



Translating research into operational procedures for reducing the risk from volcanic eruptions

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Abstract

In this perspective piece, we reflect on scientific progress in volcanic risk reduction and its prospects for future development. In spite of recent advances, a dichotomy still exists between the products of academic research and the desire for practical applications. The main themes to emerge are (1) the need to find the most effective ways to explain the ever growing amount and complexity of volcanological data to non-specialist stakeholders, and (2) how to transfer to future generations of applied scientists the lessons from practical experience that are often missed by theoretical guidelines. Recommendations for sustaining progress in these fields include improving the accessibility of knowledge and data, embracing novel tools to communicate volcanic risk and uncertainty for decision making, and investing effort on transferring practical experience across generations.

En este breve artículo, reflexionamos sobre los adelantos científicos para la reducción del riesgo de erupciones volcánicas y en las oportunidades para continuar progresando. A pesar de avances recientes, todavía existe un desfase entre los resultados de investigaciones científicas y su aplicación práctica. Los temas clave que identificamos son (1) la necesidad de encontrar maneras más efectivas de explicar la cantidad incremental de información volcanológica (y su creciente complejidad) a todos los grupos interesados, especialmente los no-especialistas y (2) cómo transmitir y transferir, a futuras generaciones de científicos, la experiencia y los aprendizajes prácticos que no figuran en directrices y manuales. Recomendaciones para mantener avances en estos campos incluyen: mejorar la accesibilidad de la información y datos científicos, adoptar nuevas técnicas para comunicar: el riesgo volcánico, la incertidumbre en información científica y para apoyar la toma de decisiones, e invertir en transferir experiencia práctica a las generaciones futuras.

Keywords Risk communication · Volcanic hazard · Emergency management · Decision making

Introduction

The core principles for managing volcanic emergencies were codified in the 1970s by the pioneering work of Michael Fournier d'Albe. Building on UNESCO's definition of risk

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as the product 'hazard x vulnerability x value', he recognised four priorities for reducing volcanic risk (Fournier d'Albe 1979): (1) to reduce hazard by improving the information conveyed in hazard maps (notably how often a hazard occurs); (2) to reduce vulnerability by incorporating into emergency response plans fundamental differences in the time-scales of social response and of the evolution of volcanic phenomena; (3) to advance monitoring and forecasting by the systematic collection of precursory data and improved methods of analysis and (4) to support decision making by formalising algorithms to define the threshold values of precursory signals required to trigger a particular emergency response, such as an evacuation.

These objectives have not changed in the past 50 years (Pallister et al. 2019), and, as described in companion papers to this collection, significant progress has since been made in modelling volcanic systems (Sparks et al. 2022; Aguilera et al. 2022), forecasting eruptions (Kilburn and Bell 2022) and the design of advanced

monitoring techniques (Ramsey et al. 2022; Poland and Zebker 2022; Thelen et al. 2022). Low-cost sensors (Crawford et al. 2021; Granados-Bolaños et al. 2021) and processing methods (Garthwaite et al. 2019) have further enhanced monitoring capabilities in countries with limited economic resources. At the same time, hazard maps are being redesigned to assist decision making by taking greater account of the cultural and social perceptions of their audience (Calder et al. 2015; Lindsay and Robertson 2018; Clive et al., 2021).

Progress, however, has brought new challenges. Recent advances have generated data at an accelerating rate (Papale and Garg 2022), creating barriers to dissemination by lengthening the time needed to process the amount of new material and, because of the additional resources required for acquisition and processing, by widening the gap between economically rich and poor countries. Overcoming these barriers is as important as obtaining the data, and new strategies are needed to break through the bottlenecks that impede the smooth translation of scientific information into practical emergency management.

Scientific information for volcanic risk reduction, planning and management

Between 1900 and 1980, the background death toll as a proportion of the populations exposed to eruptions decreased by a factor of about five (Auker et al. 2013; Brown et al. 2017). It has remained almost constant since then (Auker et al. 2013; Brown et al. 2017), in spite of a global increase in vulnerability and risk (Chester et al. 2000). The sustained low rate since 1980 has been attributed to general improvements in communicating hazards, managing emergencies and social resilience (Auker et al. 2013; Brown et al. 2015; Pallister et al. 2019). The change is indeed cause for optimism, but with caveats.

