Communication Demands of Volcanic Ashfall Events

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Abstract

Volcanic ash is generated in explosive volcanic eruptions, dispersed by prevailing winds and may be deposited onto communities hundreds or even thousands of kilometres away. The wide geographic reach of ashfalls makes them the volcanic hazard most likely to affect the greatest numbers of people. However, forecasting how much ash will fall, where, and with what characteristics, is a major challenge. Varying social contexts, ashfall characteristics, and eruption durations create unique challenges in determining impacts, which are wide-ranging and often poorly understood. Consequently, a suite of communication strategies must be applied across a variety of different settings. Broadly speaking, the level of impact depends upon the amount of ash deposited and its characteristics (hazard), as well as the numbers and distribution of people and assets (exposure), and the ability of people and assets to cope with the ashfall (resilience and/or vulnerability). Greater knowledge of the likely impact can support mitigation actions, crisis planning, and emergency management activities. Careful, considered, and well-planned communication prior to, and during,

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a volcanic ashfall crisis can substantially reduce physical, economic and psychosocial impacts. We describe the factors contributing to the complex communication environment associated with ashfall hazards, describe currently available information products and tools, and reflect on lessons from a range of case-study ashfall events. We discuss currently-available communication tools for the key sectors of public health, agriculture and critical infrastructure, and information demands created by ash clean-up operations. We conclude with reflections on the particular challenges posed by long-term eruptions and implications for recovery after ashfall.

Keywords

Volcanic ashfalls · Societal impacts · Information demands · Information resources

1 Introduction

All explosive volcanic eruptions generate tephra, fragments of glass, rock, and minerals that are produced when magma or vent material is explosively disintegrated. Volcanic ash (tephra < 2 mm diameter) is then convected upwards within the eruption plume and carried downwind, falling out of suspension and potentially affecting communities and farmland across hundreds, or even thousands, of square kilometres. Ashfall is the most widespread and frequent of the hazards posed by volcanic eruptions. Although ashfalls rarely endanger human life directly, disruption and damage to buildings, critical infrastructure services, aviation and primary production can lead to substantial societal impacts and costs, even at deposit thicknesses of only a few millimetres (Table 1; Fig. 1). Impacts vary with proximity to the volcano, how much ash has been deposited, physical and chemical properties of the ash, characteristics of the receiving environment (such as climate and land use) and adaptive capacity of the affected communities (Fig. 1; Wilson et al. 2012). Ashfall impacts are more complex and multi-faceted than for any other volcanic hazards (Jenkins et al. 2015).

Even with small eruptions generating minor quantities of ash, information demands may be heavy and complex. A recent example is the small, but locally high profile, 6 August 2012 eruption of Tongariro volcano, New Zealand. Despite its small size, following this eruption there was intense demand for information from the public, media, and government agencies on questions such as: Was this event a precursor to larger scale activity? What hazards were expected? Was the ashfall hazardous? (Leonard et al. 2014). Similarly, in Alaska, eruptions occur on average one to two times per year, ashfall deposits are typically only a few mm thick on populated areas, and impacts are considered more disruptive than catastrophic. Yet the demand for information is high. During recent eruptions in Cook Inlet, Alaska, the Alaska Volcano Observatory website received as many as 30 million page views in a single month, up to 3000 emails, and thousands of phone calls seeking information throughout the crises (Fig. 2; Adleman et al. 2010; Schaefer et al. 2011).

In this chapter, we describe the factors contributing to the complex communication environment associated with ashfall hazards, describe currently available information products and tools, and reflect on lessons learned from a range of case-study events. We discuss in more detail: ash hazard assessment tools; communication tools available for the key sectors of public health, agriculture, and critical infrastructure; and

Table 1 Volcanic ash impacts on society (adapted from GAR 2015 report: Brown et al. 2014)

Sector	Impacts	Example/photo
Public health	Exposure during an ashfall may not often endanger human life directly, except where thick accumulations cause structural damage (e.g., roof collapse) or when reduced visibility or slippery roads cause traffic accidents. However, very fine ash as PM2.5 and PM10 is a health hazard when it is readily suspended in the air by wind and traffic (Carlsen et al. 2012a; Wilson et al. 2012). Short-term effects commonly include irritation of the eyes and lung airways, and exacerbation of pre-existing asthma and chronic lung diseases (Horwell and Baxter 2006; see also www.ivhhn.org). The presence of respirable crystalline silica in some eruptions will cause much concern over the risk of silicosis, a chronic lung disease which is entirely preventable by adequate measures to reduce exposure in prolonged crises (e.g., Montserrat, 1995–2010). Affected communities can also experience psychological stress from disruption of livelihoods and other social impacts (Carlsen et al. 2012a, b).	 **Caption** Windy conditions in Jacobacci, Argentina on 9 September 2011 leading to high levels of fine airborne ash due to remobilisation of fall deposits from June 2011 eruption of Cordón Caulle. *Credit* J. Mellado
Critical infrastructure	Damage and disruption to critical infrastructure services from ashfall impacts can substantially affect normal functioning of societies. Electricity networks are vulnerable, mainly due to ash contamination causing flashover and failure of insulators (Wilson et al. 2012). Ash can also disrupt transportation networks through reduced visibility and traction; and be washed into drainage systems. Wastewater treatment systems that have an initial mechanical pre-screening step are particularly vulnerable to damage if ash-laden sewage arrives at the plant. Suspended ash may also cause damage to water treatment plants if it enters through intakes or by direct fallout (e.g. onto open sand filter beds). In addition to direct impacts, system interdependence is a problem. For example, air- or water-handling systems may become blocked by ash leading to overheating or failure of dependent systems. Specific impacts depend strongly on network or system design, ashfall volume and characteristics, and the effectiveness of any applied mitigation strategies (Wilson et al. 2012, 2014).	 **Caption** Suspended ash in waste water caused accelerated wear to pumping station impellors in Bariloche waste-water network, Argentina, following the 2011 eruption of Cordón Caulle. *Credit* C. Stewart
Agriculture	Fertile volcanic soils commonly host farming operations. Impacts will be dependent on how much ash has been deposited, characteristics of the ash, characteristics of the receiving environment, style, intensity and practises of the exposed farm, time of year (as it will determine climate and agricultural activities), and risk management actions taken by the farmer and supporting agencies (Wilson et al. 2011a). Ashfall can contaminate and (if sufficient deposition) bury pastures resulting in reduced availability of feed; contaminate, (if thick enough) lodge and bury horticultural crops, reducing yields and quality; cause adverse effects on livestock health by contaminating feed and (more rarely) cause toxicity hazards; contaminate and disrupt agricultural water supplies; abrade and corrode farm vehicles, machinery and infrastructure increasing maintenance costs; and cause disruption to essential services, such as power supplies, transportation and communication systems.	 **Caption** Chillis damaged by acidic surface coating during the Merapi 2006 eruption, Indonesia. *Credit* G. Kaye

(continued)

Table 1 (continued)

Sector	Impacts	Example/photo
	Ashfalls can be beneficial or detrimental to soil depending on the characteristics of the ash (particularly with respect to its soluble salt burden, which can add plant growth nutrients to pastoral systems). The time of year in the agricultural production cycle strongly determines the level of impact (Cook et al. 1981). For example, ripe crops are usually ash tolerant, but are vulnerable to pollination disruption and contamination when close to harvest. Under very thin ashfall (<1 mm) crops and pastures can suffer from acid damage or shading from light; as ashfall depths increase these effects intensify and loading damage may occur. Thick ashfalls (>100 mm) typically require soil rehabilitation, e.g. thorough mixing or removal, to restore agricultural production (Wilson et al. 2011a; 2015). For livestock, ashfall may cause starvation (damaged or smothered feed), dehydration (water sources clogged with ash), deaths from ingesting ash along with feed, and (more rarely) acute or chronic fluorosis if ash contains moderate to high levels of bioaccessible fluoride (Cronin et al. 2003).	
Buildings	The load associated with an ashfall can cause the collapse of roofing material (e.g. sheet roofs), the supporting structure (e.g. rafters or walls) or both and, under great enough loads (> > 100 mm), the entire building may collapse (Blong 1984; Spence et al. 2005). Non-engineered, long-span and low-pitched roofs are particularly vulnerable to collapse, potentially under thicknesses of around 100 mm or less. Under thinner ashfall (< 100 mm), structural damage is unlikely although non-structural elements such as gutters and overhangs may suffer damage (Wilson et al. 2015). Wetted ash is up to twice as dense as dry ash thus loading is correspondingly higher. Building components and contents may also be damaged from ashfall due to ash infiltration into interiors, with associated abrasion and corrosion.	 **Caption** Volcanic ash cleaned off a hospital roof in Heimaey following 1973 Eldfell eruption, Iceland (tractor for scale). *Credit* G. Oskarsson
Economy	Economic losses may arise from damage to physical assets, e.g. buildings, or reductions in production, e.g. agricultural or industrial output. Most economic activities will be impacted, even indirectly, under relatively thin (< 10 mm) ashfall, for example through disruptions to critical infrastructure. Losses may also result from precautionary risk management activities, e.g. business closures or evacuations. During or after an ashfall, clean-up from roads, properties, and airports is often necessary to restore functionality. Large volumes of ash require time-consuming, costly and resource-intensive efforts (Wilson et al. 2012).	 **Caption** 20–30 mm of volcanic ash covering aeroplanes during the 2011 Cordón Caulle eruption, Chile. *Credit* Bariloche Airport

information demands created by ash clean-up operations. Impacts of airborne ash on aviation are covered elsewhere in this volume. We conclude with reflections on the particular challenges posed by long-term eruptions and implications for recovery after ashfall.

