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Assigning a volcano alert level: negotiating uncertainty, risk, and complexity in decision-making processes

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Abstract (175 words)

A volcano alert level system (VALS) is used to communicate warning information from scientists to civil authorities managing volcanic hazards. This paper provides the first evaluation of how the decision-making process behind the assignation of an alert level, using forecasts of volcanic behaviour, operates *in practice*. Using interviews conducted from 2007-2009 at five USGS managed volcano observatories (Alaska, Cascades, Hawaii, Long Valley, and Yellowstone) two key findings are presented here. First, that observatory scientists encounter difficulties in interpreting scientific data, and in making decisions about what a volcano is doing, when dealing with complex volcanic processes. Second, the decision to move between alert levels is based upon a complex negotiation of perceived social and environmental risks. This research establishes that decision-making processes are problematic in the face of intrinsic uncertainties and risks, such that warning systems become complex and non-linear. A consideration of different approaches to negotiating uncertainty and risk that are deliberative would, therefore, be beneficial in volcanic hazard management insofar as these suggest effective practices for decision-making processes in assigning an alert level.

Introduction

Recognising the social role of scientific uncertainty will help us to see how many of our problems about risk are deeply cultural and cannot be overcome simply by the application of more and better science (Jamieson, 1996, p.43).

Volcanic activity presents a complex problem for volcanologists and civil authorities who have to forecast and manage volcanic hazards. Certainly, failures in the management of volcano crises have led to a number of unnecessary localised disasters, such as that occurring in Nevado del Ruiz, Columbia (1985), resulting in over 23,000 deaths (Voight, 1990), and the Soufriere Hills, Montserrat (1995-continuing) which has resulted in significant socio-economic impacts (Druitt and Kokelaar, 2002). Volcanic activity can also have global impacts, as illustrated by the 2010 Eyjafjallajökull eruption and the disruption of air travel throughout Europe (Donovan and Oppenheimer, 2011). Despite advances in the technology and modelling used in forecasting volcanic hazards, there is growing recognition that these failures are due not only to insufficient knowledge of the physical science of volcanology, but also to insufficient understanding of the social, cultural and institutional dynamics that play a critical role in volcano Early Warning Systems (EWS). EWS are seen as ‘a means of getting information about an impending emergency, communicating that information to those that need it, and facilitating good decisions and timely response by people in danger’ (Mileti and Sorenson, 1990, p.2-1). EWS are a key disaster risk reduction tool as part of a program of volcanic hazard mitigation (see figure 1) that brings together the physical and social sciences to enable effective decision making. A volcano alert level system (VALS) is a specific part of a volcano EWS that relates to the processes occurring before and during establishing a volcano warning, and are defined as a ‘series of levels that correspond generally to increasing levels of volcanic activity’ (Gardner and Guffanti, 2006, p.1).

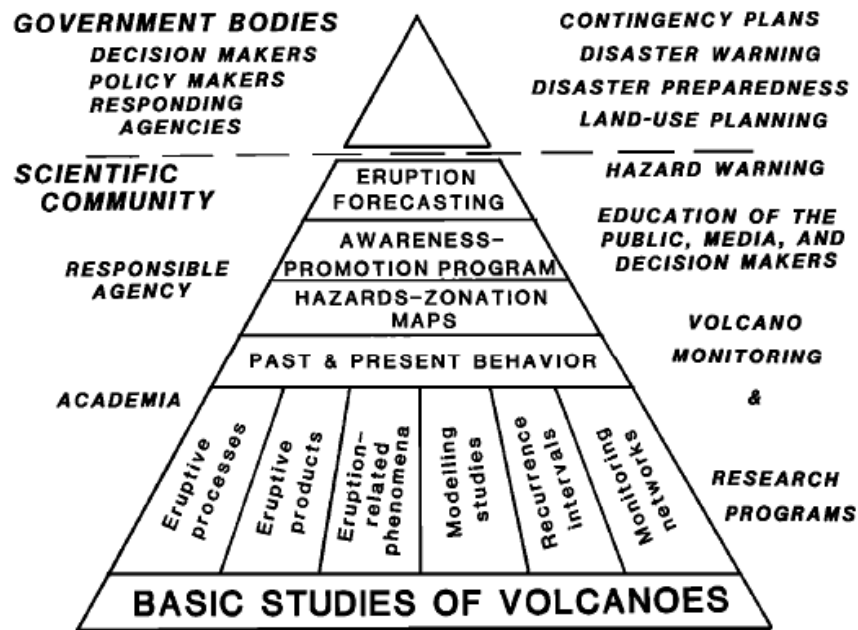


Figure 1. Volcano hazard mitigation (Tilling, 1989, p.242). This diagram contains all the elements of an EWS that work together to make warnings effective, yet Tilling clearly shows a divide between the scientific community and the government bodies involved in the EWS.

Volcano-related disasters over the last century indicate that the effectiveness of a volcano EWS is hindered by weaknesses in procedures and infrastructures; poor integration and sharing of knowledge between scientists and communities; and ineffective communication (Peterson et al., 1993), despite published guidelines on the professional conduct of scientists during volcanic crises (Newhall et al., 1999). Yet, little research has been devoted to establishing the everyday social context within which such decision-making takes place, be it what scientists want to communicate, how that information is used to take actions by government bodies, as well as the public response to information (De la Cruz-Reyna and Tilling, 2008; Metzger et al., 1999). Both EWS and VALS remain ‘black box’ concepts, in the words of Latour (1987), where the inputs and outputs are known but the inner workings, including decision-making processes, remain unexamined and hence closed to debate.

Volcano observatories play a crucial role across the world as the primary institutional sites at which data collection and analysis occurs from which warnings are issued, and they are key to an evaluation of the

efficacy of both EWS and VALS (Garcia and Fearnley, 2011). In this paper, approaches adopted by volcano observatories to manage scientific uncertainty and risk in decision-making processes are discussed, first by evaluating related literature within both physical and social sciences, and, second, analysing research conducted at the United State Geological Survey (USGS). Before this however, the methodology adopted in this study is discussed, followed by details of the case study sites.

Study Methodology

The study adopts a mixed methodology that aims to develop an understanding of how decision-making occurs in relation to the perception of what alert level should be assigned. Research was conducted at all five volcano observatories of the USGS to understand the construction and operation of the VALS used. Three weeks were spent at each location to gather data via semi-structured interviews, and document and archival collection and analysis.

In all, 93 semi-structured interviews were completed with: actors involved in the VALS; scientists within the Volcano Hazard Program (VHP), including volcanologists, seismologists, glaciologists and chemists; users of the VALS at other federal agencies; members of the Volcanic Ash Advisory Centre (VAAC); and collaborative partners, such as Universities and State officials. The interviews provided insights into the individualised experiences of scientists and users involved in the VALS decision-making processes, as well as the routinised behaviours, expectations and practical concerns animating their day-to-day work. Quotes provided in the text are anonymous to protect the interviewees' identity, however the observatory or federal agencies of the interviewee is identified to provide an appropriate context.