First, economic costs have been increasing and, between 1980 and 2019, eruptions caused some US\$12 billion of damage (Munich Re n.d.). This follows the encroachment of human activity into volcanic districts, regardless of warnings about the potential hazard.

Second, the most hazardous eruptions with a Volcano Explosivity Index of 5 or more tend to occur at intervals of decades. As a result, comparing outcomes between 1980–2000 and 2000–present may be deceptive, because it coincides with a decrease in the number of such events from four in 1980–2000 (Mount St Helens 1980; El Chichón 1982; Pinatubo 1991; and Cerro Hudson 1991) to only two since then (Puyehue-Cordón Caulle, 2011 and Hunga Tonga–Hunga Ha’apai, 2022), both of which also happened to occur in remote locations. The decrease in number is likely to be a statistical fluctuation, and so a

longer interval is required for a robust evaluation of sustained progress in emergency management.

Third, the background death rate excludes individual eruptions that killed 5000 people or more (Auker et al. 2013) and, for fatalities since 1980, accounts for less than one third of the total number of lives lost. Most deaths in this period occurred in just one event: the 1985 eruption of Nevado del Ruiz, Colombia, which killed more than 23,000 people (Voight 1990; Siebert et al. 2010; Auker et al. 2013). The eruption occurred after 68 years in repose, and the urgency of the response was hampered by unfamiliarity with the threat from the volcano (Voight 1990; Tilling 2009). Although this example may be viewed as an exception to general improvements in hazard management, it comes at the cost of having taken by far the greatest number of lives.

Long repose intervals promote delays in planning for volcanic emergencies, resulting in the need to design and implement plans *after* the start of unrest. Recent examples include the responses at Pinatubo in 1991 (Newhall and Punongbayan 1996; Sinclair 2019; Newhall 2021), and at the Chilean volcanoes Chaitén, in 2008, and Calbuco, in 2015 (Carn et al. 2009; Diaz Bouquillard 2019). The responses were successful, but in each case teams had to rely on last-minute decisions to compensate for the absence of formalised emergency plans. As summarised by Newhall and Punongbayan (1996), even when progress was being made with precautionary actions, ‘the margin by which risks were successfully mitigated ... [were] alarmingly narrow’.

The lack of formalised emergency plans continues today against a background of an ever-increasing number of published lessons, guidelines, advice and recommendations for best practice (UNDRO 1985; IAVCEI 1999, 2016; McGuire et al. 2009; Pallister et al. 2019, Lowersten et al. 2022). It shows that, although advice and lessons can be translated into theoretical guidelines, they are less readily transformed into practical policy changes (Donahue and Tuohy 2006; Mafimisebi and Hadleigh-Dunn 2018), even when the path to change has been clearly formulated (Bretton et al. 2018a, b, Tsang & Lindsay 2020). This problem is especially acute in countries with dormant volcanoes (many of which are not regularly monitored), where ‘real-world’ experience of volcanic emergencies is lost between generations of both scientists and emergency managers and, as a consequence, mistakes are repeated and similar lessons persistently rediscovered, such as the need for appropriate behaviour and communication strategies (e.g. Newhall and Punongbayan 1996; Solana and Spiller 2007; Barclay et al. 2008; Solana et al. 2008, 2017; McGuire et al. 2009; Brown et al. 2015; Harris 2015). Outstanding goals remain to develop novel and efficient methods for (a) translating scientific knowledge into practical, actionable information and (b) transferring experience and intangible knowledge to later generations.