Increasing attention is being paid to the human health, environmental and aviation

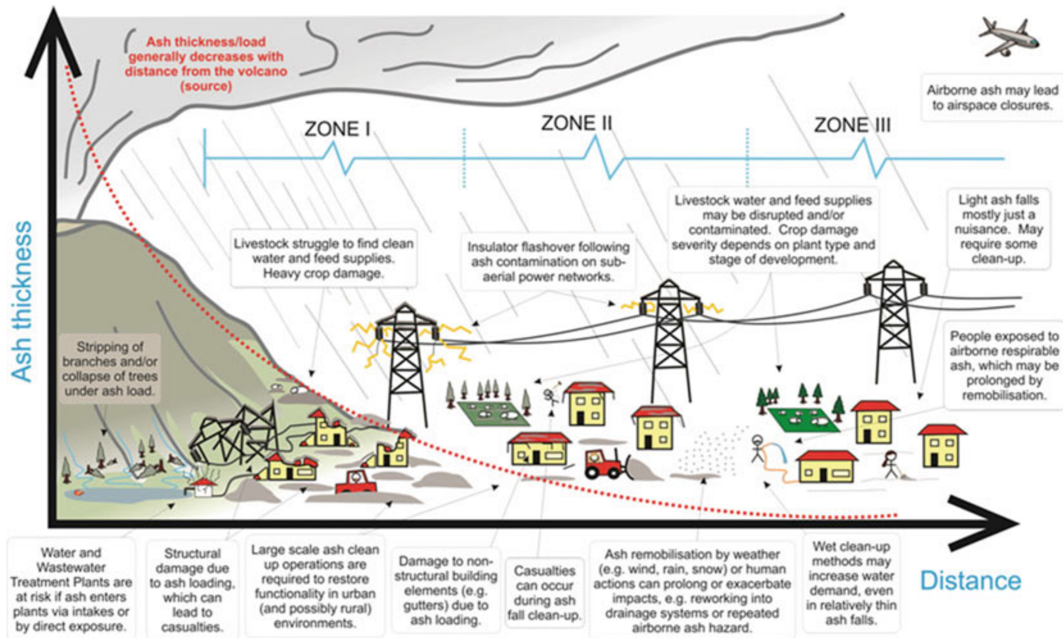

Fig. 1 Schematic of some ashfall impacts with distance from a volcano. This schematic diagram assumes a large explosive eruption with significant ashfall thicknesses in the proximal zone and is intended to be illustrative rather than literal. Three main zones of ashfall impact are defined: (1) Destructive and potentially life-threatening (Zone I); (2) Moderately damaging and/or disruptive (Zone II); (3) Mildly disruptive and/or a nuisance (Zone III). From Brown et al. (2014)

hazards of resuspension and dispersal of ash from fallout deposits (Folch et al. 2014; Wilson et al. 2011b; Hadley et al. 2004). We acknowledge the communication challenges associated with resuspension events, but consider them outside the scope of this chapter.

As a caveat, we note that we, the authors, are all based in countries with advanced economies, and thus our perspective—informed by our own experiences—may be less applicable in dissimilar countries.

2 The Complex Communication Environment Associated with Ashfalls

2.1 Disaster Risk Reduction Context

Empowering society to utilise scientific and technological advances to reduce the impacts of disasters is a well-established challenge (Alexander 2007; Few and Barclay 2011; McBean 2012; Mileti 1999; Cutter et al. 2015). Both the UNISDR Sendai Framework for Action (SFA) and Integrated Research on Disaster Risk (IRDR) programs call for more integration of research with the needs of policy and decision makers (ICSU 2008; UNISDR 2015). Few and Barclay (2011) also stress the need to promote integrated, inter-disciplinary approaches, strengthen two-way links between science providers and end-users, and support more effective research/end-user partnerships.

Because of the low recurrence rates of eruptions at many of the world's volcanoes, ashfalls can be rare events, even in volcanically-active regions. Wilson et al. (2014) note that the rarity of volcanic events can result in low risk awareness, particularly during periods of quiescence. Furthermore, even if knowledge of proximity to volcanic hazards and susceptibility to their consequences is reasonable, this does not ensure that mitigative actions will be taken, and preparedness

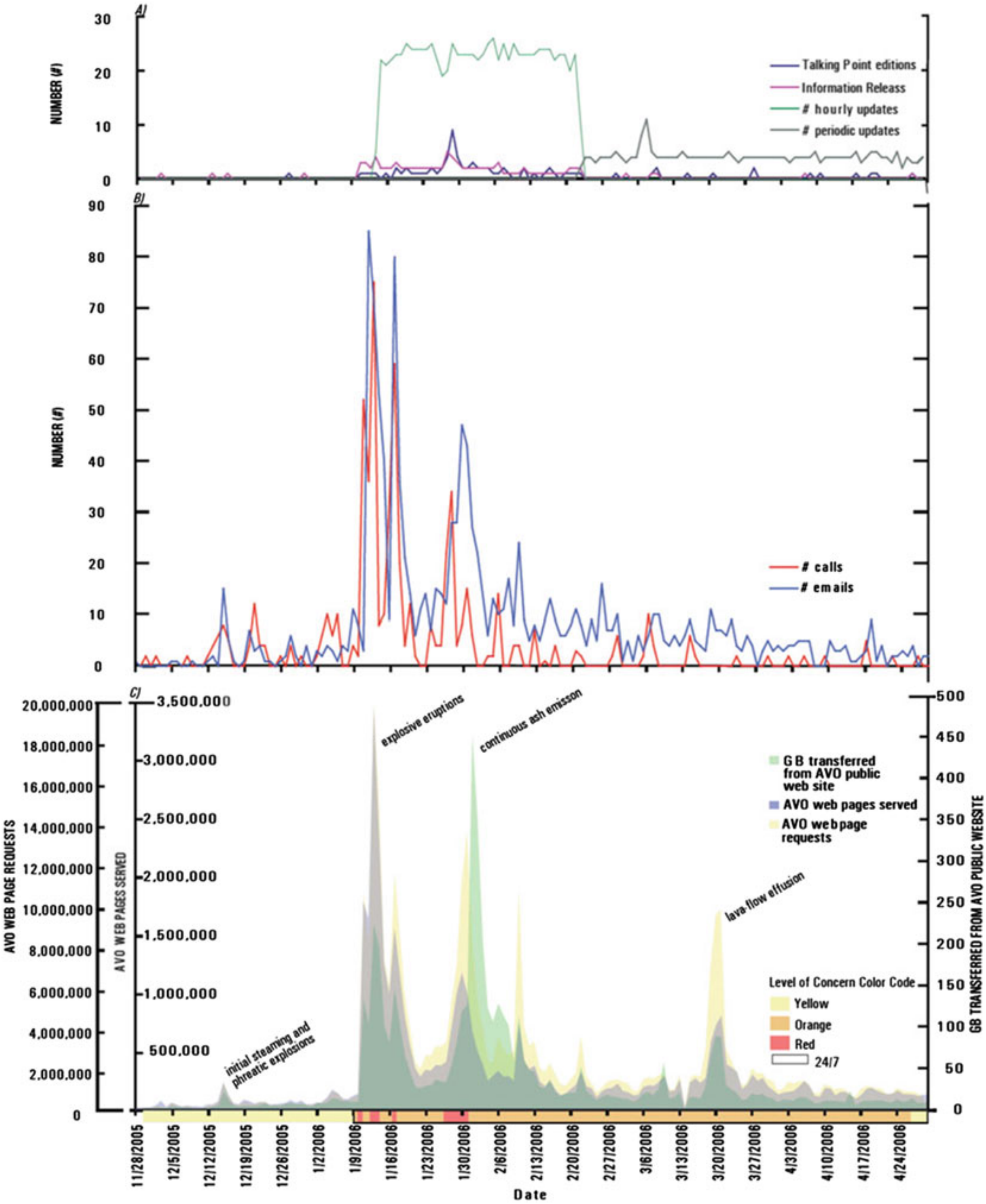

Fig. 2 *Top* Daily totals of information items produced during the 2005–6 unrest and eruption at Augustine volcano. *Middle* Daily totals of recorded phone calls and emails received. *Lower* AVO Website statistics of gigabytes transferred, webpage served and webpage requests. Reproduced from Adleman et al. (2010)

levels often remain low in proximal regions, even in developed countries (Paton et al. 2008). For risk communication, simply providing information often fails to change risk perception or motivate volcanic hazard preparedness, implying that more engaged and appropriate strategies are required. Thus, more participatory processes, whereby stakeholders (e.g. communities and organisations) actively participate as legitimate partners, are recommended (Covello and Allen 1988; Paton et al. 2005; Twigg 2007).

