Global volcanic hazards and risk

Technical background paper for the UN-ISDR Global Assessment Report on Disaster Risk Reduction 2015

A report by Global Volcano Model[1] and the
International Association of Volcanology and Chemistry of the Earth's Interior[2]

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1. The Global Volcano Model (GVM; http://globalvolcanomodel.org/) was launched in 2011 and has grown to include 31 partner institutes collaborating from across the globe representing scientists from disciplines including volcanology, engineering and social science as well as private sector institutions. GVM is an international collaborative platform to integrate information on volcanoes from the perspective of forecasting, hazard assessment and risk mapping. The network aims to provide open access systematic evidence, data and analysis of volcanic hazards and risk on global and regional scales, and to support Volcano Observatories at a local scale.
2. The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI; http://www.iavcei.org/) is an association of the International Union of Geodesy and Geophysics (IUGG). IAVCEI is the international association for volcanology with about 2000 members. The Association represents the primary international focus for: (1) research in volcanology, (2) efforts to mitigate volcanic disasters, and (3) research into closely related disciplines. There are 22 topic focussed Commissions of IAVCEI covering all aspects of volcanology, including hazards and risk.

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Cover image: The incandescent lava dome at the summit of Soufriere Hills Volcano, Montserrat. Photograph by Paul Cole.

Contents

1 Introduction

An estimated 800 million people live within 100 km of an active volcano in 86 countries worldwide [CS1][1]. Volcanoes are compelling evidence that the Earth is a dynamic planet characterised by endless change and renewal. Humans have always found volcanic activity fascinating and have often chosen to live close to volcanoes, which commonly provide favourable environments for life. Volcanoes bring many benefits to society: eruptions fertilise soils; elevated topography provides good sites for infrastructure (e.g. telecommunications on elevated ground); water resources are commonly plentiful; volcano tourism can be lucrative; and volcanoes can acquire spiritual, aesthetic or religious significance. Some volcanoes are also associated with geothermal resources, making them a target for exploration and a potential energy resource.

Much of the time volcanoes are not a threat because they erupt very infrequently or because communities have become resilient to frequently erupting volcanoes. However, there is an ever-present danger of a long-dormant volcano re-awakening or of volcanoes producing anomalously large or unexpected eruptions. Volcanic eruptions can cause loss of life and livelihoods in exposed communities, damage or disrupt critical infrastructure and add stress to already fragile environments. Their impacts can be both short-term, e.g. physical damage, and long-term, e.g. sustained or permanent displacement of populations. The risk from volcanic eruptions and their attendant hazards is often underestimated beyond areas within the immediate proximity of a volcano. For example, volcanic ash hazards can have effects hundreds of kilometres away from the vent and have an adverse impact on human and animal health, infrastructure, transport, agriculture and horticulture, the environment and economies. The products of volcanism and their impacts can extend beyond country borders, to be regional and even global in scale.

Although known historical loss of life from volcanic eruptions (since 1600 AD about 280,000 fatalities are recorded)[1] is modest compared to other major natural hazards, volcanic eruptions can be catastrophic for exposed communities. In 1985 the town of Armero in Colombia was buried by volcanic mudflows with more than 21,000 fatalities due to relatively small explosive eruptions at the summit of Nevado del Ruiz volcano that partially melted a glacier[2]. Since 1985 an estimated 2 million people have been evacuated due to eruptions or threats of eruption. Some of these people have been permanently relocated. The 2010 eruption of Merapi volcano in Indonesia caused the evacuation of approximately 400,000 people, 386 fatalities[3] and an estimated loss of US$300 million (IDR 3.56 trillion)[4]. Timely evacuations saved an estimated 10,000 to 20,000 lives. More recently the economic impact of volcanic eruptions has become more apparent on local, regional and global scales. A modest-sized eruption of the Eyjafjallajökull volcano, Iceland, in 2010 caused havoc when air traffic was restricted due to an extensive ash cloud, demonstrating the regulatory challenges for the aviation sector. The global financial losses approximated US$5bn as almost all parts of the world were affected by disrupted global business and supply chains[5]. Managing volcanic risk is thus a worldwide problem. Very large magnitude eruptions are the only natural phenomenon, apart from meteor impacts, with the potential for global disaster[6].

Volcanic eruptions are difficult to predict accurately. However, progress has been made in forecasting the onset of an eruption by using scientific interpretation of volcanic unrest[7,8]. Volcanic

[1] This report is supported by case studies with the label CS and these are located as appendices.

unrest usually precedes eruptions, and may consist of earthquakes, ground deformation, gas release and other manifestations caused by rock fracturing or magma movement below the Earth's surface. The ability to issue early warnings is improving with advances in methods of detection and scientific knowledge. Volcanic unrest may only be detected if there is a good monitoring network in place, but many volcanoes worldwide are not monitored sufficiently or at all. As some volcanic hazards can develop rapidly once an eruption begins, precautionary responses such as evacuations are commonly undertaken prior to the eruption starting or in periods of heightened activity. However, volcanic unrest does not necessarily lead to an eruption, and unrest can be hazardous even without a resulting eruption[9,10]. About half of historically active volcanoes have reawakened after a repose interval of a century or more. Some of these volcanoes have subsequently erupted more frequently, while some return to dormancy. Inexperienced communities living on long dormant volcanoes tend to be sceptical of the level of hazard posed by their volcano when it threatens to erupt.

Volcanoes present many different hazards and eruptions are often complex sequences of hazardous phenomena. Each hazard has different characteristics and can cause a wide range of impacts distributed across small to large areas. External factors can influence the occurrence and distribution of these hazards, with wind, for example, determining the direction and extent of hazardous volcanic ashfall, and rain potentially causing volcanic mudflows and landslides. Volcanic eruptions can last minutes to decades[11]. These attributes provide challenges for successful emergency management and disaster risk reduction. Volcano Observatories dedicated to monitoring high-risk volcanoes are crucial for effective mitigation and emergency management; they support resilient communities and systems. There are many factors that contribute towards exposure (i.e. the number and distribution of threatened people and assets) and vulnerability (i.e. their response) to volcanic hazards, and these require integration with hazards assessments to produce local, regional and global assessment of volcanic risk.

Volcanism has not been assessed in previous UNISDR Global Assessment Reports. Background papers for GAR15 produced by the Global Volcano Model partnership (http://globalvolcanomodel.org/) in collaboration with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI, http://www.iavcei.org/) thus provide the first comprehensive global assessment of volcanic hazard and risk. The aim is to provide a broad synopsis of global volcanic hazards and risk with a focus on the impact of eruptions on society.

This report is technical in character, but assumes a readership that does not specialise in geosciences. It contains a synopsis of volcanism from a hazard and risk perspective with selected references and links to on-line resources that will enable a reader to learn about particular topics in more detail. This technical report complements a shorter summary background paper focussed on the GAR15 agenda and designed for a wider non-technical readership. This technical report contains the following information: background on volcanoes, the cause of eruptions and the processes driving them (section 2); volcanic eruptions in space and time (section 3); volcanic hazards and their impacts (section 4); monitoring and forecasting of volcanic eruptions (section 5); methods of assessing volcanic hazards and risk (section 6); management of volcanic emergencies and disaster risk reduction (section 7); and prognosis on the ways to improve knowledge, emergency management and risk reduction (section 8).

The report contains a selection of case studies (labelled CS) that illustrate key concepts, methodologies and approaches to the assessment and management of volcanic hazards and risk. The case studies are appended to this report and provide, along with published literature, the evidence base for the GAR assessment. A separate background report concerns volcanic ash hazard and risk. In addition another complementary background report describes a country-by-country analysis of volcanoes, hazards, vulnerabilities and technical coping capacity to give a snapshot of the current state of volcanic risk across the world.

2 Background on volcanoes and volcanic eruptions

This section provides a basic background on volcanoes and hazards for those unfamiliar with the basic ideas and contemporary understanding. There are numerous books, publications and websites devoted to volcanoes, contemporary theories of volcanism and volcanic hazards. Selected books[12–16], review papers[7,17–19] and the Encyclopedia of Volcanoes[20] are recommended starting points. The US Geological Survey website[21] provides comprehensive information on volcanic processes and hazards. The Smithsonian Institution provides comprehensive and authoritative information on the world's volcanoes as well as weekly reports on volcanic activity around the World. The Smithsonian Volcanoes of the World database is the source for much of the basic information used in this report[11,22]. Version 4 of the database (VOTW4) is online[23]. The figures cited throughout this report are from VOTW4.22.

2.1 Causes of volcanism

Volcanoes are a manifestation of the Earth's internal dynamics related to heat loss. Most volcanoes are located close to the boundaries of tectonic plates and are the consequence of melting the Earth's interior at depths ranging mostly between 10 and 200 km (Figure 1). At depths of a few tens of kilometres the solid Earth is very hot (1200^{o}C or more) and close to its melting temperature. Tectonic plate boundaries are regions where the cool rigid carapace of the Earth is disrupted, like a cracked egg shell. Plates are formed where they are rifted apart (mostly in the oceans) and destroyed where plates collide and one of the plates is pushed back into the Earth's Interior (a process called *subduction*).

Numerous volcanoes form on the world's rifted plate boundaries, but mostly these are located deep below the ocean surface along submarine ocean ridges. Most active volcanoes that pose hazards are located at subduction zones, forming arc-shaped chains of volcanic islands like the Lesser Antilles in the Caribbean or lines of volcanoes parallel to the coasts of major continents as in the Andes. There are some dangerous volcanoes located where rifting plates form on land and in the shallow ocean, such as Iceland and the great East African rift valley. There are also active volcanoes within tectonic plates, the Hawaiian volcanoes being the best-known examples.

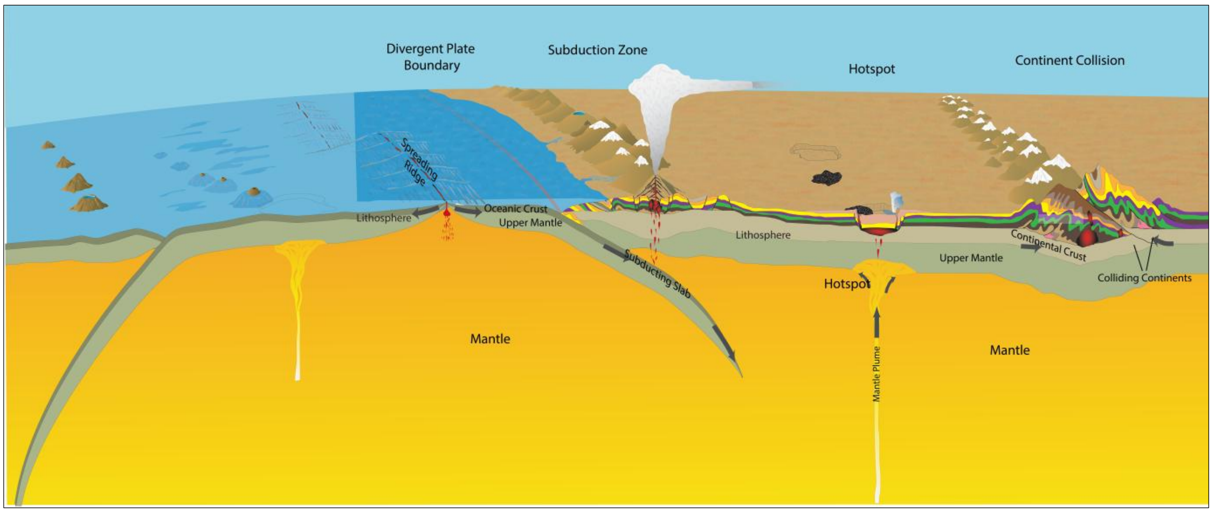

Figure 1: A cross section through the Earth's upper mantle and crust illustrating the plate tectonics and magma generation which gives rise to Earth's volcanoes at subduction zones, spreading ridges and hotspots. (Image courtesy of the Global Volcanism Program, Smithsonian Institution).