Translating scientific knowledge into practical information

Evaluations of responses to emergencies, such as the UNDRR's Global Assessment Report on Disaster Risk Reduction or GAR (UNDRR 2019), indicate that the incorporation of scientific advances into emergency procedures is often delayed by a lack of accessibility to essential information and by poor understanding of its relevance by non-specialists. Some observatories, especially those that monitor volcanoes in frequent eruption, have successfully bridged this gap, regardless of the economic resources of the country (e.g. Piton de la Fournaise, France (Peltier et al. 2022), Merapi, Indonesia (Mei et al. 2013) and Kīlauea, USA (Williams et al. 2020)). We suggest that even better results could be achieved if the broader academic community shared responsibility for converting data into forms accessible for practical response methods, as illustrated below.

(1) *Improving the accessibility of knowledge by broadening sources, audiences, languages and platforms.* The latest scientific findings are typically published for academic audiences in journals, some with expensive subscriptions. They are mostly written in English, and practical applications are rarely made explicit (c.f. Peltier et al (2022)). Uptake is thus necessarily limited among non-English speaking and non-academic audiences. Advances have been achieved with articles on applied volcanology featuring more frequently in volcanological and disaster-related journals (most notably with the creation of the Journal of Applied Volcanology). Even so, the articles still cater primarily for scientific audiences. An implicit assumption appears to be that volcano observatories should take responsibility for translating the most up-to-date scientific information into a form appropriate for emergency planners (Pallister et al. 2019). Meeting such a responsibility is often impractical, owing to a lack of resources in low-income countries and at volcanoes with long recurrence intervals.