2.2 Complex Communication Environment

Effective management of volcanic ashfall risk requires effective communication between a range of groups and individuals during crisis and non-crisis periods (Höppner et al. 2010). Some countries have coordinating structures which aid information sharing to enhance decision-making during these periods. A broad and evolving array of communication channels may be utilised. Communication between parties is ideally two-way; however, specific ashfall hazard, risk and management information needs to be generated and communicated by expert groups for stakeholders to make risk management decisions, often under urgency. Ideally this evolves into discussions as experts tailor communications to the evolving risk and social context with, for example, the media, public, critical infrastructure and other businesses providing vital situational awareness to emergency managers, and useful data to scientists.

Volcano-specific agencies and emergency managers need to work closely as a team. This multi-agency group must conduct pre-planning and joint exercises. Several communication products can and should be pre-prepared, including contingency messaging for the various possible outcomes of ash characterisation, for example in the event of high levels of crystalline silica in respirable size fractions (see Sect. 4.1.1). Other products should have a pre-planned format and framework but need to be completed dynamically in response to the specific event, such as ashfall forecast maps. As many communication channels as possible should be two-way, allowing for dialogue rather than just provision of information. Ashfall mapping, collection, and testing are substantial activities that require rapid, widespread collaboration and are necessary to inform critical communication messages. An idealised representation of the flow of communication between key actors during a volcanic ashfall crisis illustrates the complex relationships that emerge amongst organisations, processes and communication products (Fig. 3). For example, the provision of authoritative health advice to the public requires wide cooperation between organisations; integration with ash collection and analysis processes; and alignment with other communication products, all at the same time. While these three elements could be illustrated separately, the cross-dependencies would be lost. Figure 3 is adapted from an earlier version developed by Paton et al. (1999), who noted that information management during an eruption is highly complex, owing to the rarity of these events, the complexity of hazard effects and the diversity of agencies involved.

A diverse range of stakeholders have information needs that evolve throughout ashfall crises (Wilson et al. 2012). These are summarised in Table 2 for the following groups: general public, media, emergency management and emergency services, local government, public health agencies, utility managers, farmers and agricultural agencies and private businesses. Experience has shown that information demands are most intense in the following areas:

- Effects on public health from inhaling or ingesting ash (e.g., Horwell and Baxter 2006);
- Potential of ashfall to contaminate water supplies and food chains (e.g., EFSA 2010);
- Impacts of ashfall on agriculture and rural communities (e.g., Wilson et al. 2011a, b);
- Ash clean-up and disposal methods (e.g., Wilson et al. 2012).

Risks to public and animal health are typically considered most urgent by both the public and public health authorities, although often the public concern outweighs the actual risk and the role of the agencies is to allay that concern with event-specific and science-based information. For example, following the April 2010 eruption of Eyjafjallajökull volcano, Iceland, and the subsequent transport of an extensive ash plume over Europe, the European Food Safety

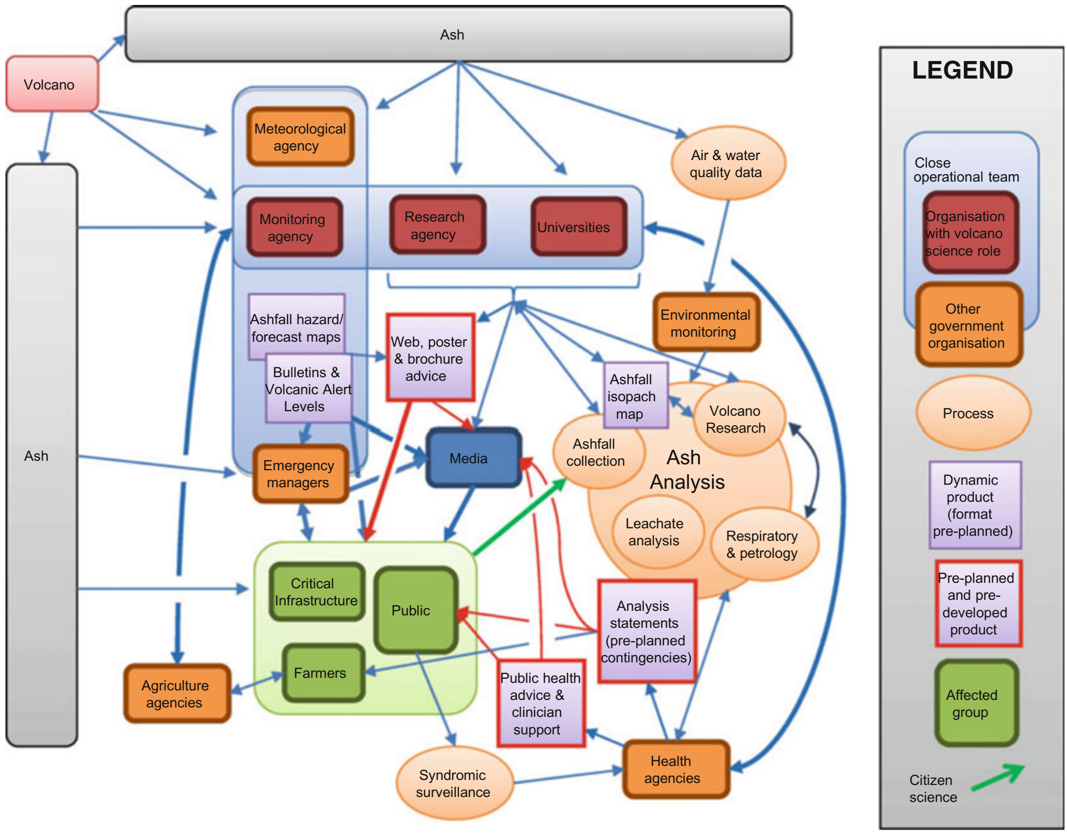

Fig. 3 Idealised flow of communication between key participants during a volcanic ashfall crisis illustrating the complex relationships that emerge amongst organisations, processes and communication products (after Paton et al. 1999)

Authority (EFSA) undertook an urgent assessment of risks for public and animal health (EFSA 2010). Information was urgently sought on questions such as the composition of the ash falling across Europe, with particular concern expressed about the fluoride content of the ash; important pathways of dietary exposure; recommendations for further data collection and comments on the effectiveness of mitigation methods.

3 Tools for Ash Hazard Characterisation and Dissemination

A range of products exists to meet the information demands of stakeholders. Some products are for an international audience and some have been produced according to local (domestic) needs. The need for the products evolves with changing risk and social context before, during and after an ashfall. We summarise, in general terms, some of these evolving needs in Table 2. Explanations about the deployment of specific tools throughout an event are provided in Table 3.

Communication tools and resources can be used during crisis and non-crisis times to contribute to societal resilience[1] to ashfall events. Effective communications summarise hazards and impacts, recommended preparedness, and

[1]*Resilience*: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions. http://www.unisdr.org/we/inform/terminology.

Table 2 Evolution of information demands throughout an ashfall crisis/event, by sector

	Typical Information Demands/Questions			
Groups	Quiescence[a]	Before ashfall (volcanic unrest)	During ashfall	After ashfall
All (including the public)	*Typically minimal interest* • If eruption occurs, how much ash will be received and what will the effects be?	• Will the ash be harmful to people? To animals? • Where is ash likely to fall? • How much ash is likely to fall at my location? • When will ashfall start? • When will ashfall stop? • What will be the impacts? • What can be done to prepare (especially for health)? • How should buildings and services be protected from ash ingress?	• Will the ash be harmful to people? To animals? • What protective measures can I take? • How much ash will fall? • When will the ashfall stop? • How should buildings and services be protected from ash ingress?	• What are the longer term health effects? • Will more ash fall? • How and when should ash be cleaned up? • How and where should ash be disposed of? • Can ash be added to gardens?
Media	See 'All'	See 'All' Questions follow public interest in eruption and are (ideally) guided by scientific communiques. • What can people do to prepare (especially for health)?	See 'All' Questions follow public interest in eruption and are (ideally) guided by scientific communiques. • Where has ash fallen and where will it fall in the future?	See 'All' Questions follow public interest in eruption and are (ideally) guided by scientific communiques. • What is the likelihood of more ashfall? Where would it fall?
Emergency Managers and Emergency Services	See 'All' • What is the risk of ashfall (function of likelihood and consequences) as part of risk assessment planning? • Information sources for hazard, impacts and mitigation	See 'All' Require broad overview of how to manage ash risk across all sectors. • How to access most up to date scientific information on eruption and ashfall crisis • How to prepare, respond, remediate and recover from ash impacts	See 'All' Require broad overview of how to manage ash risk across all sectors. • How to access most up to date scientific information on eruption and ashfall crisis • How to prepare, respond, remediate and recover from ash impacts	See 'All' Require broad overview of how to manage ash risk across all sectors. • How to access most up to date scientific information on eruption and ashfall crisis • How to respond, remediate and recover from ash impacts • What was learnt from this event?