Where there are large convection currents in the Earth's mantle beneath the plates, hot mantle rock melts as it moves towards the Earth's surface due to a reduction in pressure. This pressure reduction melting process occurs below rifting plates and volcanoes like those in Hawaii in the interior of plates. In a subduction zone, one of the colliding plates is forced back into the Earth's interior. Hydrated crust of the sea floor is subducted to depths of about 100 km where the water is released into the surrounding hot rocks. Water dramatically lowers the melting temperature of these rocks and copious melting results. Regardless of tectonic setting, intergranular melt coalesces and moves along cracks and conduits towards the Earth's surface. Volcanoes form as a consequence.

The spatial distribution of volcanoes (Figure 2) is now very well understood[22] and enables volcanologists to be very confident about where to expect active volcanoes and new volcanoes in the future. There are many parts of the World where active volcanism can be excluded, although they can still be affected by the economic, environmental and climatic impacts of volcanism.

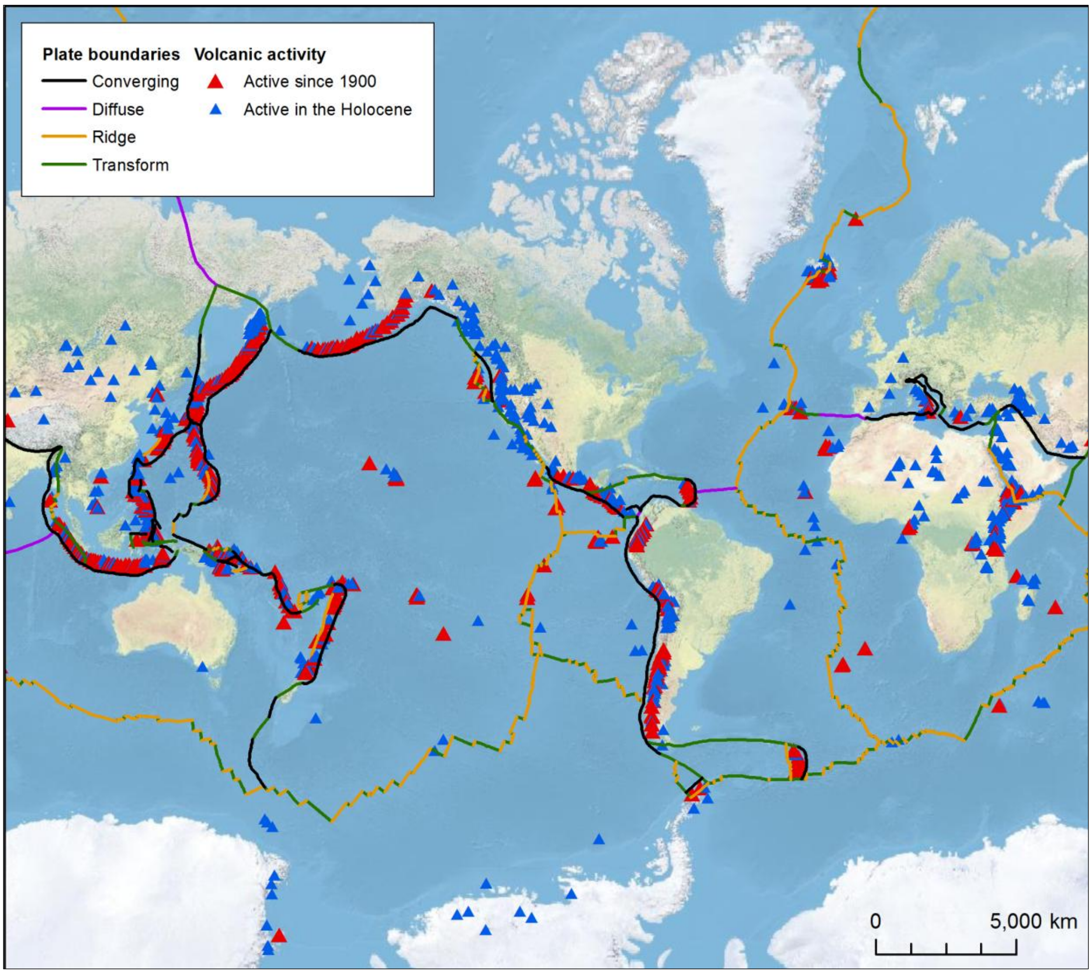

Figure 2: Global map of the distribution and status of Holocene volcanoes as listed in VOTW4.22. The distribution of volcanoes also outlines the boundaries of major tectonic plates.

2.2 Magma

Magma is subsurface molten rock, commonly mixed with suspended crystals and gas bubbles. Magmas vary in composition from those typically rich in elements such as magnesium, calcium and iron and containing about 50% silica (silicon dioxide) to those rich in alkali elements, such as sodium and potassium, with only minor amounts of magnesium, calcium and iron, and containing as much as 75% silica. The former magmas are known as *basalts* and have temperatures typically in the range 1100 to 1300°C. The latter are called *rhyolites* and have temperatures typically in the range 700 to 900°C. There are many magmas intermediate between basalt and rhyolite, the most common being *andesite*. There are a plethora of other magma types and related nomenclature that relate to variations in chemical compositions and mineralogy[24].

Volcanic gases, such as water, carbon dioxide, sulfurous gases and halogens, are dissolved in magma at the high pressures of the Earth's interior, but bubble out of the magma at low pressures near or at the Earth's surface. The same process is familiar in fizzy drinks where gas is dissolved at high pressure and bubbles out when the can or bottle is opened and pressure is released. Sometimes the gas escapes from the magma quietly and slowly to form gas-poor magma which erupts as lava. In other cases gas bubble formation is fast and violent, so explosive eruptions occur. The materials ejected in explosive eruptions are described as *pyroclastic,* and *pyroclastic deposits* are a major constituent of many volcanoes.

A critically important physical property of magma is its *viscosity* (a measure of how easily a liquid flows) as this controls many aspects of volcano behaviour. Hot basalts typically have a viscosity similar to cold honey, whereas andesite and rhyolite magmas are much more viscous by factors of hundreds to millions (i.e. much more viscous than tar). For example gas can escape quite easily from basalt and its eruptions are typically characterised by lava flows and weak explosions. In contrast escape of gas from very viscous andesite or rhyolite magma is much more difficult so eruptions of these magmas are commonly much more explosive. Volcanoes located where plates rift apart and within plates commonly erupt basalt, whereas many volcanoes in subduction zones erupt andesite and rhyolite. There is therefore a marked tendency for the most explosive and hazardous volcanoes to be located in subduction zones. However, there are very explosive volcanoes at rifted plates and those that produce mostly lava in subduction zones. Some eruptions can produce huge amounts of polluting gases, further increasing the hazard.

2.3 Magma chambers

The concept of a *magma chamber* is crucial to volcanology, forming part of the underground plumbing of a volcano. Magma chambers can be defined as a subsurface region or regions where magma accumulates, supplying the volcano during an eruption (Figure 3). They commonly form because magma ascending stalls below ground rather than erupts. Typically magma chambers can form at depths of a few kilometres to the base of the Earth's crust, which ranges in thickness from 6 to as much as 70 kilometres. The Earth's crust becomes cold and strong near the surface and magmas can be prevented from reaching the Earth's surface by various mechanisms. Magma can solidify and may have insufficient pressure to break through to the surface. Stagnation of magma can result in cooling, loss of gas and crystallisation, while heating of surrounding rocks can result in them melting and formation of more magma. Magma chambers can also form when melt is squeezed out of partially molten rocks to form lenses and pockets. These melts can merge together to form large eruptible volumes of magma. These complex processes lead to a wide range of magma volumes, compositions, temperatures and volcanic gas contents, which explains why a single volcano can erupt different magmas with a wide range of eruption styles and hazards.

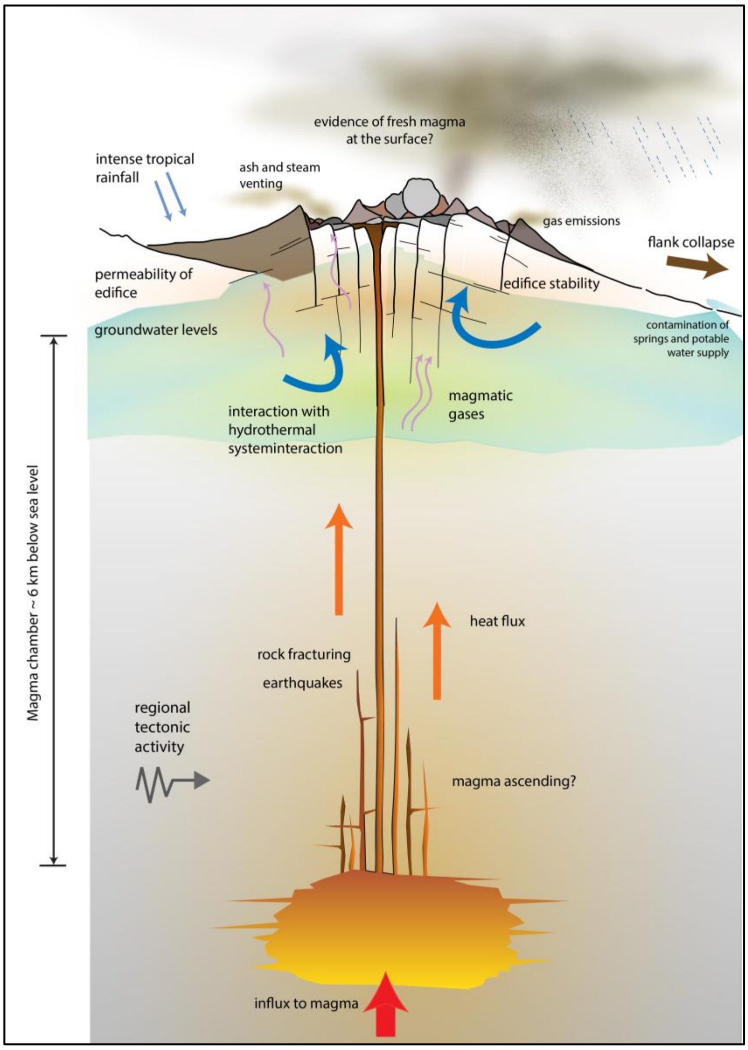

Figure 3: Schematic cross-section through a volcano in a tropical setting and its underlying magma chamber illustrating some of the major processes that lead to phenomena that are monitored on active volcanoes. The magma chamber may become pressurised, for example from influx of new magma from depth or build up of internal gas pressure as it cools and crystallises. Typically a narrow volcanic conduit connects the chamber to the surface during an eruption. The rising magma and pressure from the chamber makes the volcano deform and results in many small earthquakes. Volcanic gases are released and ground water is heated, resulting in surface hot springs and fumaroles.