Interviews were complemented by observation of the interactions between agencies, cohorts and individuals, and document analysis of the historical emergence and stabilisation of the USGS' policies. During the research no volcanic crisis was experienced by the researcher and therefore all accounts of

crises reflect the interviewee's reconstruction of the event. As such, there are a number of uncertainties and ambiguities of researching daily practices that are difficult to avoid, including contested realities and partial truths. However, the use of mixed methodology, and engaging with large numbers of stakeholders facilitates a greater understanding of how knowledge is developed. Research by Nightingale (2003) analyses decision-making processes to demonstrate that understanding different perspectives to knowledge is critical to learning how decision-making processes occur. Nightingale states that 'qualitative, interpretive methods provide rich, thick results, but combined with other methods, these results can be richer and thicker, and we can demonstrate how fragmented and situated all knowledge is' (2003, p.86).

Study Sites: The United States Geological Survey (USGS) Observatories

The USA has 108 active volcanoes, providing good reason for the USGS to provide for five well-funded volcano observatories in Alaska (AVO), the Cascades (CVO), Hawaii (HVO), Long Valley (LVO), and Yellowstone (YVO), all regions of significant volcanic hazard, high population or important infrastructure (see figure 2 for locations). Operating under a federally funded Volcano Hazard Program (VHP) established in 1980, they are also responsible for monitoring volcanoes in the Kurile Islands (SVERT), collaborate with the Kamchatkan Volcano Observatories (KVERT), and provide international assistance via the USGS/USAID Volcano Disaster Assistance Program (VDAP). Not only does the USGS have staff experienced in volcano crises in numerous countries, in particular Chile, Ecuador, the Philippines and Indonesia, but the USA also has volcanoes within six different tectonic zones (more than any other country), which means they have to monitor the most diverse range of volcanoes in the world. These vary from oceanic hotspots like Hawaii, pouring out lava every day, to stratovolcanoes violently exploding in Alaska that frequently produce abundant ash, and to massive volcanoes such as the Yellowstone caldera that rarely erupt but exhibit periods of unrest.

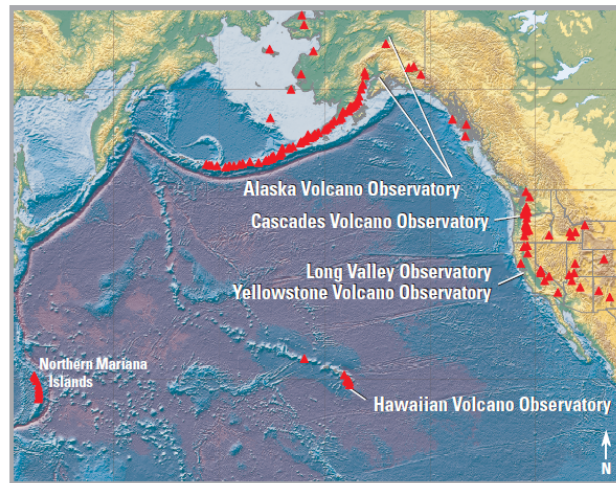


Figure 2: The U.S. Geological Survey (USGS) is responsible for monitoring at the five volcano observatories operated by the USGS Volcano Hazards Program (Gardner and Guffanti, 2006, p.1)¹

In 2006, the USGS adopted two standardised VALS (one for ground-based hazards, and the other for aviation ash hazards; see Table 1) replacing existing VALS that had been developed locally at each observatory (Gardner and Guffanti, 2006). The VALS developed by the Alaska Volcano Observatory (AVO) was adopted as the international warning system for volcanic ash by the International Civil Aviation Organisation (ICAO) in 2006, and is the first globally standardised VALS in the world. Early warning is important to the USGS, exemplified by their New Volcano Early Warning Systems report (NVEWS) (Ewert et al., 2006; Ewert et al., 2005) that addresses the need to balance monitoring, research capabilities and warning requirements to manage volcanic crises successfully. In 2009, the U.S. American Recovery and Reinvestment Act allocated US\$15.2 million to upgrade volcano monitoring to provide state-of-the-art monitoring capabilities (USGS Newsroom, 2010).

¹ As of 2012 Long Valley Observatory has been renamed as California Volcano Observatory (CalVO).

Volcano Alert Levels Used by USGS Volcano Observatories	
Alert Levels are intended to inform people on the ground about a volcano's status and are issued in conjunction with the Aviation Color Code. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption and about potential or current hazards and likely outcomes.	
Term	Description
NORMAL	Volcano is in typical background, noneruptive state or, after a change from a higher level, volcanic activity has ceased and volcano has returned to noneruptive background state.
ADVISORY	Volcano is exhibiting signs of elevated unrest above known background level or, after a change from a higher level, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
WATCH	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, OR eruption is underway but poses limited hazards.
WARNING	Hazardous eruption is imminent, underway, or suspected.

Aviation Color Code Used by USGS Volcano Observatories	
Color codes, which are in accordance with recommended International Civil Aviation Organization (ICAO) procedures, are intended to inform the aviation sector about a volcano's status and are issued in conjunction with an Alert Level. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption, especially in regard to ash-plume information and likely outcomes.	
Color	Description
GREEN	Volcano is in typical background, noneruptive state or, after a change from a higher level, volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level or, after a change from a higher level, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, OR eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely OR eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Table 1: The two VALS developed and adopted by the USGS in 2006: volcano alert levels and aviation colour codes

As part of the USGS, the Volcano Hazard Program (VHP) works on broader public, interstate and regional issues involving other agencies, referred to as ‘users’ in this paper, such as federal and state land and mineral agencies: FEMA, Emergency Services, other Federal Agencies including the U.S. Forest Service (USFS), National Weather Service (NWS), National Park Service (NPS), National Aeronautics and Space Administration (NASA); Federal and non-Federal the clients of emergency-response planning, such as the Federal Aviation Authority (FAA) and U.S. Armed Forces; and non-federal organisations such as state and private universities. The need for such diverse federal involvement in the VHP is due to the interstate, regional and national implications of volcanic disasters, including economic disruption and effect on federal lands (see figure 3)