(continued)

Table 2 (continued)

	Typical Information Demands/Questions			
Groups	Quiescence[a]	Before ashfall (volcanic unrest)	During ashfall	After ashfall
Utility Managers	See 'All' • What is the risk of ashfall (function of likelihood and consequences) as part of risk assessment planning • Sector specific hazard, impact and risk management information and what are the information sources	See 'All' • Sector specific hazard, impact and risk management information and what are the information sources	See 'All' • Sector specific impact and risk management information • Engineering characteristics of ash	See 'All' • Sector specific impact and risk management information • Engineering characteristics of ash • Sector specific best-practise clean-up methods • What was learnt from this event?
Farmers and Agricultural Agencies	See 'All' • Sector specific hazard, impact and risk management information and what are the information sources • Agriculturally relevant characteristics of ash	See 'All' • Sector specific hazard, impact and risk management information and what are the information sources • What are the implications of ashfall for food chains? • What are the agriculturally relevant characteristics of ash • What are the ash remediation strategies	See 'All' • Sector specific hazard, impact and risk management information and what are the information sources • What are the implications of ashfall for food chains? • What are the agriculturally relevant characteristics of ash • What are the ash remediation strategies	See 'All' • Sector specific hazard, impact and risk management information and what are the information sources • What are the implications of ashfall for food chains? • What are the agriculturally relevant characteristics of ash • What are the ash remediation strategies
Public Health Agencies	See 'All' • What is the risk of ashfall (function of likelihood and consequences) as part of risk assessment planning • What are information sources for hazard, impacts and mitigation	See 'All' • Health specific hazard, impact and risk management information and what are the information sources • What are the short and long term health relevant characteristics of the ash *Will be looking to inform standard public health messaging and modify if required*	See 'All' • Health specific hazard, impact and risk management information and what are the information sources • What are the short and long term health relevant characteristics of the ash *Will be looking to inform standard public health messaging and modify if required*	See 'All' • What are the short and long term health relevant characteristics of the ash • What was learnt from this event?

(continued)

Table 2 (continued)

	Typical Information Demands/Questions			
Groups	Quiescence[a]	Before ashfall (volcanic unrest)	During ashfall	After ashfall
Private Business	See 'all' • Some businesses will undertake specific ash risk business continuity planning	See 'all' • Business specific hazard, impact and risk management information and what are the information sources	See 'all' • Business specific hazard, impact and risk management information and what are the information sources	See 'all' • Business specific hazard, impact and risk management information and what are the information sources

[a]Level of interest is strongly context-dependent and may be influenced by high-profile eruptions at other volcanoes, proximity to a volcano, previous experiences, etc.

Table 3 Evolution of information products and activities throughout an ashfall event[a]

Quiescent phase	Pre-event phase	During eruption	Post-eruption
• Background hazard maps • Public hazard and risk education and outreach (e.g. information resources, public talks) • Sector-specific impact, mitigation and preparedness resources • Sector-specific hazard and risk information (e.g. volcano science advisory groups, volcanic risk professional courses, engagement with industry/sector groups) • Development and exercising of communication protocols, structures and guidelines	• Preparation of event-specific hazard maps • Deployment of ashfall forecast maps • Enhanced public hazard and risk education • Dissemination of sector-specific resources (e.g. ashfall preparedness posters for utilities) • Dissemination of sector-specific hazard and risk information • Optimisation of communication protocols, structures and guidelines	• Preparation of dynamic crisis hazard maps (iterative process) • Ashfall forecasts (modelled) • Ashfall maps (mapped and modelled) • Consistent public messaging on ashfall preparedness and impact advice • Syndromic surveillance for health intelligence • Ash analyses for: – Eruption forecasting – Health hazard assessment – Agricultural hazard assessment – Engineering hazard assessment (e.g. resistivity characteristics)	• Ongoing communication about risks of ashfall e.g. health, agriculture, etc. • Consistent public messaging on ashfall response and recovery advice • Sharing of lessons learned and revision/optimisation of existing products as required • Calibration of numerical hazard models with event data • Continued syndromic surveillance • Updating of hazard maps

[a]Evaluation and review may be necessary as needs of community evolve

response actions, over a variety of user-preferred platforms. Various media products have been developed for communicating ashfall hazard, risk and impacts, including hazard maps, traditional static media such as posters and brochures, and online resources. Websites have found considerable favour over the past decade, including global resources such as the website of the International Volcanic Health Hazards Network (www.ivhhn.org) and the U.S. Geological

Survey-hosted ash impacts and mitigation website http://volcanoes.usgs.gov/ash. Rapidly-emerging technologies include passive and active provision of information on social media and mobile phone applications (apps) (Leonard et al. 2014).

3.1 Hazard Maps (Background and Crisis)

Hazard maps are a common component of volcanic warnings. Maps can broadly be grouped into (a) background maps prepared in quiescent times, covering the range of possible future events based on past events and/or geological studies and (b) crisis maps for use during a specific event. Maps can also be grouped into those focussed on proximal hazards, generally with some implication for life safety near a volcano, or maps of more distal, far-reaching hazards, primarily ashfall. In addition, hazard maps may depict a single hazard (e.g., ashfall) or multiple hazards emanating from the volcano (including pyroclastic flows, lava flows and lahars).

Prior to a crisis, hazard maps are a tool for education and planning, providing information on areas most likely to be impacted by ashfall, and the probable accumulation of ash deposits. Hazard maps may be combined with spatial exposure and vulnerability information to estimate building and infrastructure damage, evacuation needs, likely transport and utility disruptions, and clean-up requirements. During a crisis, hazard maps are a valuable communication tool used to complement broadcasted alert levels.

Hazard maps for individual volcanic centres are often based on the extent of past eruptive deposits with local topography and environmental factors taken into account. Numerical modelling is often incorporated to help understand the uncertainties surrounding future activity and is particularly important in assessing ashfall hazard, as variations in wind conditions must be considered in conjunction with potential eruption scenarios. At a regional scale, aggregated multi-volcano probabilistic approaches can enable the long-term estimation of ashfall hazard at any particular location. For example, Jenkins et al. (2015) present global and regional maps of probabilistic ashfall hazard which show average recurrence intervals for ashfalls exceeding 1 mm (chosen as a threshold that may cause concern for aviation and critical infrastructure). These authors also presented a detailed local assessment for the municipality of Naples, Italy, merging probabilistic ashfall hazards from both Vesuvius and Campi Flegrei to generate a hazard map for ashfall loading on structures (in units of kPa).

Although every region is unique, crisis hazard maps in support of ashfall communication should contain: version, date, period of validity, impact information or links/references to get impact and mitigation information, reference to any other map types (e.g. background probabilistic), north arrow and scale, legend, and disclaimers as needed (e.g. to clarify that ashfall maps are not flight level forecasts). The triggers for revised versions, the revision process and timeframes should be considered.

If no hazard map exists, we recommend eight key areas for consideration: (1) audience; (2) purpose (e.g. life safety, disruption to infrastructure); (3) timeframe (background probabilistic versus crisis); (4) spatial scale (regional, whole volcano, vent/microzone); (5) organisations and their roles with procedures for discussion and ratification; (6) key messages from emergency managers; (7) hazards and zone styles to be depicted; (8) geological, historical and/or computer-modelled input data to be used. These topics should be considered in approximately this order.

3.2 Ash Forecasting Products

The ability to forecast where and when ashfall will occur is an essential step towards estimating potential consequences and providing useful warnings to stakeholders. Monitoring agencies and emergency managers aim to deliver warnings and forecasts of impending ashfalls to at-risk communities and organisations. Volcanic ashfall forecast products have been developed by several volcano monitoring agencies (e.g., USGS, USA; JMA, Japan; GNS Science, New Zealand). Typically, these forecast products are updated regularly leading up to and throughout an eruption, and inform which areas are likely to be impacted by ash and how much ash is forecast to accumulate. More advanced models inform forecast ashfall arrival time and ashfall duration. The forecasts can provide useful warnings to exposed stakeholders (e.g., emergency managers, public health authorities, critical infrastructure, general public, etc.). Products may be in graphical, animated graphical, numeric or text formats, but a graphical map product is most common. Generally, a graphical map product is the most easily understood, particularly if it is from a perspective rather than plan view. This information is ideally released alongside advice about what people should do before, during and after ashfall and may be paired with volcano alert bulletins.

In New Zealand, for example, basic ashfall prediction maps are automatically pre-prepared three times per day for all frequently active New Zealand volcanoes, and are available for rapid deployment within a Volcanic Alert Bulletin in an eruption event or a period of unrest. Nine scenarios are pre-calculated each time, representing combinations of three height scenarios and three volume scenarios. These maps show model results computed using the Ashfall programme (Hurst 1994) and are based on wind models supplied by New Zealand's MetService. An example of the automatically-generated map for 1800 h on 9 November 2015, for the scenario of a 1 km^3 volume eruption and 20 km plume height, and incorporating current weather conditions, is shown as Fig. 4. Figure 5 shows an example of a map that was released by the volcano monitoring agency GNS Science on 13 August 2012, following the 6 August 2012 eruption at Te Maari vent (Leonard et al. 2014). This day was forecast to have little low-elevation wind and the most-likely eruption scenario was small volume and low plume height, thus the predicted ashfall extent was localised and centred on Tongariro. While these maps were not a major communication tool during this event, as the probabilities of a larger event remained low, they would have become more important had the activity escalated (Leonard et al. 2014).