Magma chambers are an important concept in the interpretation of monitoring data at Volcano Observatories. Earthquakes, ground deformation and anomalous gas emissions, that are commonly precursors to eruptions, are often interpreted in terms of processes within magma chambers and in movement of magma and gases from a magma chambers to the surface (Figure 3). Recent research is recognising that many volcanic systems involve multiple regions of magma (Figure 4) and that there can be other causes of geophysical phenomena at volcanoes, such as movements of ground water (Figure 3), which need to be distinguished from manifestations of magma chambers.

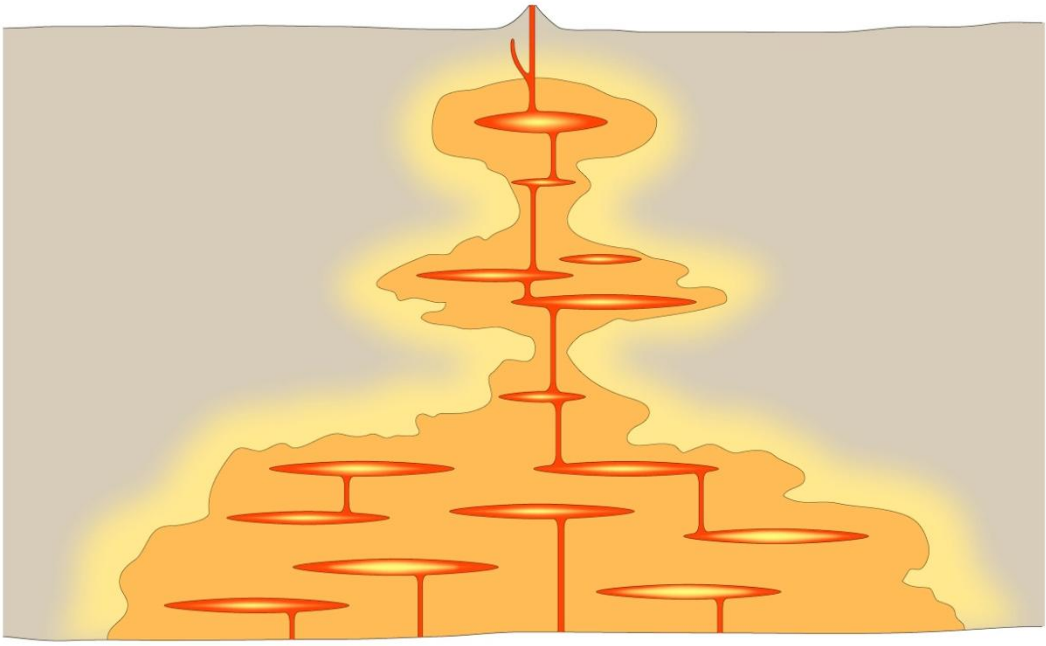

Figure 4: Schematic diagram showing a crustal region comprising several magma bodies embedded in hot partially melted rocks at different depths below a volcano. Figure 3 shows the uppermost chamber connected to the volcano.

2.4 Types of volcanoes

The Smithsonian classification[11,22] recognises 26 categories of volcano. Here only the major types are discussed. *Monogenetic volcanoes* are formed by single eruptions and typically occur in regions where eruptive vents are widely distributed in what are called monogenetic volcanic fields; the city of Auckland, New Zealand is built in such an area. *Polygenetic volcanoes* are developed by numerous eruptions in a localised area over time periods that can exceed a million years. They represent places where magma ascent is focussed. Many polygenetic volcanoes are thought to be underlain by large regions of very hot rock, containing small amounts of melt and multiple magma chambers. Polygenetic volcanoes can be broadly classified into different types based on magma chemistry, size and dominant eruptive styles.

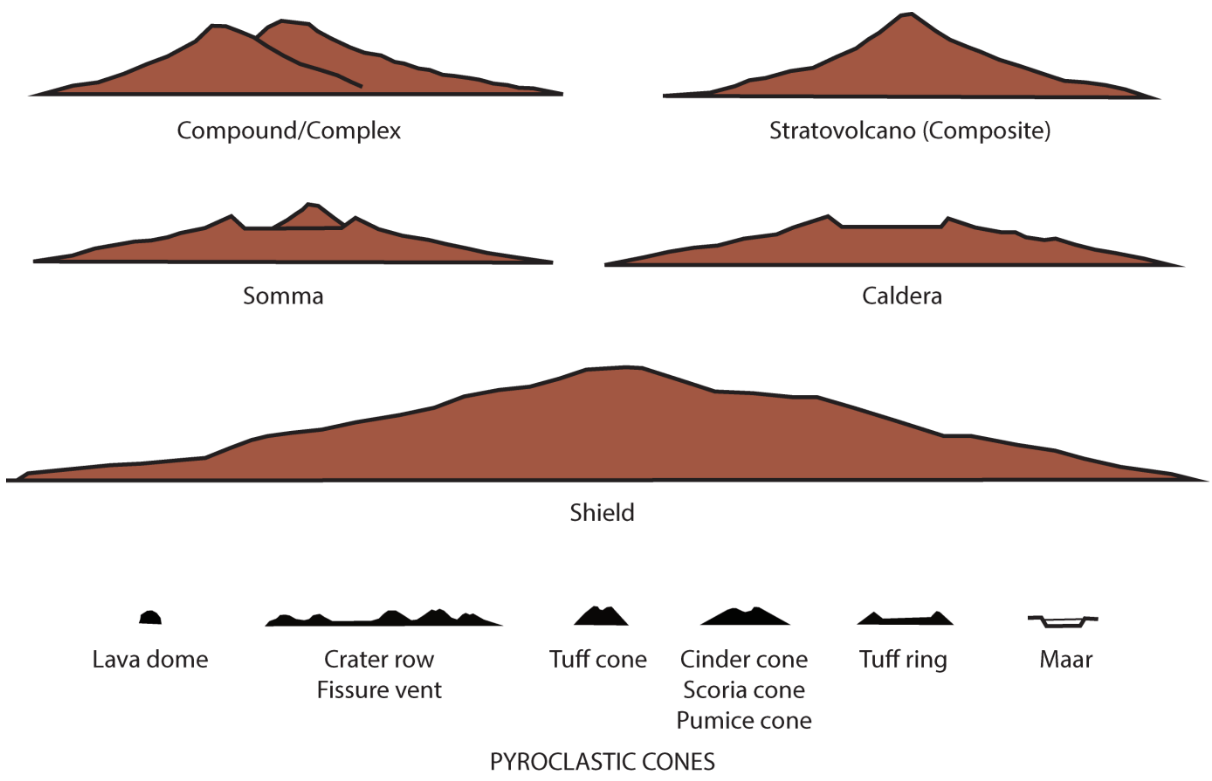

Figure 5: Volcanoes take a variety of forms as dictated by their chemistry, eruption style and products. Here the main volcano types are illustrated with a vertical exaggeration of 2:1 for the main edifice constructs and 4:1 for the pyroclastic cones[11].

Some common volcano types are illustrated in Figure 5. Fissure volcanoes are where large fractures (or fissures) form in the Earth's crust and are characterised by eruption of copious lava and gas. The 1783 eruption of Laki in Iceland is a type example (Figure 6a), when over 15 km^3 of basalt erupted over 6 months. Shield volcanoes, like Kilauea and Mauna Loa (Hawaii), are amalgamations of numerous lava flows and are typically basalts (Figure 6b). Stratovolcanoes, like Fuji (Japan) and Colima (Mexico), are typically steep-sided and are mixtures of lava and pyroclastic deposits (Figure 6c). Lava dome volcanoes, like Soufrière Hills Volcano (Montserrat, Eastern Caribbean) are made of mounds of lava known as domes, commonly andesite or rhyolite in composition, together with pyroclastic deposits (Figure 6d). Calderas are large volcanic craters (1 to more than 50 km diameter) mostly formed by large magnitude volcanic eruptions (Figure 6e). Eruption of large volumes of magma causes the ground above the magma chamber to collapse. The largest of these, like Yellowstone (USA) have been called supervolcanoes[6].

While basic classifications are useful, many volcanoes are very diverse in their styles of eruption, in their magnitudes, intensities, and frequency of eruption. For example an active volcano like Santorini (Greece) over a history of 700,000 years has behaved as a shield volcano and stratovolcano at different times, has formed several large calderas from major explosive eruptions, and has erupted basalt, andesite and rhyolite at different times. This variety comes about because the processes of magma generation and the interaction of erupting volcanoes with surface environments are complex. From a hazard perspective every volcano is thus unique in some respects and this means that forecasting of eruptions and assessment of hazards needs to be carried out at a local volcano scale. For this reason a critical aspect of living with an active volcano is to have a dedicated Volcano Observatory.