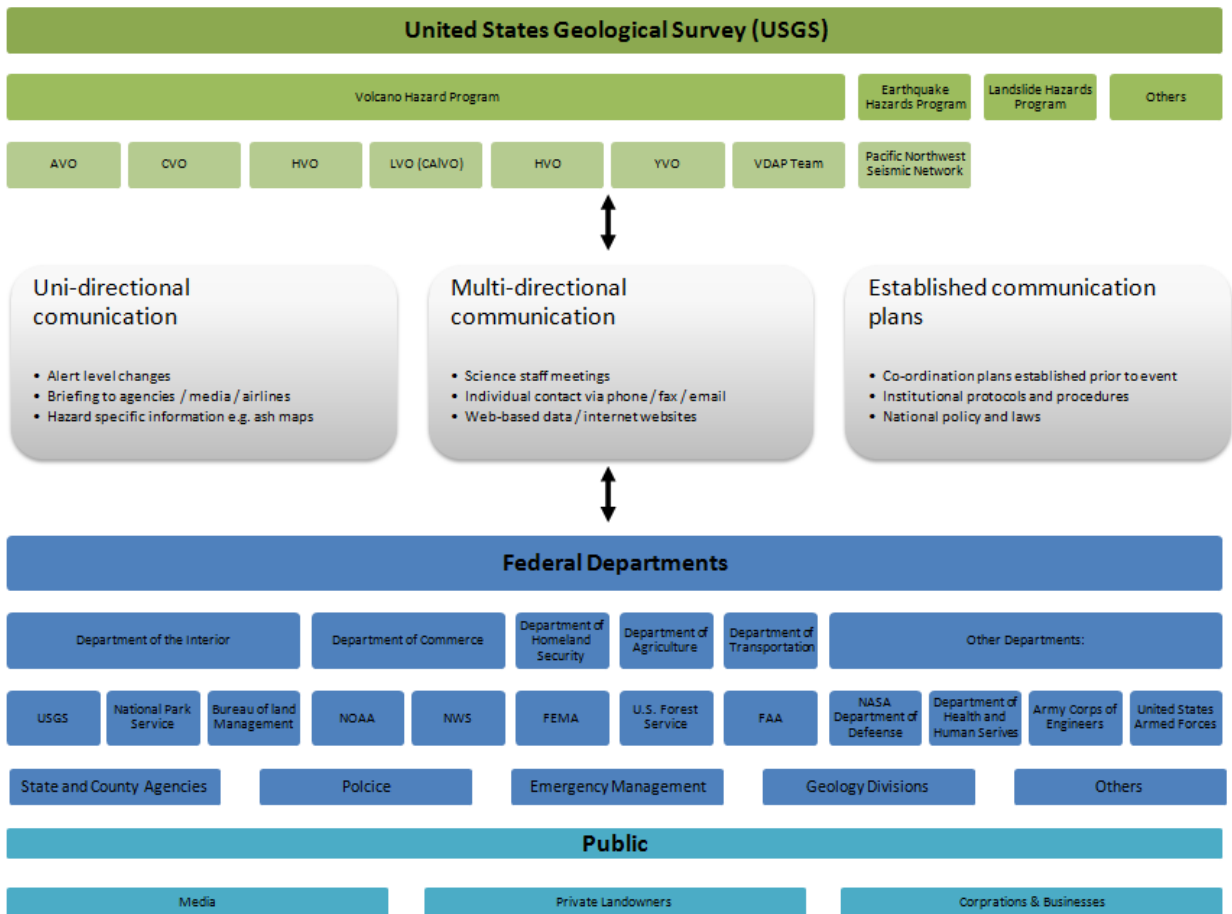


Figure 3: Organisational chart to show the relationships, responsibilities, and communication tools between the USGS and other users during volcanic crises. The exact relationships cannot be mapped as this is dependent on the nature of the volcanic hazard, location of the crisis, and the established emergency protocols for a particular volcano.

Managing Volcanic Scientific Uncertainty

Volcanoes are complex natural phenomena because, whilst their behaviour tends to follow some underlying principles, it is not linear in nature (Sornette et al., 1991). To date the volcanological community has been unable to generate accurate and reliable predictive models for use on a single volcano, let alone for the many types of volcano and styles of eruption that occur. This complexity is exacerbated by: the different tectonic settings that influence magma composition and the size, explosivity and style of eruptive activity; the range of associated hazards; and the duration of volcanic events, from days to decades, and the changes that may occur during this time. In the face of such

complexity, three methods are employed. These are: reviewing a volcano's history (Chester et al., 2005; Pareschi et al., 2000), monitoring it (McGuire et al., 1995; Scarpa and Tilling, 1996), and developing engineered structures that can mitigate or protect against volcanic hazards (Barberi et al., 1993; Ikeya, 2008; Takahashi, 2007; Williams and Moore, 1983). Once a volcano erupts there is often no time to evacuate affected regions, and therefore a precautionary approach is often adopted.

Prediction or forecasting are often considered synonymous; however, it is recommended to define a forecast as a comparatively imprecise statement of the time, place, and nature of expected activity, and a prediction as a comparatively precise statement of the time, place and ideally, the nature and size of impending activity (Swanson et al., 1985). Scientists (typically geochemists, geophysicists, geologists, volcanologists and mathematicians) have exploited a range of quantitative theoretical and statistical models of volcanic monitoring data to develop better prognoses of a volcano's behaviour, and to deal with the high levels of uncertainty involved (Kilburn, 2003). Sparks (2003) argues that 'forecasts of eruptions and hazards need to be expressed in probabilistic terms that take account of uncertainties' (p.1); and, it is generally accepted that statistical analysis of complex volcanological data can improve forecasting by developing rigorous methods for quantifying the likelihood of outcomes given a set of observations, both present and past (Mader, 2006). Some volcanologists argue that the future of forecasting lies in further statistical modelling (Marzocchi and Woo, 2009).

It is also recognised, however, that the statistical modelling of volcanic behaviour and processes inevitably has high levels of uncertainty, making decisions based on the interpretation of raw data difficult. To mitigate this issue, decision-support models are commonly applied (for example in Auckland (Lindsay et al., 2010)), based on Bayesian Belief Networks (BBN), otherwise known as causal probabilistic networks, to provide a method to represent relationships between propositions or variables, even if their relationships are unknown or unpredictable (Aspinall et al., 2003; Jensen, 1996). A method commonly used by volcanologists is the 'event tree', used as a framework to discuss the

probabilities of possible outcomes of volcanic unrest and convey hazard information to non-scientists (Newhall and Hoblitt, 2002). Additionally, combining an evidence-based approach with other formalised procedures, such as the elicitation of expert opinions, provides an auditable trail for the way scientific information has been used (Aspinall et al., 2002; Aspinall et al., 2006b; Aspinall et al., 2003). Quantifying the value of expert opinion is difficult, and has in the past generated controversy, as in the Montserrat crisis (1996-7) (Haynes et al., 2008). Eschewing expert opinion, Marzocchi et al. (2006; 2007) have developed a quantitative volcano risk metric that translates volcanological input into probability of any possible volcano-related event, to base decisions for eruption forecasting using a Bayesian Event Tree (BET_EF), and a probabilistic scheme for eruption forecasting and cost-benefit analysis (Marzocchi and Woo, 2007).