An important distinction is that ashfall prediction maps are not relevant to flight level forecasts, which are issued by Volcanic Ash Advisory Centres (VAACs). Whilst beyond the scope of a chapter on ashfall hazard communication, the International Civil Aviation Organization (ICAO) has undertaken substantial work in management and communication of ash cloud hazard for aviation, through the International Airways Volcano Watch system (IAVW). There are nine Volcanic Ash Advisory Centres (VAAC) throughout the world tasked with monitoring volcanic ash plumes within their assigned airspace. Analyses are made public in the form of Volcanic Ash Advisories (VAA) and often incorporate the results of computer simulation models called Volcanic Ash Transport and Dispersion (VATD) to analyse the extent, height and concentration of ash particles in the atmosphere for aviation safety.

A number of issues need to be considered when developing ashfall forecasts to allow broad utility and understanding:

- Forecast dissemination: Forecasts need to be actively and passively disseminated to appropriate stakeholders in an appropriate format and in a timely manner.
  - Where possible dissemination pathways should be established pre-eruption and allowing the forecast product to be made widely available.
  - Uncertainty of input parameters, such as eruption plume height and eruption duration, can limit accuracy of the modelled output, and updating these parameters based on observation during an eruption may delay forecast output. Time spent collecting more accurate input parameters and calibration information needs to be balanced with delivering a timely forecast product. Some agencies deal with this challenge by generating pre-eruption and

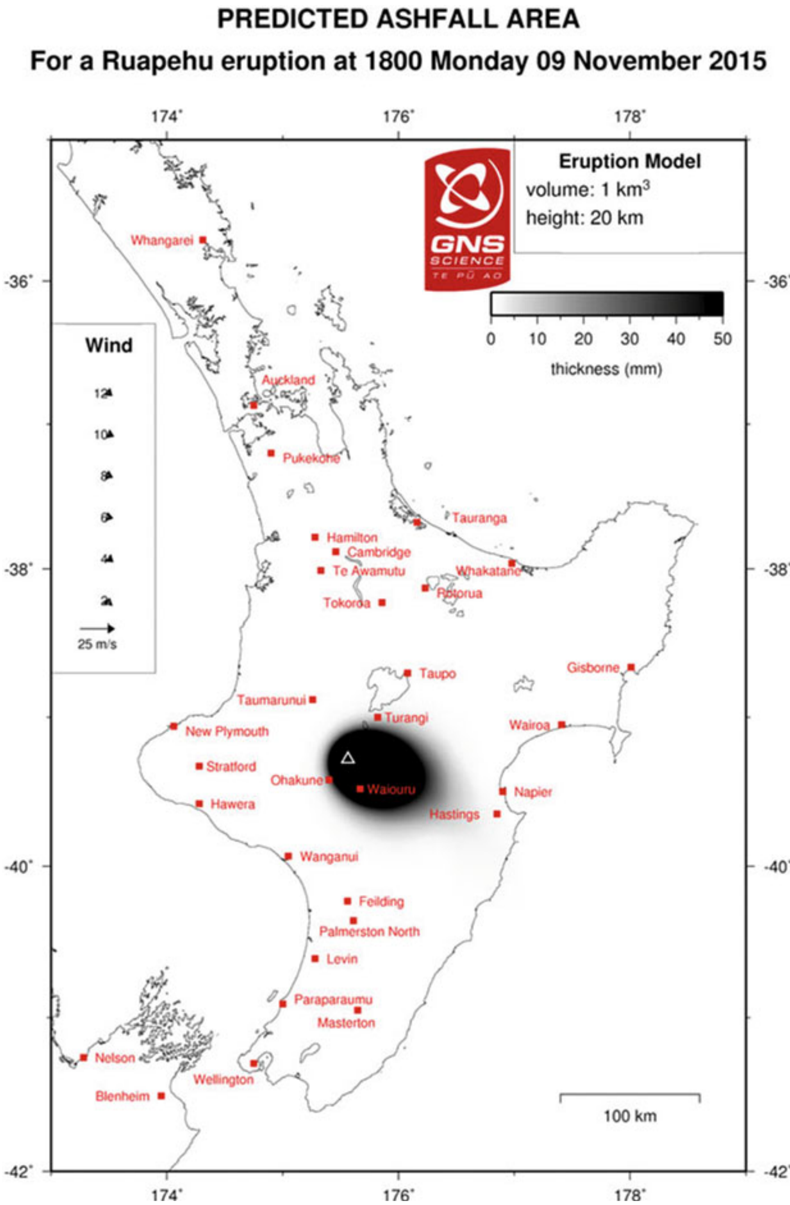

Fig. 4 Example of automatically-generated map for Ruapehu volcano for 1800 Monday 9 November 2015, showing predicted ashfall extent for one of nine pre-calculated scenarios (1 km^3 eruption volume, 20 km plume height)

syn-eruption forecasts, with each forecast utilising improved eruption and wind input information. Post-eruption simulations may involve calibration with observed ash accumulation data.

- Hazard intensity measure: Stakeholders may require different hazard intensity measures (HIMs). For example, ash loading (kg/m^2) is critically important for impacts such as roof collapse and loading onto pastures, whereas ground-level airborne particle concentrations ($\mu g/m^3$) are more directly relevant to assessing exposure to respirable ash, and visibility. Some users may require multiple HIMs. For example, both airborne particle

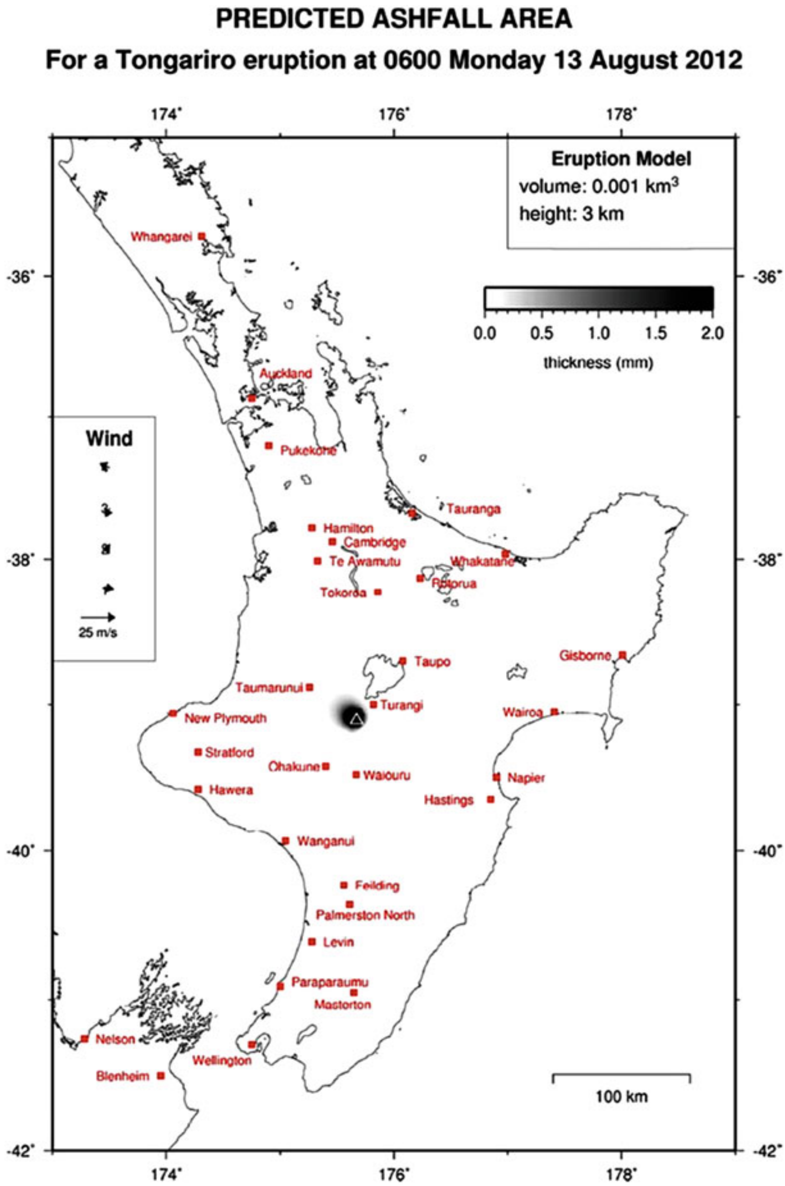

Fig. 5 Ashfall prediction map released with Volcanic Alert Bulletin TON-2012/17 (Geonet 2012) on 13 August 2012. The most likely eruption that might occur was small, and there was little wind that day, so the predicted ashfall extent was localised and centred on Tongariro

concentrations and ashfall loading may be relevant to the management of road networks through impacts on visibility and traction, respectively.