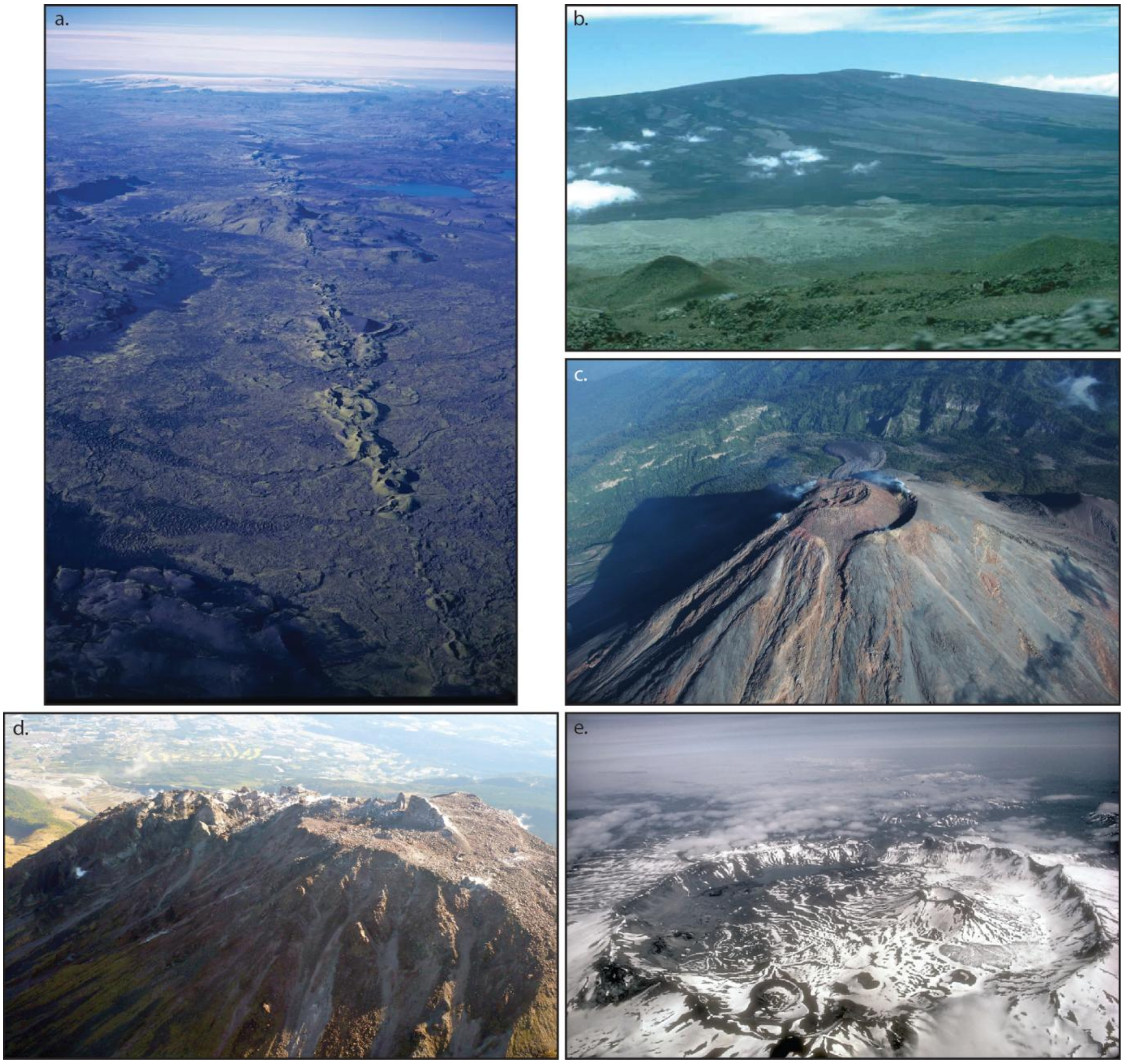

Figure 6: Examples of volcano forms. (a) Fissure from the 1783 Laki (Iceland) eruption (O. Sigurdsson). (b) The Mauna Loa shield volcano, Hawaii (US Geological Survey archive). (c) Colima stratovolcano (Mexico) (S. Brown). (d) The lava dome at Soufrière Hills volcano, Montserrat (P. Cole). (e) The 10 km diameter Aniakchak caldera, Alaska (US Geological Survey archive).

2.5 Styles of eruption

At the most basic level volcanic activity can be divided into effusion of lava and explosive eruptions (Figure 7). In some cases eruptions are only explosive while in others they are dominantly effusive. However, many eruptions are a mixture of explosive and effusive activity, which can sometimes occur simultaneously or in complex alternating sequences. Explosive eruptions can vary from discrete explosions lasting a few minutes to sustained and intense discharges over many hours. Explosions can result from violent release of volcanic gases dissolved under pressure in the magma (Figure 8a and b) and by interaction of hot erupting magma with water (Figure 8c). Lava represents magma that has lost most of the originally dissolved gases prior to eruption. Basalt magmas with low viscosity can form rapidly moving rivers of thin lava when the effusion rate is high (Figure 8d), while more viscous andesite and rhyolite form much thicker lavas and domes (Figure 8e).

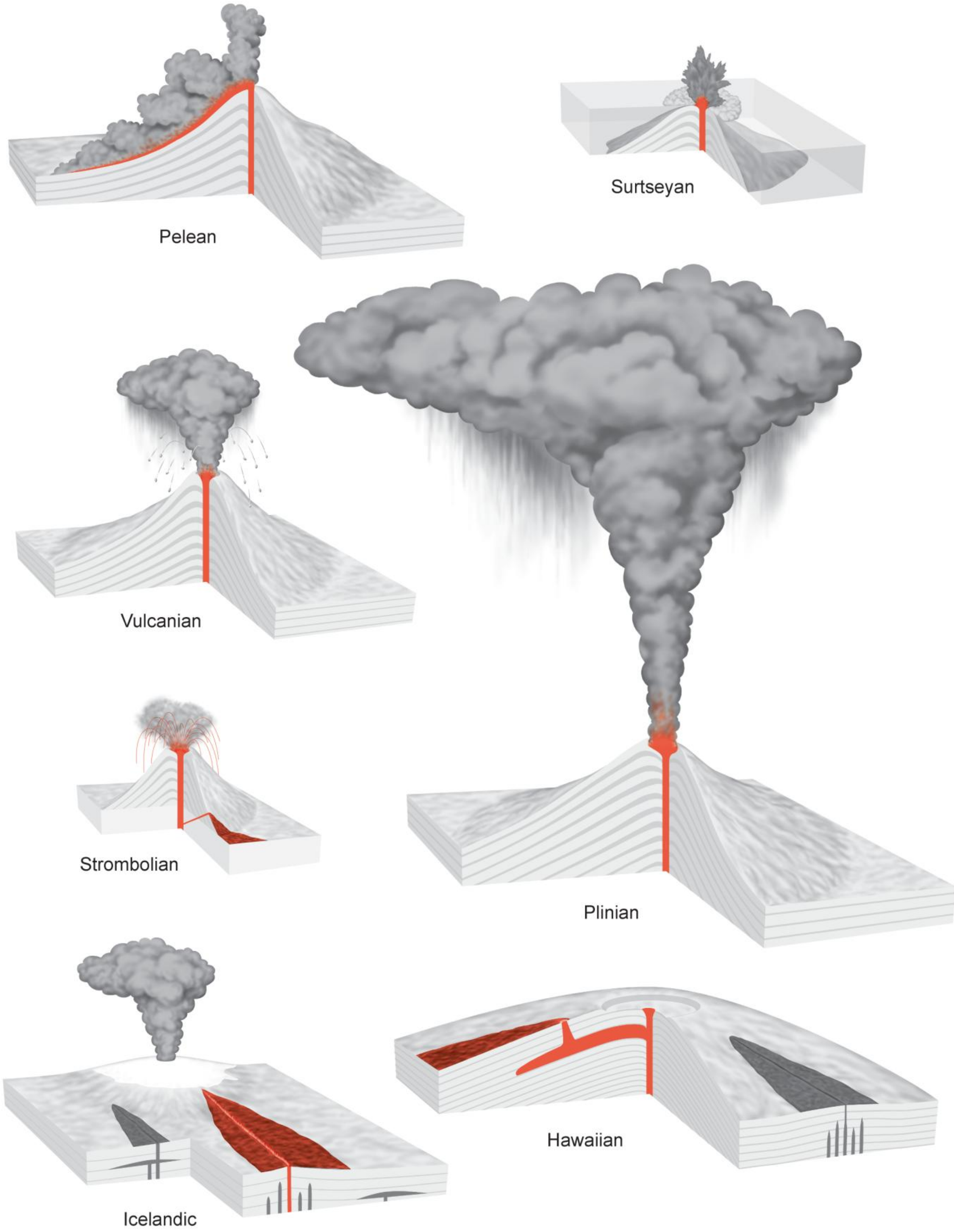

Figure 7: Eruption styles vary from effusive lava outflows in Hawaiian style eruptions through to large explosive Plinian eruptions, which can inject ash into the Stratosphere. Here the main eruption styles are illustrated[11] *See Figure 8 for examples.*

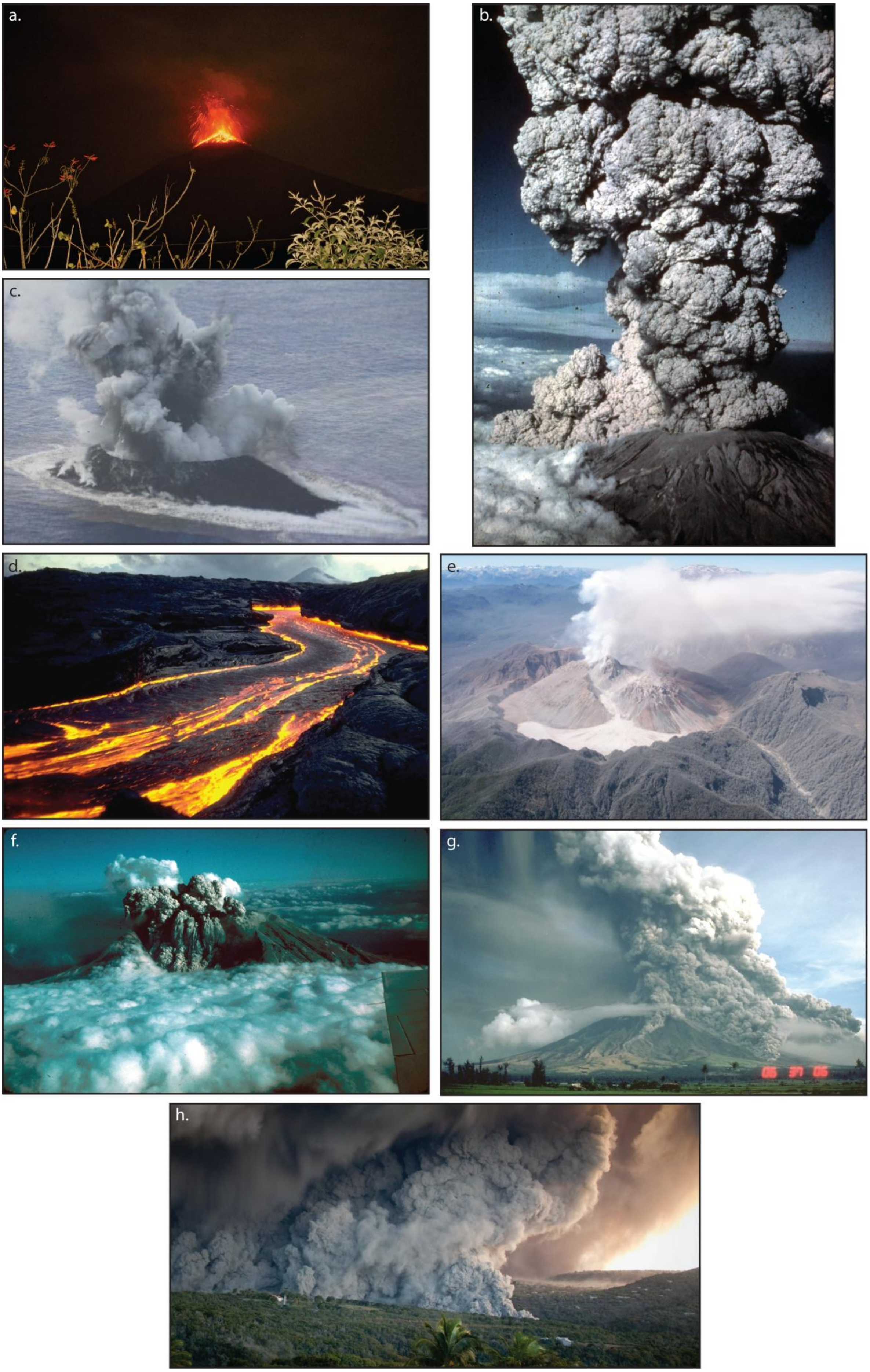
a.
b.
c.
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Figure 8: Major styles of volcanic eruptions and their associated hazards. (a) Strombolian explosive eruption at the summit of the basaltic volcano Fuego in Guatemala, 2014 (J. Crosby). (b) Explosive eruption of Mount St. Helens, USA, in 1980 displays the characteristic turbulent clouds of ash, gas and hot air rising to heights of over 15 kilometres into the atmosphere. These rising clouds are known as plumes. A pyroclastic flow moves down the flanks of the volcano generating a smaller ash cloud. (US Geological Survey archive) (c) An explosive eruption of the submarine Nishino-shima volcano, Japan, 2013 (ERI, University of Tokyo). (d) Basalt lava flow on Kilauea volcano, Hawaii, about 1 km south of the Kupaianaha vent in 1987 (S. Rowland). (e) Rhyolite lava dome at Chaitén volcano, Chile in 2009. The 2008-2009 eruption of the volcano occurred after 7,400 years of dormancy and resulted in the evacuation of 900 people from the town of Chaitén (A. Amigo). (f) The collapse in a fountain like structure of the eruption column at Mount St. Helens in 1980 due to the density of the column, forming a pyroclastic flow (US Geological Survey archive). (g) Pyroclastic flow from the 1984 explosive eruption of Mayon, Philippines (C. Newhall). (h) Pyroclastic flow from a dome collapse on Montserrat (H. Odbert).