Quantifying the decision to change alert levels

Of particular interest to this study is the quantitative approach adopted to *change* an alert level (Aspinall et al., 2003; Baxter et al., 2008). As Aspinall et al. remark,

Volcanic crises may be represented as a staged progression of states of unrest [and] if the state conditions can be interpreted physically, e.g., in terms of advancing materials failure, this knowledge could be used directly to inform a decision on alert level setting (Aspinall et al., 2006a, p.112).

By developing an expert elicitation system, Aspinall et al. have proffered an ‘optimal’ value emerging from a measure of the spread of expert views (see figure 4). Although Aspinall et al. recognise the difficulty in identifying the ‘state’ of the volcano, they suggest that by using such a decision-support tool ‘the assessed probability of an event to any number of such varying and variable factors can be resolved *objectively* in terms of an evidence-based decision’ (Aspinall et al., 2003, p.284) (author’s emphasis). And yet, Aspinall et al. go on to state that in practice there will ‘often be a multitude of observations,

theories, models and expert opinions to consider, most of which can address only partially the issue of a volcano's state and its possible progress to eruption, and some of which will be contradictory' (Aspinall et al., 2006a, p.113), implying that there are no objective interpretations (Donovan et al., 2012).

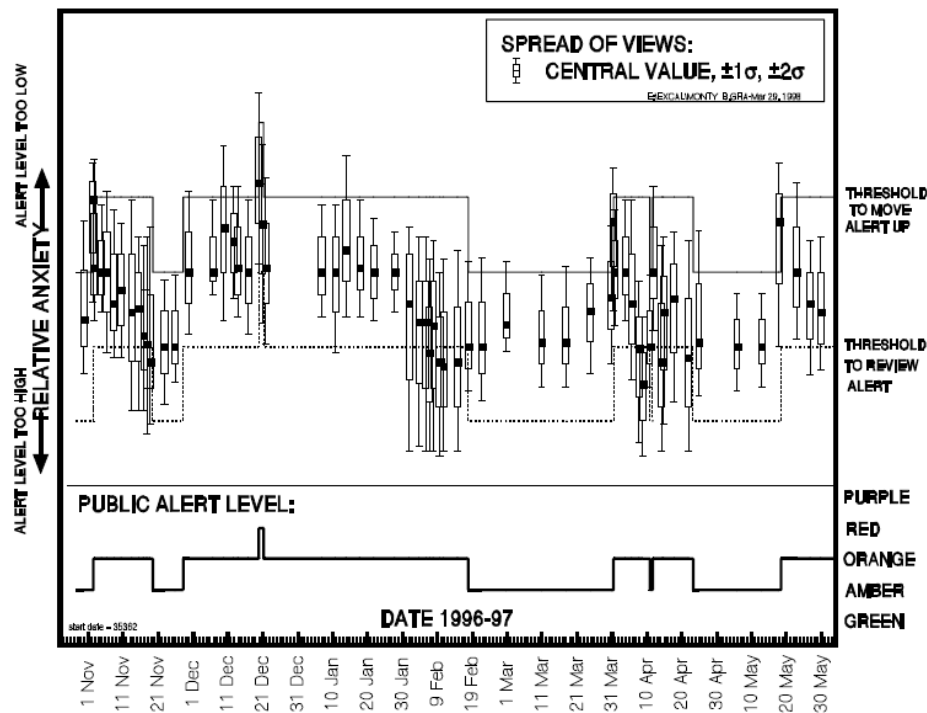


Figure 4. Repeat appraisals of volcanic alert level using expert judgement elicitations (Aspinall and Cooke, 1998, p.4)

The use of such quantitative and/or expert-based risk assessment techniques, including 'varying forms of scientific experimentation and modelling, probability and statistical theory, cost-benefit and decision analysis, and Bayesian and Monte-Carlo methods' (Stirling, 2007, p.309), reflect academic groups working in risk management that prioritise a range of intrinsically reductive processes, translating complex and contested realities (i.e., what a volcano's activity is) into a discrete set of ordered categories (such as alert levels).

A traditional risk assessment uses a powerful set of methods when evaluating risk, but they are not as relevant within conditions of high uncertainty (Aven, 2003). Knight established the distinction between risk and uncertainty: 'a measurable uncertainty, or 'risk' proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all. We [...] accordingly restrict the term 'uncertainty' to cases of the non-quantitative type' (Knight, 1921, p I.I 26). Consequently, there have been numerous attempts to better frame uncertainty including: 'post-normal science' by Funtowicz and Ravetz (1993); Wynne's identification of different types of uncertainty: risk, uncertainty, ignorance, and indeterminacy (1992); and Spiegelhalter and Riesch who developed a five level structure for assessing and communicating uncertainties focusing on inadequacies in the modelling process and disagreements in the framing process (2011). Building on Wynne's model (1992), Stirling (2007) developed the concept of 'incertitude' that combines uncertainty, ignorance, ambiguity and risk to provide a more holistic view of knowledge, or lack of.

The sub-table on risk in Table 2 synthesises the volcanological literature that evaluates methods of assessing risk, usually adopted under conditions when volcanic systems are familiar, to show studies that have considered risk, uncertainty, ambiguity, and ignorance in isolation. The sub-table on uncertainty reviews the methods used to analyse the complex behaviour of volcanoes that typically deploy historical data to understand the volcano's past behaviour and thus indicate future behaviour, and that formulate possible outcomes via event trees. Ambiguity here relates to the contested framings, assumptions and disagreements between experts, and relates to the impact of behaviour, trust, compliance, ethics and equality when assessing risk and uncertainty and making sense of data. Volcanological approaches to ambiguity have predominantly revolved around the work conducted on expert elicitation and guidelines developed for scientists during a crisis. In short, the quest to understand incomplete knowledge and unanticipated events is driven by experimental research, the monitoring of volcanoes, and the development of databases to share knowledge across space.

Decision-making in uncertainty

Making decisions in contexts of high risk and uncertainty is challenging, requiring a number of actors from different discourses and experts to come together to 'establish cooperation and heterogeneity' (Shackley and Wynne, 1996, p.293). They believe that such 'boundary-crossing' is essential to allow scientists to translate uncertainties so its reduction is understood, as well as to preserve scientific integrity, particularly in policy development. In support, Jasanoff states that 'the construction of stable knowledge interpenetrates with the formation of core elements that stabilize society: identities, institutions, discourses and representations, among others' (2010, p.236) forming what she terms 'co-production'. Jasanoff argues that 'environmental knowledge achieves robustness through continual interaction – or conversation – between fact-finding and meaning-making' (Jasanoff, 2010, p.248). In the context of volcanic crises, where there are numerous actor and stakeholders involved, this implies that not only should different experts be involved in the co-production of knowledge given significant uncertainties, but that representations of the environment (such as an alert level) 'do not arise from scientific activity alone, through scientists' representations of the world as it *is*, but are sustained by shared normative and cultural understandings of the world as it *ought* to be' (Jasanoff, 2010, p.248).