- Ashfall model uncertainty: Uncertainty associated with eruption parameters and climatic conditions, and simplifications applied in numerical simulation, make it challenging to forecast ash dispersal accurately, especially in near real-time. Therefore such forecasts nearly always have some degree of uncertainty attached to them, which can be challenging to communicate to end-user recipients.
- Relating ashfall hazard to consequences: The numerical models increasingly used to produce both deterministic and probabilistic ashfall hazard forecasts usually do not relate the predicted ash

accumulation to potential consequences. However, this information is essential for stakeholders to make meaning of the forecasts and ultimately improve risk management decision making.

- Advice: As with any warning product, ashfall forecasts should either provide or direct recipients to advice so they may take appropriate action.
- Cartography: Not all users have a good level of map literacy, thus other forms of communication may be more suitable for some end users in addition to graphical products. Thompson et al. (2015) have noted that map properties (such as colour schemes and data classification schemes chosen) can influence how users engage with and interpret probabilistic volcanic hazard maps.

Many of these issues are dependent on the requirements of the end user and the specific context within which the warning is being received. Developing ashfall forecast products with stakeholders, along with regular review, can optimise communications. This process is also supported by research which relates ashfall quantity, subsequent effects, and appropriate action.

3.3 Public Involvement in Ashfall Mapping: The Role of Citizen Science

First-hand observers of ashfall are among the best sources of information because their reports can include details about the timing, amount and nature of ashfalls over vast geographic areas, and they can provide physical samples for detailed characterization. Local residents may be best placed to make observations before ash is removed, remobilised, or compacted. For decades, Alaskans have reported ashfall by telephone, email, web, mail, and social media campaigns (Adleman et al. 2010) to the Alaska Volcano Observatory, as a result of a long-running two-way communication effort by AVO. A web-enabled database, "Is Ash Falling?" collects ashfall observations and encourages sample collections from the public (Wallace et al. 2015). This tool will soon be operational at other U.S. volcano observatories. It is open-source, and can easily be exported and modified for use at other observatories or agencies that collect information on ashfall around the world.

In the United Kingdom, citizen science-based methods were integrated into a suite of methods used to quantify ash deposition from the May 2011 eruption of Grímsvötn, Iceland (Stevenson et al. 2013). The British Geological Survey in Ecuador, Bernard (2013) has suggested a design for a home-made ash meter, constructed from simple, low-cost materials, to improve field data collection.

3.4 Media Releases

Scientists and emergency managers regularly release information to the media in the form of structured media releases. These are often timed to include new warnings or forecasts or are triggered by significant events. The most effective media agencies are those that already understand their importance as a communication device prior to a crisis, have relationships and trust developed with officials, and who feel empowered as part of the crisis-management team or process.

3.5 Informal Communication

A substantial proportion of communications between all groups takes the form of telephone calls, emails and face-to-face meetings. These are often not considered as formal communication devices, but they may constitute a large proportion of the time and effort of communicating during a crisis. Ideally these should be linked to the other types of communication and incorporate reference to warnings, hazard maps, and other supporting resources (e.g., preparedness resources). We also note that agencies must have an authoritative, and preferably interactive, presence on social media channels or else misinformed members of the community may occupy this space.

3.6 Standard Protocols for Determining Hazardous Characteristics of Ash

As part of the immediate emergency response, there should be rapid dissemination of information about the physical and chemical properties of the ash and its hazardous potential. Volcanic ash can be highly variable in its characteristics, both among and within eruptions. Therefore, it is necessary to assess the hazardous characteristics of ashfall *specifically* for each eruption, and with sufficient sampling to capture within-eruption spatial and temporal variability.

Specific protocols to assess hazardous characteristics of ash have been developed by the IVHHN and are described further in the following sections. These protocols are intended for use by scientists who then communicate their findings to public health and agricultural agencies, who may then modify their standard public advice messages as required. For example, after the 6 August 2012 eruption of Tongariro volcano, health and agricultural agencies were strongly interested in the levels of available fluorine (F) in the ashfall, because of reported livestock deaths from fluorosis following the 1995–1996 eruptions of Ruapehu volcano (Cronin et al. 2003). Expedited analyses of the available F content of the ash enabled distribution of results to public health officials by 10 August 2012. While the F content of the ash was moderate, the hazard to human and animal health was limited by the small volume of ash produced (Cronin et al. 2014).

3.6.1 Protocol for Assessment of Respiratory Health Hazards

A protocol for analysis of bulk ash samples for respiratory health hazard assessment (introduced in Damby et al. 2013) has been developed by the International Volcanic Health Hazard Network (IVHHN) and can be downloaded from www.ivhhn.org. The initial (rapid analysis) phase of this protocol involves particle size analysis to determine the proportion of respirable size fractions in each sample. Samples containing <1 % (by volume) <4 μm or <2 % <10 μm are not considered respirable and do not require further analysis. 'Respirable' samples may require more detailed characterisation (e.g., crystalline silica content for non-basaltic ash), particularly if there is significant or prolonged public exposure to airborne ash (e.g., long-duration eruptions or resuspended ash), to ascertain long-term health hazards. Important health-relevant characteristics of volcanic ashfall include particle size distribution (Horwell 2007), crystalline silica content (Le Blond et al. 2009), and particle surface reactivity (Horwell et al. 2007).

3.6.2 Protocol for Assessment of Hazards from Leachable Elements

Freshly-erupted ash may contain a range of potentially toxic soluble elements such as fluorine, which may be released either rapidly or more slowly upon contact with water or body fluids. A protocol to assess the leachable element content of fresh volcanic ashfall has been developed by the IVHHN (Stewart et al. 2013). The methods include a general purpose deionised water leach, relevant to assessing impacts on drinking water supplies, livestock drinking water, fish hatcheries, and availability of soluble elements for plant uptake; and a gastric leach for a more realistic assessment of the hazards of ash ingestion for livestock.

4 Sector-Specific Considerations for Communication of Ashfall Hazards and Risks

4.1 Public Health

There are wide differences among the responses in high- and low-income countries to the hazards of volcanic ashfall, as reflected in their infrastructure, transport and communication systems. From the health standpoint, low-income countries (where many active volcanoes are located) may have different epidemiological profiles to those of advanced economies with divergent health concerns to match.

Typical public concerns about the health impacts of ashfall (see Table 1) include the effects of inhaling ash; the potential for long-term effects; and the effects on vulnerable groups (Horwell and Baxter 2006). Most concern revolves around vulnerable groups within the population: children, the elderly and those with pre-existing health problems such as cardiovascular and respiratory diseases.

The World Health Organization currently recommends that communities stay indoors during ashfall and wear light-weight, disposable face masks should they go outside. However, staying indoors is impractical during long-duration events and there is currently little evidence that lightweight masks, such as surgical masks, are effective at blocking the inhalation of respirable ash particles (although an IVHHN study is underway). The IVHHN has produced a pamphlet on "The Health Hazards of Volcanic Ash: A Guide for the Public" (downloadable from www.ivhhn.org). This internationally-ratified pamphlet provides *generally applicable* advice for the public, and is available in nine languages, and is supported by a second pamphlet on how to prepare for ashfall, "Guidelines on Preparedness

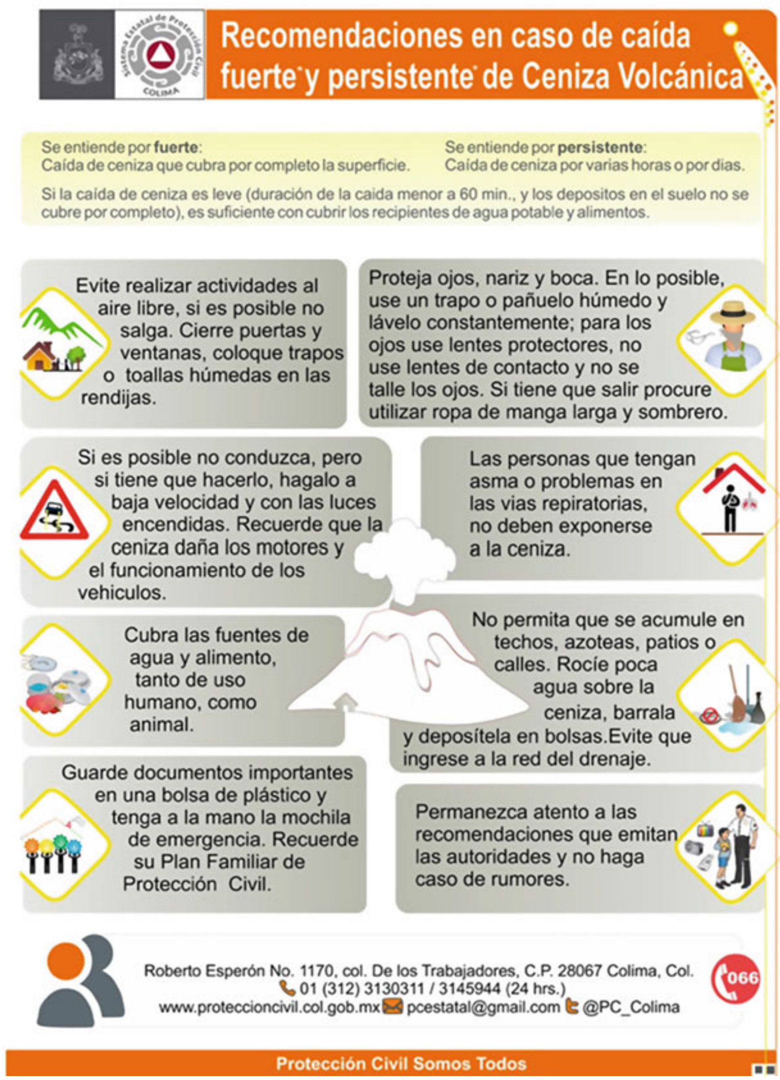

Fig. 6 Civil defence advice for ashfall, Sistema Nacional de Protección Civil, Colima, México. *Source*: Dr Maria Aurora Armienta, UNAM, México City, México

Before, During and After Ashfall", aimed both at the public and emergency managers. Many countries have also developed their own civil defence advice, typically addressing topics such as covering open water supplies, protecting human and animal health, and cleaning up private property (e.g., Fig. 6).