Explosive eruptions are responsible for much of the threat to life. Explosive eruptions discharge mixtures of hot volcanic rocks, volcanic gases and sometimes surface-derived water into the atmosphere. These flows are highly turbulent so large amounts of air are engulfed and heated (Figure 8b). In some cases this mixture, ejected at speeds of tens to hundreds of kilometres per hour, rises as a plume to great heights in the atmosphere, reaching the stratosphere in the more powerful eruptions (Figure 8b). In other cases the mixture is so full of rocks and ash that erupted mixture collapses (Figure 8f) and forms a dense flow (called a pyroclastic density current) that moves along the ground under gravity (Figure 8g). Over 43% of deaths directly attributed to volcanic hazards are caused by such flows[1]. Similar flows can be formed with the eruption and collapse of lava domes, which are highly unstable (Figure 8h). Volcanic hazards are discussed in section 3.

2.6 Size and intensity of eruptions

There are two main measures of volcanic eruptions, namely magnitude and intensity. The magnitude is defined as an erupted mass while intensity is defined as rate of eruption or mass flux. Magnitude, M, is defined as the base 10 log of the mass erupted in kilograms minus 7. Magnitudes range over 9 orders of magnitude with magnitude 9 eruptions being the largest and the largest Holocene (the last 10,000 years) eruption being magnitude 7.4[25]. Intensity is usually expressed as kg/s or m^3/s. The range of intensities is likewise very large, from a few kg/s up to a billion kg/s in exceptional rare events.

Neither magnitude nor intensity is easy to measure accurately. Volume is often used rather than mass as it is typically easier to estimate. A widely used index for the size of explosive eruptions is the *Volcanic Explosivity Index* (VEI)[26], which is used by the Smithsonian Institution to categorise all explosive eruptions based on multiple criteria (Figure 9). VEI is on a scale from 0 to 8 and is approximately equivalent to the Magnitude, which is based on a logarithmic scale of mass. VEI is usually estimated from volumes of volcanic ash, but can also be estimated from eruption column height if volume information is not available. VEI only applies to explosive eruptions and a magnitude scale that includes both effusive (lava) and explosive products is more general.

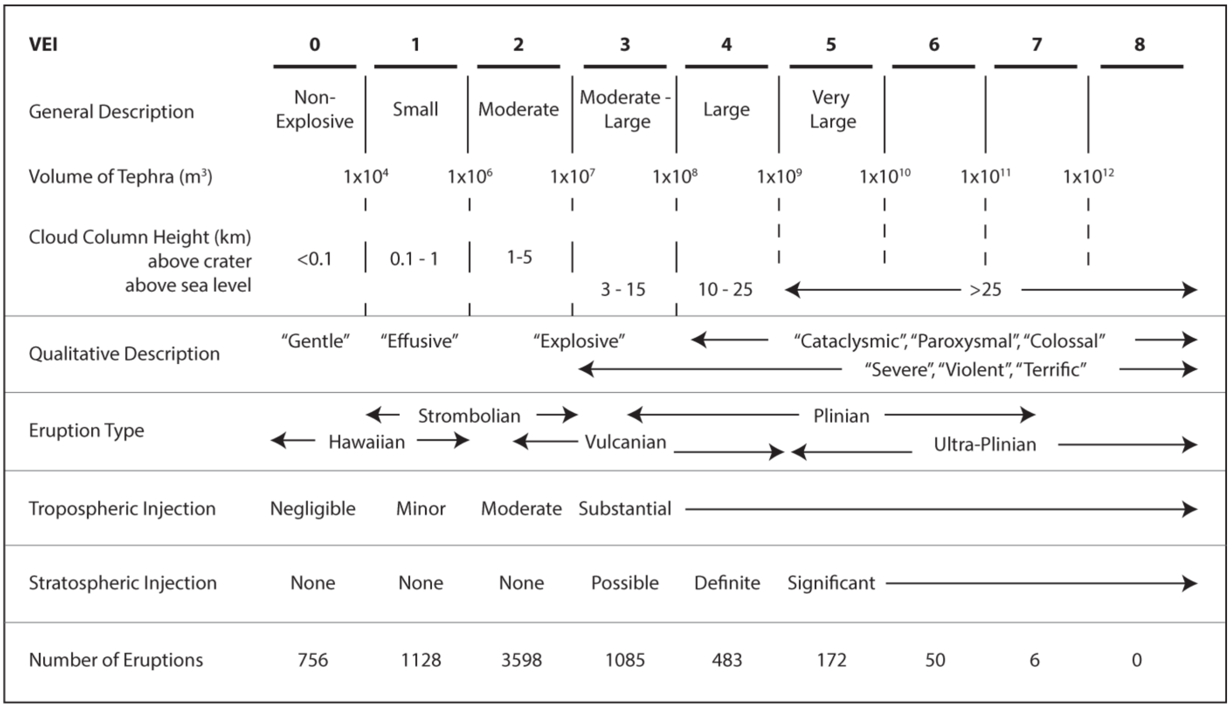


Figure 9: Scheme to illustrate the assessment of Volcanic Explosivity Index (VEI) from diverse observations[26]. VEI is best estimated from erupted volumes of ash but can also be estimated from column height. The nomenclature of common kinds of explosive eruption and typical duration of the eruptions are indicated. The number of confirmed Holocene eruptions with an attributed VEI in VOTW4.22 are shown.

There is a widely used classification of explosive volcanic eruptions based on the well-known eruptions at type volcanoes, such as Vulcanian, Hawaiian and Strombolian (Figure 7). Some of the most common terms are indicated in Figure 9 and are qualitatively correlated with VEI and intensity of eruption. The term Plinian comes from the AD79 eruption of Vesuvius and highlights the seminal description of a major powerful explosive eruption by Pliny the Younger. The eruption of Mount Pinatubo (Philippines) in 1991 is a modern example of a Plinian eruption.

The height of a volcanic eruption column generated in an explosive eruption is related to intensity[27,28] which cannot be measured directly. Adjustments are required for wind in the case of weak eruptions[29]. Many eruptions are sequences of different styles of eruption (e.g. explosions and lava flows) of varying intensity and magnitude. Volcanic eruptions vary greatly in duration from just a few minutes to decades. There are several volcanoes that erupt almost continuously, such as Stromboli in Italy, which has had countless small explosions over at least two millennia.

3 Volcanoes and volcanic eruptions

Since 1960 the Smithsonian Institution has collated data on the World's active Volcanoes. Their Volcanoes of the World database[11,23] (VOTW4.0) is regarded as the authoritative source of information on Earth's volcanism and is the main resource for this study. Data cited in this report are from VOTW4.22.

3.1 Volcano inventory

VOTW4.0 contains a catalogue of 1,551 volcanoes. Their distribution is shown in Figure 2. There are 596 volcanoes that have an historical record since 1500 AD, and 866 volcanoes with known Holocene eruptions (the last 10,000 years). There are 9,444 eruptions in VOTW4.0. There are many more volcanoes that have been active in the Quaternary period (defined as the last 2.6 million years). The LaMEVE database[30] lists 3,130 Quaternary volcanoes. Some of those that are not catalogued in VOTW4.0 may well be dormant rather than extinct. Individual volcanoes can change from one of these categories of activity to another as more information becomes available. For example, prior to the 2010 eruption of Sinabung in Indonesia, the volcano had no historical record and was classified as a dormant Holocene volcano. Evidence of Holocene activity in those volcanoes without historical records is based on geological studies. However, many Quaternary volcanoes still remain unstudied, including numerous small monogenetic volcanoes that have not been systematically catalogued. Remote sensing using synthetic aperture radar is recognising unrest in volcanoes previously thought to be long dormant or even extinct[31]. There are likely many thousands of active submarine volcanoes along the Earth's ocean ridges, most of which have never been catalogued or explored. From a hazard and risk perspective it is those volcanoes close to communities that are of most concern; however, even remote and uninhabited island volcanoes pose a threat to aviation and distal populations.

3.2 Rates of eruption

A key question is how often do volcanoes erupt? This is not a straightforward question to answer as many volcanoes do not have long historical or geological records[32]. Indeed analysis of VOTW4.0 data established that only about 30% of the World's volcanoes have any information before 1500 AD while 38% have no record earlier than 1900 AD. All of the records that exist are affected by severe under-recording[25,33,34], that is the historical and geological records become less complete back in time. For example statistical studies of the available records[25,33,34] suggest that only about 40% of explosive eruptions are known between 1500 and 1900 AD, while only 15% of large Holocene explosive eruptions are known prior to 1 AD. Most volcanoes alternate between long periods of repose and short bursts of activity. Since the repose periods can be decades to millennia or more there are very few volcanoes with long enough or complete enough records to enable statistical models of eruption frequency to be developed.

Analysis of global data for explosive eruptions shows a decrease in the frequency of eruptions as eruption magnitude increases (Table 1), as observed for many other Earth systems (e.g. earthquakes, tropical cyclones and high-latitude winter storms. Up to M 6.5 the data define a comparable decrease of average return period with magnitude to that seen in earthquake data. However, for M ≥6.5 the average return periods become greater than this empirical law and the decrease becomes greater for larger magnitudes. Here we note that super-eruptions[6] like those that took place in Yellowstone are defined as having a magnitude of M = 8 or greater. The estimate of a global average return period of 130,000 years for super-eruptions indicates events of very low probability in the context of human society.

