Appl Volcanol 4:3
Wilkinson E, Lovell E, Carby B, Barclay J, Robertson REA (2016) The dilemmas of risk sensitive development on a small volcanic island. Resources 5 (2):21. doi:10.3390/resources5020021
Wright TL, Pierson T (1992) Living with volcanoes. No. 1073. US Geologic Survey
Wynne B (1992) Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm. Glob Environ Change 2:111–127