In the light of the above, it becomes all the more important to examine how such decision-making takes place in daily practice. In the following section, research conducted at the volcano observatories of the United States Geological Survey (USGS) is analysed to examine how uncertainty and risk are managed operationally in the decision-making process to assign a volcano alert level.

Risk: State of incomplete knowledge: familiar systems, controlled conditions, engineering failure

Ambiguity: State of incomplete knowledge: contested framings, questions, assumptions, methods, comparing incommensurables, disagreements between specialists, disciplines; issues of behaviour, trust and compliance; interest, language; matters of ethics and equity

Methodological Responses	Related Volcano Literature	References
Risk assessment	Mapping and historical evidence	(Pareschi, Cavarra et al. 2000)
Multi-attribute utility theory	Statistical models – predictive and hazard specific	(Varley, Johnson et al. 2006)
Cost-benefit, decision analysis	Decision analysis with cost benefit models	(Marzocchi and Woo 2007)
Monte Carlo modelling	Monte Carlo models	(Jaquet, Carniel et al. 2006)
Bayesian methods	BET modelling	(Marzocchi, Sandri et al. 2007)
Usually managed using statistical errors, levels of proof		

Methodological Responses	Related Volcano Literature	References
Participatory deliberation	Expert solicitation, stakeholder negotiation	(Aspinall, Mader et al. 2006)
Stakeholder negotiation	IAVCEI crises guidelines	(Newhall, Aramaki et al. 1999)
Q-method, repertory grid	None known	
Scenario workshops	Conducted in several countries	(Laughery 2006)
Multi-criteria mapping	Multi-criteria mapping in decision-making processes	(Mitchell 2006)
Usually managed by interactive modelling		

Uncertainty: State of incomplete knowledge: complex, non-linear, open systems

Ignorance: State of incomplete knowledge: unanticipated effects, conditions; surprises, unknowns

Methodological Responses	Related Volcano Literature	References
Burden of evidence	Geological reports looking at eruption styles	(Tilling 2002)
Onus of persuasion	Research further to understand volcano behaviour	(Dzurisin 2007)
Uncertainty factors	Use event trees and databases	(Newhall and Hoblitt 2002)
Decision heuristics	None known	
Interval Analysis	Volcano interval analysis	(Pyle 1998)
Usually managed using sensitivity analysis		

Methodological Responses	Related Volcano Literature	References
Targeted research and horizon scanning	Monitoring volcanoes	(McGuire, Kilburn et al. 1995; Ewert, Guffanti et al. 2005; Ewert, Guffanti et al. 2006)
Transdisciplinary and institutional learning	Experimental research	(Johnson, Aster et al. 2008)
Open-ended surveillance and monitoring	Overseas assistance	USGS VDAP team
Evidentiary presumptions	Databases	WOVOdat
Usually managed by adaptive management		

Table 2. Studies within the volcanological community that address the methodological responses to risk decision-making, and ‘uninvestigated’ responses framed by Stirling’s model of incertitude (Stirling, 2003, 2007)

Decision-Making in Practice: Negotiating Uncertainty and Risk

Decision-making is a core component of VALS that revolves around such questions as what the monitoring data are indicating about volcanic behaviour, how this affects the alert level, whether to change the alert level and when, and what information to communicate to users and stakeholders. Each alert level has a 'description' that acts as criteria for that level. This criteria is based only on the physical aspects of the volcano and hazards produced, and does not provide any guidance for mitigative actions (see figure 1), thus adhering to the 1988 Robert T. Stafford Disaster Relief and Emergency Assistance Act (public law 100-707)(USGS, 2004). Consequently, for the scientists, decisions primarily relate to a volcano's behaviour however; there are secondary considerations for vulnerable populations and infrastructure for which they have responsibility, along with institutional protocols.

Constructing expert knowledge

Before scientists discuss what alert level volcanic activity should be assigned, there is a rigorous process of establishing what is going on within the volcanic system. This process depends upon the observatory's capacity to set up and maintain monitoring equipment, interpret and analyse the data, and develop warnings. In practice, there are also 'incomplete data sets, some individual familiarity, [and] pattern recognitions' that play into the scientists' understanding of a volcano's behaviour (AVO senior scientist 5) (8/04/2008). The more monitoring equipment available, the more confident scientists are in determining what is going on (CVO scientist 13) (2/05/2008). This is because effective monitoring of a volcano's many 'symptoms' provide for a better understanding of normal background activity, such that abnormal activity can be more readily identified. The following quote from a scientist at CVO highlights the individuality of volcanoes:

When I try and describe this problem to people I often use a medical analogy. You know there is a tremendous amount of information about the population of people, about the percentage of people who will have heart attacks [...] but when you come down to one

person, you can't say 'well you are going to have a heart attack at the age of 63'. We can say that 35% of population will have a heart attack by 63, but we can't say anything about an individual (CVO senior scientist 7) (23/05/2008).

Understanding a volcano is 'part science, partly an art' (CVO senior scientist 7) (23/05/2008), since volcanoes can behave in unexpected ways; becoming familiar with these patterns is considered crucial to generating more precise forecasts. Even so, 'volcanoes can have long-term illness or heart attacks' (AVO senior scientist 5) (8/04/2008).

Although monitoring data can provide specific measurements about what is happening at the volcano, it is clearly difficult to interpret in a meaningful (that is, predictive) way what these measurements imply about the volcano's behaviour. In establishing this decision, negotiation within the group of scientists is key. All VHP observatories have procedures in place for committees to convene if abnormal monitoring data are identified, either by automated alarms or observation. The committees commonly include the scientist in charge (SIC) who is the head/representative of the volcano observatory, their deputy and representatives from different or relevant scientific groups within the observatory such as seismic, deformation, gas and ash, and satellite imagery. Together they review the data, interpret them, and establish possible scenarios for forecasts. This involves discussing the data, historical behaviour at the volcano or similar volcanoes, and the value and significance of one particular data stream (e.g. seismicity) versus several different streams (e.g. ground deformation, geochemical anomalies). It also involves making clear where uncertainty lies.

In communicating forecasts, the main goal is, in the words of one scientist, to 'alert people, tell people as much as we can. Whether it is right or wrong is less important' (HVO senior scientist 3) (18/06/2008). Many users, however, have difficulty in distinguishing between a prediction and forecast (Swanson et al., 1985). As a scientist in Hawaii stated, 'we try and use precise language in science but

the public does not speak this language' (HVO scientific collaborator) (12/06/2008). There are complications, then, not only in developing forecasts based on current monitoring data, but also in the interpretation of them by users and their understanding of the uncertainties involved.