Magnitude	Return Period (years)	Uncertainty (years)
≥4.0	2.5	0.9
≥4.5	4.1	1.3
≥5.0	7.8	2.5
≥5.5	24.0	5.0
≥6.0	72	10
≥6.5	380	18
≥7.0	2925	190
≥7.5	39,500	2500
≥8.0	133,500	16000

Table 1: Global return periods for explosive eruptions of magnitude M, where $M = Log_{10}m - 7$ and m is the mass erupted in kilograms. The estimates are based on a statistical analysis of data from VOW4 and the Large Magnitude Explosive Volcanic Eruptions database (LaMEVE) version 2 (http://www.bgs.ac.uk/vogripa/)[30]. The analysis method takes account of the decrease of event reporting back in time[34]. Note that the data are for $M \geq 4$.

The global eruption record since 1950 is considered largely complete for eruptions on land. Eruptions of submarine volcanoes are largely undocumented, though they likely exceed eruptions on land in number. There are 2,208 confirmed eruptions recorded in the VOTW4.0 database since 1950, from 347 volcanoes. Despite our knowledge of 1,551 volcanoes, the number of individual erupting volcanoes each year varies within a relatively narrow range, from 44 to 77 volcanoes, with on average 57 volcanoes in eruption in any given year. The average number of eruptions ongoing per year since 1950 is 63, with a minimum of 46 and maximum of 85 eruptions recorded per year, including on average 34 new eruptions beginning per year. VOTW4.0 counts all eruptions occurring less than three months after the preceding eruption to be part of the same single eruption; those occurring after three months of repose are counted as new eruptions, unless clearly shown to be otherwise.

3.3 Examples of volcanic activity

Examples of volcanoes and their eruptions are presented in this section to illustrate the wide range of behaviours together with implications for risk. A key point is that every volcano and volcanic region is in some respect unique.

In 1943 farmers in the Mexican state of Michoacán witnessed the ground in cornfields break open and a new volcano, named Paricutin, formed[35]. There was no official warning, although many small earthquakes had been noticed in the months before. The eruption lasted nine years, generating huge volumes of ash and lava. Paricutin is an example of a monogenetic volcano, i.e. one that erupts only once. Auckland, New Zealand, home to 1.4 million people and over a third of New Zealand's population, is built on top of the Auckland Volcanic Field (AVF) and illustrates the issues in regions of scattered monogenetic volcanoes [CS2][36]. The AVF covers 360 km^2, has over 50 eruptive centres (vents), and has erupted over 55 times in the past 250,000 years (Figure 10). The most recent eruption, Rangitoto, occurred only 550 years ago. Most vents are monogenetic, i.e., they only erupt once. This poses a considerable problem for emergency and risk managers, as it is unknown where or when the next eruption will occur.

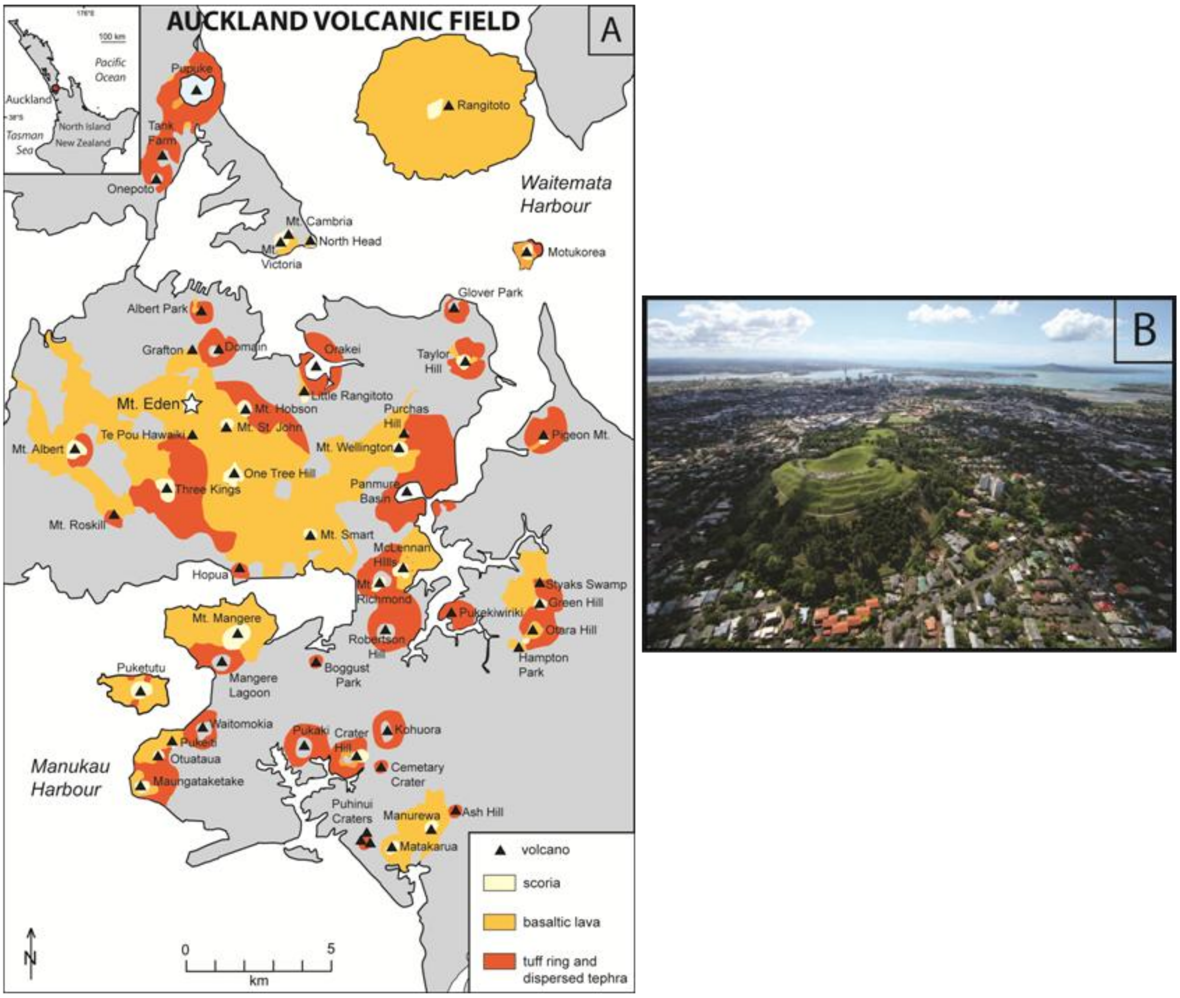


Figure 10: (a) Map of Auckland Volcanic Field (AVF, modified from[37]) showing the distribution of volcanic vents and products in the city of Auckland, New Zealand. Star shows the location of Mount Eden. (b) View of Mount Eden looking to the north, highlighting the complete overlap of AVF and city (©Auckland Council).

With over half of the world's population now in cities, volcanic risk to large urban communities is considerable. Naples is one of the cities in the world with the highest volcanic risk [CS3]. Millions of inhabitants are directly threatened by three active volcanoes, namely Vesuvius, Campi Flegrei caldera and Ischia (Figure 11). The Osservatorio Vesuviano (OV) of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) continuously monitors these volcanoes using advanced techniques to record the time and spatial evolution of seismic activity, ground deformation, geochemical signals, and many other potential pre-eruptive indicators. OV provides updated hazard information to the Italian Civil Protection Department that is responsible for planning risk mitigation actions. There are great challenges in planning for the evacuation of hundreds of thousands of people from large cities close to active volcanoes.

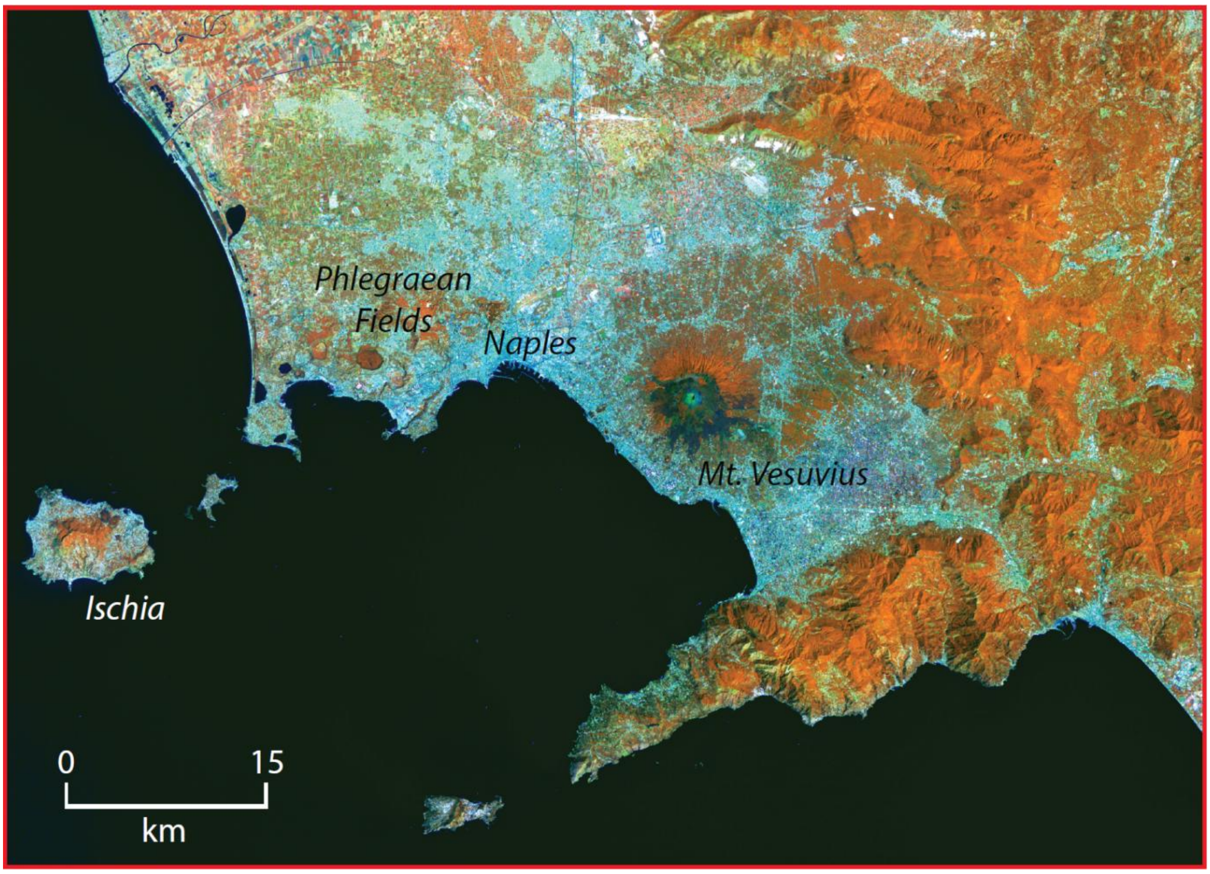


Figure 11: Satellite image of the Naples area where over 2 million people live on the flanks of the three active volcanoes of Vesuvius, Campi Flegrei and Ischia.