Another common concern is risks to drinking-water supplies, livestock and crops contaminated by ashfall as fresh ash can carry a soluble salt burden that is readily released on contact with water (Stewart et al. 2006). The leachate protocol, described in Sect. 3.6.2, addresses these concerns.

Finally, we note that social and economic disruption resulting from volcanic activity may cause psychological stress that may outweigh physical impacts, particularly for long-lived eruptions. Avery (2004) notes (in relation to the long-lived volcanic crisis on Montserrat) that the social and economic disruption has had a far more profound influence on the health of the ~4500 residents of Montserrat than any purely physical effects related to ash inhalation.

4.1.1 Crystalline Silica

The most hazardous eruptions are those generating fine-grained ash with a high content of *free crystalline silica*, as this mineral has the potential to cause silicosis (a chronic lung disease resulting in scarring damage to the lungs and impairment of their function). Silicosis is primarily an occupational disease associated with occupations such as stone-cutting, tunnel building, and quarrying. To date, no cases of silicosis have been attributed to exposure to volcanic ash, although this may be due to the relatively small population affected.

Rapid determination of quantities (wt%) of free crystalline silica in bulk ash samples after ashfall, using reliable methods, is important (e.g., Damby et al. 2013). Particular care must be taken by agencies conducting and reporting on analyses to avoid any confusion between free crystalline silica (where the individual minerals cristobalite, quartz and tridymite are quantified) and total silica content (commonly used to quantify the bulk composition of ash). Within days of the 1980 eruption of Mt St Helens, there were reports in the media that the Mt St Helens ash contained 60 % or more free crystalline silica—far greater than the actual 3–7 % in the sub-10 µm size fraction (Mount St. Helens Technical Information Network 1980). This misinformation occurred because of a misunderstanding of the difference between free and total silica, and difficulties interpreting the X-ray diffraction pattern due to overlapping feldspar peaks.

In the event of prolonged population exposure to airborne respirable ashfall with a substantial crystalline silica content (in particular, if the eruption is long-lived or ash is being continuously remobilised by wind) it may be necessary for public health officials to conduct more detailed studies on population exposure by using cyclone air samplers to collect samples of airborne respirable dust. The results can then be compared to occupational and environmental exposure limits (Searl et al. 2002).

The groups most heavily exposed are outdoor workers who have to conduct their jobs while exposed to ash (Searl et al. 2002). They include police and traffic controllers, rescuers, emergency staff in utility companies, road and repair workers, clean-up crews, and farmers, who will need specific health messages and advice on personal protective equipment and occupational health risk assessments. There are occupational exposure limits for respirable crystalline silica and to adhere to these will require occupational health and safety input to monitor exposure of workers and to show legal compliance. For the general public the most appropriate exposure limits for health risk assessment are those for particulate matter (see Sect. 4.1.2). Neither of these enforceable sets of limits were designed for volcanic eruptions and so are unrealistic except as guides for communicating potential health risks; specialist advice will be needed for every new eruption, taking into account local circumstances, as was applied after Mount St Helens in 1980 and the volcanic crisis on Montserrat in 1995 onwards (Baxter et al. 2014).

4.1.2 Particulate Matter

In 2013, a review by the World Health Organization concluded that inhalation of any particulate matter sub-2.5 µm diameter (known as $PM_{2.5}$) may impact chronic and acute morbidity and mortality in relation to a range of diseases including cardiovascular and respiratory diseases (World Health Organization 2013). In the USA and European Union countries, there are legal standards on ambient air quality and established air monitoring networks, together with general awareness about the health effects of low levels of air pollutants from sources such as traffic emissions.

Major concerns exist about the health impacts from breathing in air containing elevated levels of respirable ash particles (of non-specific composition), especially in children, and the measures needed to prevent such high exposure. A significant problem after explosive eruptions in dry or semi-arid regions, or during unseasonal droughts, is the resuspension of ash deposits by wind and traffic, leading to exceedances of daily PM_{10} and $PM_{2.5}$ air quality targets by at least one order of magnitude until rain helps to clear the air and consolidate the material, which can be exceedingly fine (including sub-micron particles). The consolidated deposits in inhabited areas should be removed to prevent remobilisation. Strategies such as placing restrictions on vehicle speeds and dampening ash deposits with water may be helpful (Wilson et al. 2013).

Health conditions like asthma and chronic obstructive pulmonary disease are common in the general population, and symptoms of these are likely to be aggravated by exposure to ash. Patients with pre-existing health problems may need to discuss with their physicians the wisdom of moving away from badly affected areas until air quality improves. Public health officials and physicians will need to become well-versed in the acute and chronic health issues surrounding ambient $PM_{2.5}$ in particular. These are complicated for non-specialists to grasp. A further challenge is the development of expertise in communicating the potential health risks associated with exposure to levels of $PM_{2.5}$ that are considerably higher than typical ambient levels in regulated urban environments. Syndromic surveillance (where real-time data are collected from existing public health networks used to monitor the outbreaks of disease) may be useful in communicating the need for health protection strategies where impacts (such as an increase in asthma cases) are recorded (Elliot et al. 2010).

4.2 Agriculture

Impacts of ashfall on agricultural depend on a complex array of factors (Table 1), as well as the inherent vulnerability of the exposed farming systems, on scales ranging from regional (e.g., related to climate) to individual farm-scale (e.g., availability of shelter and supplementary feed). While certain impacts tend to be commonly observed, others may be more site or eruption specific. Thus, in addition to generic impact and mitigation advice, more tailored mitigation strategies may be required.

The assessment of the potential for ashfall to contaminate food chains, as required by modern agricultural production and food safety regulations, is critical. This is essential information for a wide range of stakeholders, from farmers who need to manage and minimise impacts, to food safety organisations. Considerable anxiety can be created for farmers, agricultural markets, and consumers if this issue is not managed and communicated effectively. For example, during the 2010 Eyjafjallajökull, Iceland, eruption, the European Commission asked the European Food Safety Authority (EFSA) to assess the possible short-term threats to food safety in the European Union (EU) from ashfall. The EFSA had no prior information on this hazard and so had to rapidly review and compile scientific information for its assessment (EFSA 2010). No ashfall composition information was available at the time to guide their review. The ESFA identified fluoride as the main component that could pose a short-term risk to food and feed safety, although the risk was assessed as negligible given the very small quantities of ashfall on mainland Europe.

Public anxiety around this issue was considerable, requiring rapid and authoritative communication of the risk to reassure consumers and agricultural markets.

Information demands from farmers, agricultural support organisations, media and other key stakeholders before, during and after an ash-generating eruption can be considerable and diverse, and typically evolve as the risk context changes. Topics on which information is sought include all aspects of volcanic activity, ashfall hazard, likely impacts, and recommended mitigation actions.

From our experience conducting post-event interviews with farmers and farming support organisations, we identify the following information demands that commonly arise before, during, and after ashfall:

1. Will I receive ashfall, and if so, how much and when?
2. What impacts will it have on my farming operations (including effects on pasture, soil, crops, livestock, and farm infrastructure?
3. When will hazard characterisation of the ash be completed? (e.g., characterisation of the environmentally available elements)
4. What actions can I take to mitigate potential consequences before, during, and after ashfall?
5. What support is available? (including sources of advice and direct financial assistance)

In our experience, pre-existing and regularly maintained relationships, protocols, and information resources can greatly ease communication and management demands in a crisis.

The U.S. Geological Survey hosts an ash impacts website, delivering information on ashfall impacts and mitigation for the agricultural sector (U.S. Geological Survey 2015). However, we note that case studies on tropical agricultural systems are limited. Country-specific information resources have been developed for New Zealand (MPI 2012).

4.3 Infrastructure

Ashfalls of just a few millimetres can be damaging and disruptive to critical infrastructure services (also known as 'utilities' in some countries), such as electricity generation, transmission and distribution networks, drinking-water and wastewater treatment plants, roads, airports and communication networks (Wilson et al. 2012). Additionally, disruption of service delivery can have cascading impacts on wider society. Specific impacts of ashfall vary considerably, depending on factors such as plant or network design, ashfall characteristics (e.g., loading, grain-size, composition and levels of leachable elements), and environmental conditions before and after the ashfall (Wilson et al. 2011a, b). Evidence is growing that a range of preparedness and mitigation strategies can reduce ashfall impacts for critical infrastructure organisations (Wilson et al. 2012, 2014).