Deciding an alert level

The scientist in charge (SIC) has the responsibility to allocate an alert level. In practice, the process of interpreting monitoring data and setting an appropriate alert level usually occurs during a meeting between the scientists at the observatory, held regularly (daily, weekly, monthly) or infrequently depending on the activity of the volcano. During fieldwork at CVO, for example, a meeting that reviewed the alert level for Mt St Helens was attended. Most CVO staff attended, with the University of Washington (their academic partner) and other agencies dialled in by telephone to participate in the debate. The decision-making process was 'democratic' in that each specialist scientific group (e.g. seismologists, geochemists) presented their data, the possible interpretations, and their consensus. Other scientific groups asked questions about the data, often leading to discussion. Following the views of all specialist groups, the group as a whole discussed the implications of the data presented, and what the data inferred about the volcano's current activity.

On most occasions the SIC follows the consensus, unless they are privy to additional information usually relating to other social or institutional factors (CVO senior scientist 2) (9/05/2008). Interestingly, throughout the process observed there was no use of probabilistic models or event trees (although they could have been used to guide the discussion by each scientific group); instead, open discussion and debate was used to make decisions.

A majority of the scientists interviewed thought that event trees provide a 'very effective way for both the scientists to think through the logic of sequence of events and the accumulative probabilities [...] give you a good sense of the uncertainties involved in the full process' (CVO senior scientist 7)

(23/05/2008). Bayesian Event Trees are used within the VHP as a tool for stimulating discussions internally or with other actors about the likelihood of events. Some scientists, however, expressed concern at their use; 'it's all a fairly subjective expert opinion thing, but you base it on what the behaviour of this volcano was in the past and ask what it is capable of doing; what do you think is the likelihood?' (CVO senior scientist 8) (1/05/2008).

In interviews, it also became apparent that a probabilistic approach was considered problematic in that it requires input from a number of different volcanoes, and in any one crisis 'each volcano is unique and so you might get generalities out of probabilistic assessments, [...] but it's really more than generality that you really want to know about that particular volcano' (HVO senior scientist 5) (16/06/2008). Some of the scientists regard an alert level as an 'implicit probabilistic risk assessment' (AVO scientist 4) (14/04/2008). Yet, for some, it seems inevitable that event trees will be used more in the future as they provide a semi-quantitative basis for decision making (VHP manager 3) (21/08/2008), as Aspinall and Cooke have already explored (1998). Using quantitative methods for deciding alert levels provides an audit trail of the decision-making process, which is critical when scientists are concerned about accountability. Whilst such statistical models exist for volcanoes, they are not necessarily useful since 'what is not communicated [to the users] is any sense of the uncertainty of that number' (CVO scientist 3) (7/05/2008). People have different perceptions of risk and so percentages are regarded differently dependent on that person's risk perception (Slovic, 2000). Experience can play a large part in expert elicitation, however, by enabling more flexible methods of decision-making, such as deliberation; the decision to assign an alert level can also incorporate experience (albeit only that of the scientists involved) and local environmental and social contexts.

In the absence of significant databases on each volcano and their behavioural characteristics, prior experience, familiarity with the volcano, and 'gut feeling;' clearly plays a vital role in interpreting what is going on at the volcano. Alert levels are not simply changed because some seismic activity meets some

criteria level; ‘it has to be a conscious, scientific decision whether we change levels [...] you just can’t do it by modelling, you can’t do it by theoretical methods. There is no magical threshold at which at some point the volcano erupts’ (VHP manager 4) (23/05/2008). At AVO, one senior scientist provided a representative view of the process, outlining the difficulties in deciding when to change and the role uncertainty plays:

There is a big difference between ramping up the colour code and ramping back down. We tend to ramp up relatively quickly, and then probably tend to stay at colours for longer than we should. With 20/20 hindsight we probably ought to ramp up sooner than we do. We always seem to be ‘look at this’, and this comes into how we forecast volcanic eruptions and many people are upset or bothered by the fact that it is still as much an art as it is a science. It doesn’t come from the idea that we understand this is what is going to happen and we can assign a probability to it and say well, we understand exactly what’s happening at this volcano and it is going to erupt next Tuesday (AVO senior scientist 5) (8/04/2008).

The desire to not adhere to criteria for the alert level indicates that the scientists are aware of the need to interpret large sets of data, rather than pigeonhole one set of data on which to make decisions. As a scientist from AVO outlines, the decision-making process is also different for different stages of volcanic activity, especially if eruptions are imminent:

The early colour code decisions are more *strategic* in nature. I think when you get towards an eruption they are much more *tactical*; you know an event just happened, what do you do? And those [decisions] have to be very quick. The early strategy of [...] ‘how [are] you going to get people buying into the idea that things are changing and it could lead into an eruption’ are much more strategic and involve a large group of people. When you get down to tactical responses the damage has happened and it typically involves a much smaller

group of people who have to be on top of the game in realising that something significant just happened, because then the timeframes are compressed and [people] really want to get things out as quickly as possible (AVO scientist 3) (11/04/2008) (author's emphasis).

The type of volcanic activity occurring affects the strategic and tactical response to change alert levels, whether it is quick, changeable or significant. This alludes to the consideration of risk when changing alert levels, certainly, but also indicates the strategic use of VALS to create awareness of something occurring at the volcano. This can be seen in the following quote from a scientist at CVO who explains that sometimes the decisions of the VALS in the observatory do not reflect 'true' levels of volcanic activity or even concern:

Internally, we tend to be a little out of sync with the colour code that we present to the public, and the reason for that is we see something is going on, we watch it for a little while and we ramp ourselves up before we ramp the colour code up, and then on the reverse side ramp down, before the colour code ramps down, that's our own way of dealing with these things (CVO scientist 3) (07/05/2008).

Credibility also plays a crucial role. It is a case of 'professionalism' (AVO collaborator 1) (17/04/2008) and the SIC wants to make decisions that are defensible to their peers and the government. There is always the concern that an event will happen once an alert level has been downgraded and that this may affect the credibility of the VALS and the observatory. One scientist at AVO had a number of philosophical discussions with their colleagues about this dilemma, observing that there are two key schools of thought on this issue:

One school of thought says that if there is a geophysical anomaly then you are completely ok to go to Yellow and if nothing happens then fine, that's just the way the world works

but you have done your job because there was a geophysical change. The other school of thought would say it doesn't matter, we can't say we know enough about it to know for sure if activity goes up or down whether that means something is going to happen. So in such a case it is better to be conservative i.e. don't risk being wrong, and not change colour code until you are really certain that something is going to happen (AVO collaborator 1) (17/04/2008).