In 1992 small earthquakes were felt on the island of Montserrat in the eastern Caribbean. In 1995 a major andesite eruption of the Soufrière Hills Volcano began, which may still be ongoing[38]. There are no records of historical eruptions at Soufrière Hills since the island was colonised in 1642. Periods of small earthquakes in 1896-97, 1933-37 and 1966-67 had been experienced, but they had not led to eruptions. These episodes are an example of volcanic unrest and are sometimes described as failed eruptions. The present eruptive period has been long (1995 to 2013) and complex with many different hazards. There were 19 fatalities on 25 June 1997 and the population of the island was reduced from about 10,000 to about 3,000, with major economic consequences[39].

After sleeping for over 500 years, Mount Pinatubo (Philippines) began to stir in mid-March 1991, producing a giant eruption on 15 June 1991, the second largest of the 20th century [CS4][40]. About ~1,000,000 lowland Filipinos lived around the volcano and 20,000 indigenous Aetas lived on the volcano. Two large American military bases, Clark Air Base and Subic Bay Naval Station, were also at risk. Earthquakes, emissions of sulfur dioxide gas and small to moderate sized explosions preceded the paroxysms of 15 June. As many as 20,000 lives were saved as a consequence of the prompt action of authorities to evacuate, based on advice from the Philippine Institute of Volcanology supported by the US Geological Survey Volcano Disaster Assistance Program with funding from US Aid [see CS21]. Despite considerable uncertainties, the eruption was correctly forecast and more than 85,000 were evacuated by 14 June with many aircraft also protected from the eruption. The duration of the hazards lasted far beyond the eruption and indeed eruption-related hazards continue today, although at a much-reduced level. Voluminous rain-induced volcanic mudflows (lahars) continued for more than 10 years, and sediment-clogged channels still overflow today during heavy rains. Although about 200,000 were "permanently displaced" by lahars, only about 400 fatalities are attributed to lahars. Timely warnings from scientists and police helped to keep most people safe.

Montserrat and Pinatubo are examples of a common situation where a long dormant volcano with a limited record erupts. Populations, civil protection services and political authorities have had no previous experience of activity at the volcano. In a case like Montserrat the periods of unrest with no eruption may also make a population hesitant to listen to scientists, or to respond appropriately. Chaitén Volcano, Chile, is another example of a volcano that erupted after a period of quiescence of approximately four centuries[41].

The emergency in 1976 of La Soufrière Volcano, Guadeloupe (Eastern Caribbean) illustrates the difficulty of assessing the outcome of an eruption [CS5][42]. A major eruption had occurred in the 16th century. However, there had been numerous periods of unrest and very small eruptions related to heating of groundwater by magma in 1690, 1797-1798, 1812, 1836-1837 and 1956[43]. Increasingly intense earthquakes were recorded at La Soufrière one year prior to the eruption, which began with an explosion on 8 July 1976 followed by 25 explosions over a period of nine months. There was no real way of knowing whether a devastating major explosive eruption might occur or another period of unrest and minor steam explosions. Intense earthquakes and steam explosions in 1976 led to the precautionary evacuation of 73,000 people for four months in August 1976. They returned when three months later the volcano quietened without a major eruption. High levels of uncertainty and evacuations that are retrospectively identified as unnecessary are a major issue for management of volcanic crises. The importance of volcano observatories is that they can refute false reports of activity, and provide warnings and forecasts of hazardous activity.

Some volcanoes are frequently active. The classic andesite Merapi stratovolcano on the island of Java, Indonesia, has been active for much of the last 200 years [CS6 and CS7][3]. The frequent eruptions have fluctuated in intensity and magnitude, and there have been periods of quiet, which usually do not last more than a few years. In such cases communities become acquainted with and quite knowledgeable about volcanic activity and learn to live with the volcano. Even in such cases the volcano can be dangerous if unexpectedly large eruptions occur that are beyond the range experienced by the population. On the first day of the 2010 eruption, on 26 October, the second most violent explosive paroxysm of the entire eruption occurred and took the lives of 38 people. The eruption continued to escalate to climax 11 days later and on 5 November 2010 a large explosive eruption discharged hot pyroclastic flows down the flanks to distances almost twice as far as in previous historical eruptions[3]. The volcanologists recognised unusual and threatening behaviour [CS6]. Although the eruption was considered responsible for 367 deaths[44], the authorities evacuated approximately 400,000 people prior to the eruption based on the recommendations of scientists from the Centre of Volcanology and Geological Hazard Mitigation (CVGHM) who operate the Merapi Volcano Observatory [CS7]. An estimated 10,000 to 20,000 lives were saved. The case highlights the need for awareness that volcanoes will not always behave as they have in the past and that for long-lived centres the maximum credible event possible has to be determined from geologic field investigations that extend to time periods well beyond the historical period. The 2010 eruption of Merapi also underscores well that in some cases, paroxysmal activity can occur at the very onset of the eruption but that additional and even more violent activity can occur later in the eruption as well.

Quite small eruptions can cause major problems. In 1985 a medium sized explosive eruption (VEI 3) took place at the summit of Nevado del Ruiz in Colombia, which was covered by an ice cap[2]. The eruption melted ice rapidly and intense floods discharged down several major valleys. As they moved they incorporated loose rock, sand and soil and turned into devastating flows of mud and debris which buried the town of Armero, 45 km away with the loss of 23,000 lives and flooded the village of Chinchina with a loss of 1,927 lives. Here there seems to have been a lack of communication between the authorities and these communities with tragic consequences.

Volcanic eruptions can coincide with very difficult political or social situations, exacerbating the problems. In January 2002 a major eruption of Nyiragongo volcano (Democratic Republic of Congo) occurred in the midst of a complex humanitarian emergency [CS8][45]. A basalt lava flow erupted from the crater and inundated the city of Goma producing major devastation, forcing the rapid exodus of most of Goma's 300,000-400,000 inhabitants across the border into neighbouring Rwanda. This situation caused international concerns about an additional humanitarian catastrophe that could have worsened the ongoing regional ethnic and military conflict. Lava flows destroyed about 13% of Goma, 21% of the electricity network, 80% of its economic assets, 1/3 of the international airport runway and the housing of 120,000 people. The eruption caused about 470 injuries and about 140-160 deaths, mostly from CO_2 asphyxiation and from the explosion of a petrol station near the active hot lava flow[46]. The eruption caused a major humanitarian emergency that further weakened the already fragile lifelines of the vulnerable population. The limited number of fatalities in 2002 is largely a result of the timely recognition by the Goma Volcano Observatory (GVO) of the reactivation of the volcano about 1 year prior the eruption and their efficient communication with authorities once the eruption began, memory of the devastating 1977 eruption triggered life-saving actions by the population, the presence of a large humanitarian operation in Goma, and the occurrence of the eruption in the morning.

Extreme volcanic eruptions have potential for regional and global consequences. The 1991 eruption of Mount Pinatubo, Philippines, was one of the biggest explosive eruptions of the 20th century. Sulfur dioxide and sulfuric acid aerosol pollution spread around the equator within 3 weeks and it took over 2 years for the global atmospheric pollution to dissipate. The pollution was so great that the trend of increasing CO_2 in the atmosphere was momentarily halted, there was global cooling and there was a significant reduction in ozone over northern Europe. The two largest eruptions in recent history are the Laki basalt lava eruption (Iceland) in 1783 and the magnitude 7 explosive eruption of Tambora (Indonesia) in 1815. Up to one third of Icelanders (8000) died from the magnitude 6.7 Laki eruption, largely through famine due to the environmental catastrophe[47] and there is compelling evidence that there were tens of thousands of deaths in England and France related to the resulting sulfur pollution and crop failures[48]. Likewise the Tambora death toll was an estimated 70,000, mostly related to post-eruption famine[1]. There was major northern hemisphere cooling of about 1°C in the two years following the eruption of Tambora. In 1816 after Tambora erupted, summer frosts destroyed crops in New England and there was the "year without a summer" in Europe.

The critical culprit in the effects of large explosive eruptions on climate is sulfur dioxide[49]. Sulfur dioxide gas reacts with atmospheric water to form tiny droplets of sulfuric acid, which can remain in the stratosphere for several years. Solar radiation is reflected back into space and absorbed by the aerosol. Thus the lower atmosphere becomes abnormally cool and the stratosphere is heated. There is about a 1 in 3 chance of an eruption similar in magnitude to Laki or Tambora in the 21st century. In the modern globalised and interconnected World the economic and societal impacts of such an eruption would be considerable.

About 75,000 years ago the largest volcanic eruption in the Earth's recent history took place at Toba in Sumatra, Indonesia[6]. Thick layers of volcanic ash were spread over the Indian Ocean, south-east Asia and probably most of China. The eruption ejected about 3,000 cubic kilometres of volcanic ash, 10,000 times more ash than Mount St Helens produced in 1980. The biggest volcanic crater on Earth (Lake Toba) formed with a length of 80 km and width of 30 km. Atmospheric pollution from such an eruption could cause major climatic deterioration for a decade or more. Eruptions on this scale (magnitude 8 or above) have been described as super-eruptions[6]. Volcanoes capable of super-eruptions include, but are not limited to, Yellowstone (USA), Taupo Volcanic Centre (New Zealand) and the Campi Flegrei (Italy). Such eruptions would have severe global impact but they occur very infrequently, roughly every 130,000 years or so (**Error! Reference source not found.**), although this s about 5 to 10 times more frequently than meteorite impacts that would have comparable global impact.

Recent studies have shown that large magmatic reservoirs that feed VEI or M 7-8+ eruptions can recharge and become critically primed for large eruptions on much shorter time scales (decades to months) than previously thought[50]. Moreover, the return period for ≥ VEI 6.5 eruptions might be shorter than currently estimated as recent large eruptions have been newly identified (e.g. the VEI 6-7 Samalas-Rinjani in Indonesia that occurred in 1257AD[51]). Hence, although very infrequent, extreme volcanic events (i.e. ≥ VEI 6.5) that have potential for regional and global consequences must be integrated into long-term risk assessment and yet we have no experience of such events in recent historical time[6].

4 Volcanic hazards and their impact

Volcanoes produce multiple hazards[15,16], that must each be recognised and accounted for in order to mitigate their impacts. Depending upon volcano type, magma composition and eruption style and intensity at any given time, these hazards will have different characteristics. Thus reliable hazard assessment requires volcano-by-volcano investigation. An important concept in natural hazards is the *hazard footprint*, which can be defined as the area likely to be adversely affected by hazard. The following is a brief account of the major kinds of volcanic hazards that create risks for communities with examples to illustrate their impacts.