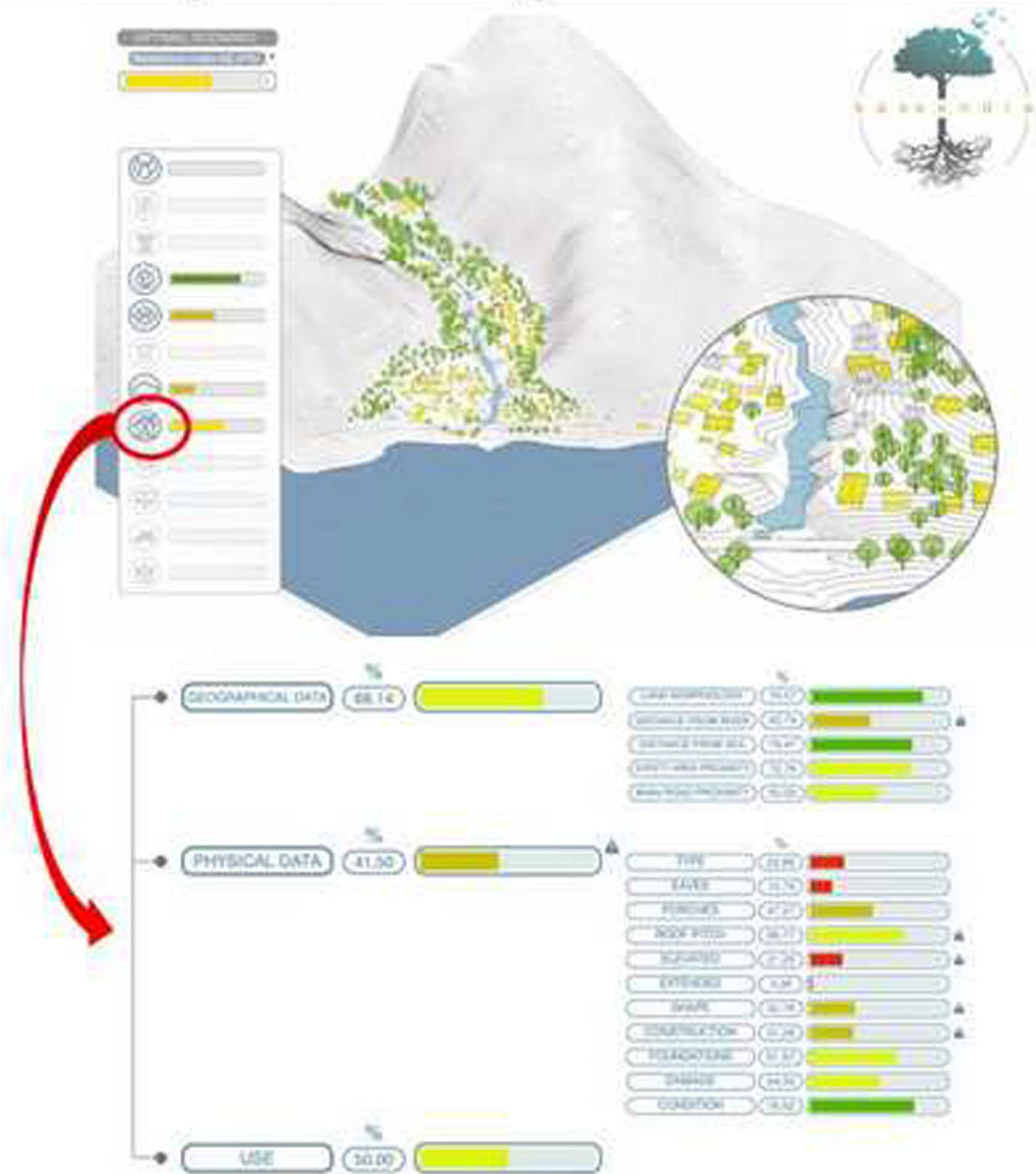
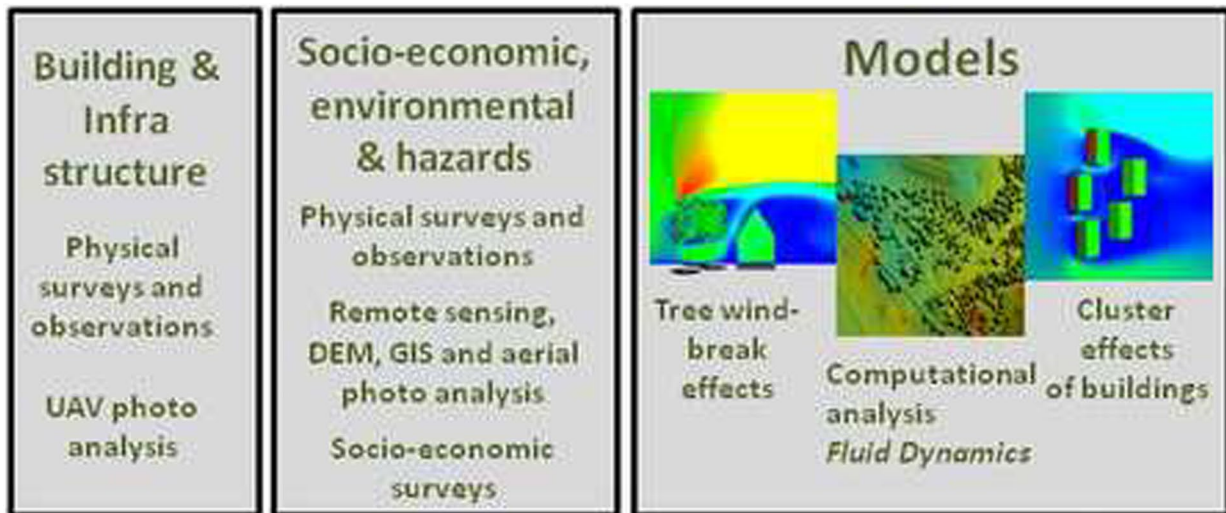
A potential solution is for the wider academic community to assist in preparing information designed for decision makers. Methods of support include disseminating research results in non-academic fora; applying visual aids, such as infographics (Charlton et al. 2020) and film (Hicks et al., 2017); using accessible terminology in local languages (e.g. Harris et al. 2017) (particularly when information refers to a specific volcano) and increasing partnerships to co-design dissemination strategies with end users (Hicks et al. 2017, 2019).