Volcanic eruptions that produce heavy ashfall are, in general, infrequent and somewhat exotic occurrences and consequently, in many parts of the world, infrastructure managers may not have devoted serious consideration to management of a volcanic crisis. Therefore, during non-crisis periods, risk communication activities should be primarily concerned with volcanic ashfall hazard and impact awareness and education, and making utility companies aware of where information and expertise resides. This incorporates hazard, impact and risk assessment, vulnerability analysis, and formal and informal network building (Daly and Johnston 2015). During crisis periods, provision of specialist, sector-specific impact information is essential to enable rapid decision making in order to minimise consequences. In both instances, preparation of pre-prepared information resources has been beneficial (Leonard et al. 2014). Ideally, a collaborative, participatory process develops these resources for reach region (Twigg 2007).

A successful example of a collaborative process is the creation of a suite of ten posters designed to improve preparedness of critical infrastructure organisations for volcanic ashfall hazards (Wilson et al. 2014; see download link provided in Sect. 4.4). Key features of this process were: (1) a partnership between critical infrastructure managers and other relevant government agencies with volcanic impact scientists, including extensive consultation and review phases; and (2) translation of volcanic impact research into practical management tools. Whilst these posters have been developed specifically for use in New Zealand, the authors propose that these posters are widely applicable for improving resilience to volcanic hazards in other settings (Wilson et al. 2014).

4.4 Clean-up

The removal of ash from urban areas is vital for recovery. However, clean-up operations are more complex than just removal; the ash also needs to be disposed of and stabilised to avoid future problems from remobilisation. Areas exposed to ash hazards should have clean-up plans in place beforehand, covering the following aspects:

- Personnel and equipment requirements, including mutual support agreements for ash clean-up as part of regional emergency management contingency planning.
- Provisions for management of health and safety risks.
- An incident management system/database to manage the clean-up operation.
- Identification of potential disposal sites.
- Strategies for stabilisation of deposits.

Volunteers commonly assist with clean-up operations following an ashfall. Volunteer labour can significantly speed up these operations, but requires effective management and integration with professional crews. An effective communication strategy should include regular briefings of volunteers, liaison officers and health and safety support (Wilson et al. 2014). Clear and ongoing communication with the public during clean-up operations aids efficiency, public trust and goodwill. Guidance on appropriate clean-up methods aids effectiveness, and the coordinated clean-up of neighbourhoods will optimise use of resources and reduce recontamination of cleaned sections.

An example of the value of having pre-existing plans in place, and then communicating them clearly to the public, comes from the May 2010 eruption of Pacaya volcano, Guatemala, which deposited an estimated 11,350,000 m^3 of medium to coarse basaltic ash on Guatemala City, covering approximately 2100 km of roads to depths of 20–30 mm (Wardman et al. 2012). The municipality of Guatemala City utilised a pre-existing emergency plan originally devised for clearing earthquake debris (as a local response to the devastating earthquakes in Haiti and Chile earlier in 2010). An important factor in the success of this clean-up was clear communication with the public. The public were instructed to clear ash from their own properties (roofs and yards), collect it in sacks and to pile the sacks on the street frontage or take them to designated collection points. Sacks were obtained from local sugar and cement companies (Director of Public Works, Municipality of Guatemala City; 2010, pers. comm.). Streets were cleaned with street sweepers or manually, and the ash loaded onto lorries with small excavators. While there were some ongoing problems with flooding caused by ash ingress into storm drains, the main transport routes in Guatemala City (which generates 70 % of the GNP of Guatemala) were cleared within days and the city returned rapidly to its pre-existing level of functionality.

Lessons from this and other eruptions are summarised on the poster "Volcanic Ashfall: Advice for Urban Cleanup Operations" (Auckland Lifelines 2014).

5 Ongoing Communication Demands: Managing Long-Duration Eruptions

In some cases volcanic activity is not confined to a short period of time, but may continue to threaten populations for many years. Some current examples of long-duration and/or ongoing eruptions include: Sakurajima, Japan (intermittent since 1955); Rabaul, Papua New Guinea (intermittent since 1994); Merapi, Indonesia (events every few years since the turn of the 20th century); Soufrière Hills, Montserrat (1995 to present); and Tungurahua, Ecuador (1999 to present). Long-duration eruptions generate hazards of varying intensity over time, where more frequent hazards include ashfalls, gases and acid rain. These hazards can generate widespread losses across societies (Table 1). In long-duration eruptions, this may undermine resilience in the long-term as losses are often not accounted for by governments and businesses, and become absorbed by households and communities. The recurrent nature of the hazards creates challenges for recovery (Sword-Daniels et al. 2014). The complex range of impacts and losses for infrastructure and societies, their cumulative nature, and their long-term manifestations are not well known (Sword-Daniels et al. 2014; Tobin and Whiteford 2004). In general, there are few studies to inform appropriate communication and management strategies and long-term mitigation options for long-duration eruptions.

At some frequently active volcanoes, communication strategies have been developed between disaster managers and communities, but because hazards may vary over time, challenges in communication can arise when the type of hazard changes or is unforeseen (De Bélizal et al. 2012). In many long-duration eruptions, the type of activity can suddenly switch from effusive (dome-building) to explosive, with each presenting entirely different hazards and impacts for the affected communities. For long-duration eruptions, communication strategies, therefore, need to be flexible under changing hazard conditions, must reach and meet the needs of a diverse range of stakeholders and residents during hazard events, and become established such that they can be quickly enacted even after periods of quiescence.

In Montserrat, West Indies, the onset of a long-duration eruption in 1995 (ongoing at the time of writing) of the Soufrière Hills volcano prompted the creation of an exclusion zone in 1996, and relocation of the population further from the volcano. Despite this, ongoing ashfalls, acid rain and gases intermittently affected populated areas of this small island (e.g. from November 2009 to February 2010), and continued for prolonged periods of time (Wadge et al. 2014). Communication strategies for managing ashfalls have developed and improved over time, creating both formal (often broadcast via radio) and informal local information networks. These provide information about which areas of the island are affected by ashfalls and any temporarily affected infrastructure and services; and advice for residents about protective actions for public health and safety. In particular, dome-forming eruptions, such as Soufrière Hills, create ash containing abundant crystalline silica which has the potential to cause diseases such as silicosis (Baxter et al. 1999, see Sect. 4.1.1). Thus, monitoring and reporting on the crystalline silica content (to government agencies) allowed informed decision-making on population exposure, and was an important part of hazard communication during this eruption (Baxter et al. 2014).

6 Communication Demands During Recovery

Each recovery context is unique, depending on the level of impact (where different impacts are experienced by different groups), available resources, and the social, political and economic context (Smith and Birkland 2012; Tierney and Oliver-Smith 2012). Recovery plans should ideally be in place before a hazard event so that all stakeholders share a common understanding and expectations of the recovery process (Phillips 2009). Tools and strategies that promote community engagement and participation are essential in order to account for multiple perspectives, the needs of different groups, and to guide the recovery process. Effective communication requires clarity and transparency in decision-making during all stages of the process.

In the early stages of recovery after an ashfall event, information and communication should focus on providing emergency assistance (where necessary), undertaking damage assessments, ashfall clean-up activities, restoring the function of infrastructure and services, access to livelihoods, and providing psychosocial support. Rapid responses may reduce longer-term impacts.

In the longer-term, tools and strategies need to transition to become focused on any changes that can be made to increase resilience. Aspects that may be considered include: livelihood diversity, possible adaptations, improvements in reconstruction techniques, land-use planning for future development, ensuring social wellbeing and social security mechanisms, the preservation of culture, and strategies for long-term economic stability.

7 Lessons

Lessons from volcanic ashfall events point to the following key considerations for effective communication:

1. Consistent messages must be delivered from different official agencies wherever possible. This may be fostered through regular inter-agency meetings and structures (e.g., Leonard et al. 2014; Madden et al. 2014) and requires a high level of situation awareness and information sharing.
2. Messages need to be repeated periodically during a prolonged event.
3. Planning needs to allow for time-varying messages. Messages are often evolving, with more data becoming available over time.
4. Agency jurisdictions—over who is authorised to issue different types of messages—need to be discussed and formalised before crises. Usually scientists give information on the volcano status and emergency managers give messages on public safety and instructions to evacuate. However, this needs to be formalised (e.g., Madden et al. 2014).
5. Key messages should be pre-planned wherever possible to ensure complete coverage of essential advice and to reduce workload during crisis periods (e.g., standard public health messaging). However, there needs to be flexibility in line with the evolving situation.
6. Volcanic ashfall hazard awareness should start with sector-specific background information delivered during quiescent times.
7. Information needs before, during, and after ashfall events vary for different audiences; thus pre-planned messages and resources should be developed and tested with diverse audiences in mind.

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