This narrative indicates at least the belief that in some cases a more precautionary approach is taken, and in others a more reactive approach. A scientist who adopts a precautionary approach recognises that their role goes beyond doing their job, and that users may be interested in this information, no matter how irrelevant the scientists think it is. Equally, there is a desire not to over-concern users with information that may be irrelevant. Concerns about how to assign a volcano alert level, when to ramp-up and reduce the levels, and the worry of being wrong, all require 'the scientist to think about the alert levels rather than the science' (HVO senior scientist 5) (16/06/2008). The seemingly confident articulation of risk in warnings, however, can sometimes overlook the state of knowledge at the time:

You have to pretend to understand the volcano well enough to know you can go, 'aha, we now go onto another level'. That's when you start fooling yourself. It's obviously vitally important to understand the volcano well enough to know that it's time to go from one level to another, but vitally important is not the same as being able to do it (HVO senior scientist 5) (16/06/2008).

In a context of significant uncertainties in scientific knowledge of volcanic behaviour and the complexity of the physical processes involved, as well as its own institutional practices, the USGS appears to follow, to a degree, a 'post-normal science' (PNS) approach, by which science can no longer be treated as 'normal' where there is universal, objective and context-free knowledge (Gibbons, 1994).

Instead, open discussion between different groups of scientists reveals that, ‘facts are uncertain, values in dispute, stakes high and decisions urgent’ (Funtowicz and Ravetz, 1993, p.744) And yet, while there is often (but not always) an extended peer community of scientists, partner organisation experts, and external experts of a particular volcano during these discussions (as witnessed at CVO), this expertise is still limited to that of the attending scientific community.

Considering risk when assigning an alert level

The decision to assign an alert level at the USGS should be based on the activity of the volcano (Gardner and Guffanti, 2006); yet, nearly every VHP interviewee discussed the role that risk plays in assigning an alert level, making the process less 'black and white' than many assume. This section reviews the scientists’ consideration of risk when deciding an alert level, and highlights the fact that negotiating between science, uncertainty and risk is at the core of the decision-making processes that occur within the VALS ‘black box’ (Latour, 1987).

Local contingencies at each observatory and each volcano are important, affecting decision-making and the setting of alert levels. Scientists often consider these contingencies, and their impact on risk, by reviewing their users’ needs and circumstances, institutional issues, and social, economic and political factors. A scientist at AVO described the compromise of balancing volcanic activity and risk in deciding alert levels as a ‘dangerous game, as the job is to be aware of risk, but the job is really to provide a scientific basis [on which] to make decisions’ (AVO collaborator 1) (17/04/2008). Most scientists acknowledged that it was difficult to avoid the issue, since they were concerned for people's safety. They describe shying away from questions from users and the public such as ‘should I fly today’, related to the need for greater scientific study, to ‘how much ash can a ship ingest before it stops?, a risk related question. Most observatory scientists stated they felt uncomfortable in answering such questions, because,

Those are risk decisions, and those aren't things that we as volcano scientists should be involved in. But it is always the question you get asked; should my kids go to school today? Should we not have school today? We play around the edges there and try [...] to put the information in terms that allow people who are making decisions on risk to make informed decisions. But we have to be very clear, careful, not to slip into that realm [...] or you] end up in a place you shouldn't be as [you] don't know all the factors that affect these decisions (AVO scientist 3) (11/04/2008).

Despite this, risk does remain a factor considered by the scientists when assigning alert levels or writing information statements. A consideration of particular vulnerability, and therefore the needs of the decision-makers, can inform the process. For example, lahars (a wet debris flow of volcanic material) are confined to valleys, but only a short warning notice can be generated. Although this information is communicated to the users, an understanding of the vulnerable populations and possible threats may influence the speed and type of information provided to these groups. Therefore, whilst risk is not officially part of the warning decision-making process, it becomes an implicit component in shaping the urgency to change alert levels, whether the change of alert level is useful for users, how long to maintain alert levels, and what kind of information is issued with an alert level change.

In interviews, political context was often noted as a motivating factor, wherein,

Change in a colour code is not necessarily purely volcanic, it is also political [...] Sometimes a volcano can be 'burping' but not really affecting anybody, and in that respect we may not change the colour code. And other times when it is doing the exact same thing but a pilot saw and reported it, we would have to do something about it, so the politics is driving it a little bit. There has been speculation that sometimes people leave [alert levels] at slightly

elevated levels so to have a bigger political profile at Washington D.C. I've never officially heard of that happen or not, but it could (CVO scientist 10) (6/05/2008).

Political and economic factors were also evident in the Long Valley crises during the 1980s to 1990s, when volcanic unrest threatened to affect the development of internationally renowned ski resort of Mammoth Mountain (Hill, 1998).

There are also economic drivers. When an Orange or Red aviation alert level is issued, many airlines have procedures in place to reroute around the erupting volcano to avoid ash, but this requires extra fuel. Since there are economic repercussions if aviation alert levels Orange or Red are assigned, the SICs want to make sure their decisions are defensible. This pressure can result in some erupting volcanoes not assigned as an Orange or Red alert level since it may not be considered to pose any significant risk for aviation users (AVO scientist 4) (14/04/2008). In addition, the decision to go to an Orange / Watch alert level is not made lightly because, according to VHP institutional protocols, it requires the observatory to go into 24-hour watch mode (except at HVO). This is a costly process because the observatory requires additional staff, and normal functions are put on hold while they focus on the volcanic crisis. Economic influence is also relevant to ground-based hazards, as emergency managers can align their response actions with specific alert levels: a SIC may be hesitant about issuing a Watch alert level if they know that the response will be too drastic for the event. Describing a change in the hazard infers there should be a response to that risk (CVO collaborator 1) (14/05/2008).

All of these examples illustrate the difficulties involved in making decisions and demonstrate that there is a negotiation taking place between the risk perceived by the scientists, and the needs and capabilities of the local user (which may also cause conflict between users). It must also be noted, however, that a few scientists indicated that if an alert level needed to be at a certain level it would be set no matter what pressures there might be:

If it needs to be at Orange, we are going to go to Orange, but we are not going to be flippant with it. We are just not going to cover ourselves by going to Orange, we are going to say, here is the criteria, here are the reasons, we are at Orange regardless of who, how it affects our users economically (AVO senior scientist 1) (10/04/2008).

The decision to change an alert level requires interpretation, analysis, discussion and action within a tight timeframe depending on the speed of the volcanic activity. At AVO, an eruption can be detected suddenly, requiring a speedy change in alert level, and so the SIC may make that decision without much consultation or discussion with colleagues except for those who observed the monitoring data. In many cases, a significant amount of time is taken to consider the implications of assigning alert levels, rather than informing the people concerned as soon as possible. In some sense, this facilitates more negotiation between understanding the science, uncertainty and risks involved. However, some scientists argue that the danger of discussing which alert level to assign is that information does not get out quickly enough.