(2) *Designing novel systems to improve data analysis and accessibility.* Contrasting obstacles to disaster risk reduction are a lack of available data on the one hand and an overload of data on the other. Lack of data is a long-established problem (UNDRR 2019) and remains acute at remote and dormant volcanoes. The problem of data overload has emerged with the growth of new technology and data-gathering capabilities. Satellites and low-cost ground-based instruments have greatly

enhanced the amount of geophysical and geochemical data that can be acquired for volcano monitoring (Papale and Garg 2022; Poland and Zebker 2022). Larger amounts of data are generally seen as an asset for interpreting volcanic unrest. Paradoxically, however, they can hinder decision making during a crisis. First, they increase the possibility of unprocessed data (and related metadata) being disseminated in a form that is not user-friendly and so open to the spread of misinformation. Second, greater amounts of raw data require more complex processing and can yield a greater choice of interpretation (Newhall, pers. comm.)—a combination that may promote greater uncertainty in selecting the most appropriate information for operational use. Big data projects may thus inadvertently widen the gulf between advances in research and advances in emergency management.

A strategy for closing the gulf is to present data and metadata in forms designed for all decision makers, rather than for scientific analysis alone and to present data already analyzed in open-access, user friendly formats, such as the WOVODat database of volcanic unrest (WOVODat n.d. Newhall et al. 2017, Costa et al. 2019). This could be developed further by including case studies of how data have been used during volcanic crises (e.g. how was it acted upon by different stakeholders, or, if not used, why was it discounted). Another example is the EU Copernicus Emergency Management Mapping Service, which was activated in 2020–2021 for the eruptions of La Soufrière on St Vincent, in the Caribbean, and of La Palma in the Canary Islands (Copernicus n.d.). A natural extension would be to create so-called data cubes, which organise data into multi-dimensional (or multi-parameter) spreadsheets, so that users can select the relevant combination of information required to investigate a particular question. They are well established in business analysis (Chin 2020a,b) and have been emerging in the geosciences (Lewis et al. 2017; CommonSensing Project n.d.). Data cubes designed for shared use by all stakeholders (Wilkinson et al. 2016) would be ideally suited in volcanology as a common source for emergency managers and scientists.

(3) *Improving visualisations, models, maps and support systems.* Maps continue to be one of the principal methods of displaying and communicating information on volcanic hazard and risk and to support decision making and planning (e.g. Nave et al. 2010; Calder et al. 2015; Charlton 2017; Pallister et al. 2019; UNDRR 2019; Charlton et al. 2020; Clive 2021; Lowenstern et al, 2022). Advances in communicating spatial hazard information have been facilitated by computer-assisted visualisations of maps that include perspective and topographic detail (Haynes et al. 2007), incorporate people's experiences (Taylor et al. 2020), compile real-time observations through citizen-science initiatives (Sandri et al. 2020; EUROVOLC n.d.) and support integrated decision making by combining scientific, geographical, political and socio-economic information, as illustrated by the Kassandra project (n.d.) for planning resilient urban growth in times of climate change (Fig. 1). Continuing goals



| | | | | | |
|--------------------------|-------|--|-----------------------------|------|--|
| GEOGRAPHICAL DATA | 68.14 | | LAND OCCUPATION | 65.0 | |
| | | | SETBACK FROM ROAD | 47.0 | |
| | | | SETBACK FROM RAIL | 50.0 | |
| | | | SETBACK FROM HIGHWAY | 57.0 | |
| | | | SETBACK FROM WATER | 60.0 | |
| PHYSICAL DATA | 41.00 | | TYPE | 22.0 | |
| | | | LEAVES | 21.0 | |
| | | | BRANCHES | 27.0 | |
| | | | NOOF FRUIT | 34.0 | |
| | | | SHADE | 27.0 | |
| | | | EXTENSION | 3.0 | |
| | | | SHALL | 21.0 | |
| | | | CONSTRUCTION | 22.0 | |
| | | | REARSCREEN | 37.0 | |
| | | | DAMAGE | 44.0 | |
| USE | 30.00 | | COASTLINE | 33.0 | |

Fig. 1 Example of the outputs produced by the Cassandra decision support system. The simplified illustration shows the optimum combination of parameters for minimizing hurricane vulnerability in the community of Coulibistrie, Dominica, WI (source: University of Portsmouth and Cassandra internal report). It displays the main data input (*top*), output (*centre*) and an example of the components for one of the resilience parameters (for infrastructure) used by the Cassandra system. Although the example shown is for hurricanes, the parameters could be adapted to evaluate the changes in resilience to volcanic hazards from different decision scenarios

are to capture the limitations and uncertainty of the data displayed, to consider cascading and coincidental hazards and to show gradations in threat. A potential drawback is that maps of increasing complexity can become less intuitive (Schmidt et al. 2011), and so, for operational purposes, compromises can be expected between how much information is displayed and how readily it is understood.

(4) *Increasing efforts for effectively communicating uncertainty before and during an emergency.* This is a recurring topic and highlights a protracted problem. Methods for forecasting the basic features of an eruption (such as size, style, volume and duration) are still in development and hence forecasts are still uncertain. New work has thus focused on methods for better managing and communicating uncertainty (e.g. Doyle et al. 2014a, b a,b, Harris 2015), for designing simple volcanic alert systems (Fearnley et al. 2017) and for exploring the benefits of legally binding protocols on how this information is presented (Bretton et al. 2018a, b a, b). Artificial intelligence and machine learning are also promising tools for removing bias in interpreting data and reducing delays in decision making. In medical circles, for example, such tools have provided diagnoses that are more reliable than those by human experts (Savage 2020), while machine learning has shown promise in identifying volcanoes with analogous behaviour to assist forecasting procedures (Costa et al. 2019). Investing in these support tools is a priority for scientists in charge and decision makers.

Transferring experience across generations

Transferring experience between generations is the second key field for development in the next decade. While the skills for the collection and analysis of monitoring data are routinely passed on through training and volunteer programmes at volcano observatories, intangible skills—from confidence in interpreting and communicating data to managing the stress of responsibility during a crisis—are rarely addressed (but see Newhall (2021)). In the case of emergency response, the traditional method of transferring experience through mentoring and internships is complicated by the limited resources and opportunities available for these activities and the practicalities and logistics involved (e.g. allowing trainees from external institutions or countries to

observe discussions by scientific advisory committees or by emergency managers during a crisis).

For members of volcano observatories, experience is normally transferred by attending bespoke international conferences (Pallister 2019), such as IAVCEI's Cities on Volcanoes programme, or through simulation exercises (Marzocchi and Woo 2007; Constantinescu et al. 2016; Lowenstern et al. 2022). The methods are supportive but cannot always be fully realised. For example, the cost of international meetings can present financial and language barriers to prospective participants. Exercises provide opportunities to improve operational procedures (Doyle et al. 2015), but they cannot replicate the pressure and responsibility of a live emergency. To address such limitations, civilian emergency services use body-worn cameras during crises to train staff in responding to low-frequency high-risk situations. Although not without controversy (Lum et al. 2019), such cameras have proved invaluable for recalling incidents accurately, transferring experience and reviewing and improving decision making (SHP 2018, Richards et al. 2018 and practitioners' pers. comm.), and they show promise as a potential asset in volcanic emergencies.

Prospects for the future

Great strides have been made in preparing for volcanic emergencies since the basic requirements were codified more than four decades ago (Fournier d'Albe 1979). Scientific advances have increased understanding of how volcanoes behave; technological advances have increased the range and quality of techniques available for monitoring volcanoes and for processing the data obtained; advances in governance have promoted agreed policies on disaster risk reduction; and advances in social-science studies have increased awareness of how populations react under stress. Nevertheless, gaps remain in the smooth transformation of new data into useful and practical information. A dichotomy still exists between the products of academic research and the need for practical applications, which in turn reflects dichotomies between research-based and observatory-based scientists, between countries rich and poor in resources for emergency management and even between planning for crises at frequently and rarely erupting volcanoes. Resolving these dichotomies will drive a step change in the support available to practitioners for designing new and effective emergency procedures and, with these, for better protecting vulnerable communities against the threat from volcanic behaviour.

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