There is a clear dilemma between scientists' desire to remain neutral and report on the scientific information only, which is their area of expertise, and the importance of providing information on hazard and risk, which is regarded by many to be an essential component of a warning system. A scientist from HVO stated that 'the corollary with observatories issuing an alert level is that they know what the repercussions are of issuing them. The higher the alert level, the more action the public officials have to put pressure on the scientists, I don't think that is right' (HVO senior scientist 5) (16/06/2008). In the USA the legal responsibility for emergency response lies with the user federal agencies involved, not the USGS who are supposed to only advise on the science of volcanic activity. There is a conflict also in the need to issue information that is usable, but which is subject to deep uncertainty. As one scientist stated, 'I don't think that we scientists should strive to make the jobs of

public officials any easier. I think that we should tell them honestly what we don't know as well as what we know, they have tough choices to make and should not be spoon-fed' (HVO senior scientist 5) (16/06/2008).

So, what are the challenges in simply providing an alert level to users? First, since volcanic activity is generally infrequent it is not something that emergency managers or other users such as land owners may be particularly aware of or have expertise in. Some scientists even related examples of decision-makers denying the existence of a volcano within their area of responsibility (CVO scientist 13) (2/05/2008). Even if users acknowledge the threat of volcanic hazards, few will have a good understanding of volcanology or the implications of different volcanic hazards, such as ash, or the possible risks that hazards pose (e.g. for asthmatic people). To reduce this knowledge gap, a user may turn to the scientist for more guidance:

For emergency managers, even though it's very much their decision what to do with those people at risk, it is not the scientists' decision, yet emergency managers will lean on you as hard as they can and they will come back and blame the scientists for whatever decisions are made. So the scientists are in the hot seat no matter what, and what we normally factor for is to just communicate and put out as plain and consistent a message as possible (HVO senior scientist 4) (11/06/2008).

In turn, scientists have knowledge and experience not just of volcanology, but how hazards impact people. However, they do not always know the land, infrastructure, emergency resources, or social activities occurring at each vulnerable location at the time, which may impact the judgement of a user in taking action.

Second, the VHP scientists feel a moral obligation or responsibility to help as much as possible. Scientists often get asked off-the-record questions such as ‘what would you do in this situation’ and ‘tell me what you really think’ when assessing a change in volcano alert level or some new issuance of information (VHP manager 4 (23/05/2008)/ CVO scientist 6 (30/04/2008)).

What the official wants is certainty, 'can you guys tell me what day and what hour it will erupt?' All we can do is tell them based on the information we have, 'this is probably what might happen, we can't give you a time window exactly' (VHP manager 4) (23/05/2008).

Difficulties in pinning down ‘what, where and when’ for volcanic activity or a hazard creates uncertainties that are difficult for users to manage (AVO user – NWS 1) (23/04/2008). Often probabilities or statistical tools to convey the uncertainties are seen as useful by the scientists if they put ‘it into context without getting too mathematical for the officials that they can apprehend a little easier’ (VHP manager 4) (23/05/2008). Rather than try to evaluate the information provided, many scientists have said that users base their decisions on the scientist's judgements:

In reality a lot of emergency managers probably say, 'ok, you are not supposed to tell us whether to evacuate but what would you do if you were living in this place?' So the line between us providing advice and them making decisions is, I don't think it is ever as quite an abrupt a line as we would like it be in an ideal circumstance (CVO scientist 6) (30/04/2008).

Many scientists said they did not like to be put in the position of providing their own judgement, in case they turned out to be wrong, but many users argued differently:

Whatever decision you make it will be better than your customer, because you will be making an educated guess and they don't have the educational background training that you [scientists] do. You need to make your best guess for them [users], and that is what we need these guys to do; don't worry too much about getting it too exact, just get your best guess out there, and be confident about it. If it is too 'wishy washy' we have to throw it out anyways (AVO user – NWS 2) (22/04/2008).

Many interviewees, both scientists and users, argued that VALS provided just such a bridge, reducing the gap in decision-making between the scientists and user groups:

How do you make the bridge between the scientific data, to practical actions that the officials can take? Alert level systems are part of that, they are part of that bridge and it is something you make the transition with. It is where science and reality kinda meets the road (VHP manager 4) (23/05/2008).

Discussion and Concluding Comments

This research establishes two key findings. First, the observatory scientists encounter difficulty in interpreting scientific data and making decisions about what a volcano is doing when dealing with complex volcanic processes and high levels of scientific uncertainty. These decisions include interpreting monitoring data, how this affects the alert level assigned, whether to change the alert level and when, and what information to communicate to the VALS users. There is an additional inherent difficulty in 'boxing' volcanic activity into a predefined alert level when nature acts as a continuum. Second, the decision to move between alert levels is based upon more than an evaluation of volcanic activity, with broader social and environmental risks playing a key role in changing alert levels. These include the contingencies of local institutional dynamics (protocols, procedures), and the plural social, political, economic, and cultural contexts within which each VALS is embedded. Once an alert level is

issued, users will interpret it to decide what actions to take and when; therefore scientists believe it is critical to issue the 'right' alert level.

Assigning an alert level can be interpreted as an adaptive process, in part because of the complex physical systems and social contexts involved that result in a negotiation between the intrinsic uncertainties and risks. To overcome the physical complexities involved the USGS scientists use a deliberative process to assign an alert level; a process of consultation between different scientific areas of expertise, based on monitoring data and understanding of the volcano, and ultimately a decision made by the scientist-in-charge of the observatory. In practice, the USGS, scientists makes limited use of event trees or other statistical models in final decisions to assign an alert level. Perhaps because it is questionable how far statistical approaches to forecasting can be used to assign an alert level since they only consider the physical hazard rather than these contingencies. The very construction of VALS presumes a closed system focusing solely on science, which, moreover, negates an awareness of its own construction and the importance of hazard information. Yet, there are volcanologists in other countries such as the Philippines and Indonesia that openly consider risk factors in their decision to assign an alert level. Given this is also occurring at the USGS, perhaps it should be recognised and formalised as part of the process. This would enable and legitimise a greater level of co-production of knowledge, and assist in understanding the uncertainties and risks involved in different spatial and temporal, and environmental and social contexts.

In practice, local context is vital to the decision-making produces, but with increasing levels of standardisation occurring in VALS, nationally and internationally (for volcanic ash) there are questions as to how VALS can remain standard yet remain effective at a local scale (Fearnley et al., 2012). Further to this, the linear methodological approach prescribed by VALS becomes somewhat paradoxical in that it proceeds to exclude as subjective the very local context and perception that contributes to the assignment of an alert level. Further investigation into the everyday interaction between scientists and

civil authority decision makers is required. I would suggest to establish a typology of effective practices in specific environmental and social contexts, particularly since numerous countries adopt different approaches to uncertainty and risk management processes that could help prevent future natural hazard crises.

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