Not all hazards are generated in every eruption or by every volcano. Individual volcanic eruptions are characterised by their magnitude (mass of erupted material), intensity (the rate of mass eruption), duration and eruptive phenomena (e.g. lava flows or explosions). Each eruption will have its own set of "hazard footprints", which can be defined as the areas affected by each of the hazardous processes. These hazard footprints can evolve during an eruption as it progresses.

Figure 12: Volcanic hazards and their impacts. (a) The turbulent eruption column of the 2011 Grímsvötn eruption, Iceland (Ó. Sigurjónsson). (b) The2010 plume of Eyjafjallajökull, Iceland, which went on to cause mass disruption across Europe as air travel was grounded (S.Jenkins). (c) Burial of houses in thick ash deposits during the eruption of Soufrière Hills, Montserrat (H. Odbert). (d) Extensive damage 6 km from the vent after pyroclastic density currents occurred at Merapi, Indonesia in 2010 (S. Jenkins). (e) Only the roofs of 2-storey buildings are visible in Bacolor after repeated inundation by lahars following the 1991 eruption of Pinatubo, Philippines (C. Newhall). (f) Cars buried in lavas from the 2002 eruption of Nyiragongo in Democratic Republic of Congo (G. Kourounis).

4.1 Ballistics

Ballistics (also referred to as blocks or bombs) are rocks ejected by volcanic explosions on cannon ball-like trajectories. They are typically decimetres to a couple of metres in size. In most cases the range of ballistics is a few hundred metres to perhaps two kilometres, but they can be thrown to distances of five kilometres or more in the most powerful explosions[15] and so the hazard footprint remains close to the volcano Fatalities, injuries and structural damage result from direct impacts and very hot ballistics can start fires. Tourists and scientists have proved to be particularly vulnerable: the unexpected explosion of Mount Ontake, Japan on 27 September 2014 resulted in the deaths of 50 hikers. At Aso in Japan, bomb shelters have been built in case of unexpected explosions. Intense volcanic explosions can cause shock and infrasonic waves in the atmosphere, which can shatter windows and damage delicate equipment (e.g. electronic doors) at distances of several kilometres from the volcano.

4.2 Volcanic ash and tephra

All explosive volcanic eruptions generate tephra, fragments of rock that are produced when magma or vent material is explosively disintegrated. Volcanic ash (tephra <2 mm diameter) is then convected upwards within the eruption column and carried downwind, falling out of suspension and potentially affecting communities across hundreds, or even thousands, of square kilometres. Ash is the most frequent, and often widespread, volcanic hazard. Although ash falls rarely endanger human life directly, but threats to public health and disruption to critical infrastructure services, aviation and primary production can lead to potentially substantial societal impacts and costs, even at thicknesses of only a few millimetres. A comprehensive volcanic hazard assessment must include ash fall in addition to more localised hazards such as pyroclastic density currents. However, the impacts of ash fall are arguably more complex and multi-faceted than for any of the other volcanic hazards and therefore a separate background technical report on volcanic ash fall hazard and risk has been included in the package of information for GAR-15 (see Jenkins et al., section III).

Forecasting the dispersal of ash in the atmosphere and how much will fall, where, when and with what characteristics are major challenges during eruptions. Volcanic ash may be transported by prevailing winds hundreds or even thousands of kilometres away from a volcano (Figure 12 b) and very large explosions can inject volcanic ash into the stratosphere. The dispersal of volcanic ash depends principally on meteorological conditions, including wind (speed and direction) and humidity, the grain size distribution of the ash, and the height of the volcanic plume, which depends on the intensity of the eruption. Hazard footprints of both ashfall on the ground and dispersal of hazardous ash concentrations in the atmosphere can be very large (up to millions of square kilometres in the largest eruptions) and can affect many different countries. The dispersal of volcanic ash is therefore of global concern.

Near the volcano, thick accumulations of tephra and ash can cause roofs to collapse and lead to consequent fatalities and injuries (Figure 12c). In the 1991 eruption of Pinatubo [CS4] about 300 people died from roof collapse during the eruption. Moderate ash falls of several centimetres may damage infrastructure (e.g. power grids), cause structural damage to buildings and create major clean-up demands [CS9][15,52,53]. Even relatively thin falls (≥ 1 mm) may threaten public health, damage crops and vegetation, and disrupt critical infrastructure services, aviation, primary production and other socio-economic activities over potentially very large areas[53].

Very fine ash at ground level is a health hazard to both animals and humans [CS10][54,55], and can also be readily remobilised by wind which can prolong exposure to airborne ash[53,56] . Inhalation of fine ash may trigger asthma and other acute respiratory diseases[55], although these effects are inconsistent between different eruptions. To date, no longer-term diseases such as silicosis have been attributed to exposure to volcanic ash, although this may be due to inadequate case collection[57]. Ash can carry a soluble salt burden that is readily released on contact with water or body fluids. This can lead to both beneficial effects (such as the addition of agronomically-useful quantities of plant growth nutrients to pastoral systems[58]; and harmful effects (such as fluorine toxicity to livestock). Famines have occurred following some major eruptions due to destruction of food supplies.

Airborne volcanic ash is a major hazard to aviation [CS11][59] and other forms of transport, jeopardising supply chains, provision of emergency services, and many essential services. Eruptions at Galunggung volcano, Indonesia in 1982 and Redoubt volcano, Alaska in 1989 caused engine failure of two airliners that encountered the drifting volcanic ash clouds. Concern over aviation safety resulted in the establishment of nine Volcanic Ash Advisory Centres (VAACs) around the world to issue notices, observations and forecasts of volcanic ash dispersal to civil aviation authorities. VAACs, hosted by meteorological services, work closely with Volcano Observatories.

4.3 Pyroclastic flows and surges

Volcanic explosions and rockfalls (a type of landslide) from lava domes may generate high velocity mixtures of hot volcanic rocks, ash and gases that flow across the ground (Figure 8g,h) called *pyroclastic density currents*. *Pyroclastic flows* are concentrated avalanches of hot ash, gases and blocks that are typically confined to valleys (Figure 8g), while *pyroclastic surges* are more dilute turbulent clouds of hot ash, gases and rocks that can spread widely across the landscape. Flows and surges (pyroclastic density currents) typically occur together with a more dilute surge overlaying a more concentrated flow. A *volcanic blast* is a term commonly used to describe a very energetic kind of pyroclastic density current which is not controlled by topography and is characterised by very high velocities (more than 100m/s in some cases) and dynamic pressures[44].

Pyroclastic density currents are the most lethal volcanic hazard, travelling at velocities of tens to hundreds of kilometres per hour and with temperatures of hundreds of degrees centigrade. Escape is difficult and survival unlikely. They can cause severe damage to buildings, infrastructure, vegetation and agricultural land[15,44,60]. The Roman town of Pompeii was devastated by pyroclastic density currents and buried by their deposits in the AD79 eruption of Vesuvius. A pyroclastic density current from Mont Pelée volcano on the Caribbean island of Martinique destroyed the town of St Pierre in 1902 with the loss of 29,000[1] people. The current took only three minutes to reach the town 6 kilometres from the volcano summit.

Pyroclastic density current footprints are influenced principally by topography, by the intensity of the explosion, and, in the case of lava domes, by the volume of collapsed lava. Pyroclastic flows are typically confined to valleys, but the associated surges can spill out of the valley and can reach unexpected places. In 1991 a surge from an eruption of Mount Unzen, Japan killed 43 people on a ridge a few tens of metres above the valley floor. They had judged that they were safe because pyroclastic flows had not reached this location. The distance pyroclastic density currents can travel ranges from a few kilometres in smaller eruptions to over 100 kilometres in the largest and most intense eruptions.

A volcanic or lateral blast is a term commonly used to describe a very energetic kind of pyroclastic density current. These more energetic currents take little account of topography, and may be hundreds of metres thick and travelling at hundreds of kilometres per hour. In 1980 the volcanic blast of Mount St Helens devastated 600 square kilometres in only four minutes, reaching distances of 25 kilometres from the volcano; 56 people were killed. Even the explosion of relatively small pressurised volcanic domes can produce devastating and mobile high-energy pyroclastic density currents such as at Merapi in 2010[44,60,61]. In large, explosive eruptions, pyroclastic density currents can travel over the sea and cause fatalities on islands and neighbouring coasts at considerable distances from the volcano. During the 1883 eruption of Krakatoa (Indonesia) pyroclastic density currents flowed over 80 km causing 150 deaths on the island of Sebuku, 30 km from the volcano[62].

Pyroclastic density currents account for one third of all volcanic fatalities[1]. There is no plausible protection; shelters or bunkers can become buried in the hot deposits. Thus the only response to the threat of an imminent pyroclastic density current is evacuation.

4.4 Lahars and floods

Lahars and floods are a major cause of loss of life in volcanic eruptions, accounting for 15% of all historical fatalities[1]. *Lahars* (an Indonesian word) are fast-moving mixtures of volcanic debris and water, sometimes referred to as volcanic mudflows. There are many causes of lahars, but they commonly occur when intense rain moves loose volcanic deposits formed during an eruption. Lahars can persist and continue to threaten an area for years or even decades after an eruption if there are significant thicknesses of unconsolidated ash, as was the case after the 1991 eruption of Pinatubo volcano in the Philippines [CS4].

In addition to being triggered by rain, lahars can be caused by volcanic activity melting ice caps and glaciers. The moderate VEI 3 eruption of Nevado del Ruiz (Colombia) in 1985 produced pyroclastic density currents that melted some of the ice cap and generated lahars, causing ~23,000 fatalities in the town of Armero and village of Chinchina[2]. Breaching of lakes, notably in craters and reservoirs, is another mechanism that can generate lahars. There are also examples of hot mud being discharged directly from fissures and vents on volcanoes, likely the result of magma heating, disturbing and pressurising ground-water. Lahars tend to bulk up and grow in volume as they flow down steep valleys and incorporate loose material (boulders, trees, soil etc.), a process that increases their energy and destructive potential. On flatter ground they lose energy and drop their sediment load, and can turn into muddy floods. They can be hot, for example when pyroclastic flow deposits are mobilised into lahars, and typical speeds of tens of kilometres per hour mean that they cannot be out-run, so moving quickly to higher ground is the best response.

Large energetic lahars are very destructive and are able to move car- and house-sized boulders great distances. Bridges and other structures can be destroyed due to impact and burial (Figure 12e), and escape routes may be cut off. Lahars are confined to valleys, and close to volcanoes it is usually straightforward to identify vulnerable areas. Farther from the volcano in more subdued topography and on floodplains they can inundate large areas. Channels shift frequently as sediment fills one channel and erosion opens another. Lahars can directly affect areas at distances of tens of kilometres from a volcano and may cause flooding hazards at even greater distances as channel capacity is lost to sediment fill. Communities in the hazard footprint of an imminent lahar should be evacuated or have identified escape routes to high ground if a warning is given.

4.5 Debris avalanches, landslides and tsunamis

Many volcanoes are steep-sided mountains, often partly constructed from poorly consolidated volcanic deposits and rocks weakened by alteration. Volcanic edifices are thus prone to instability[63,64]. Landslides are therefore common on volcanoes, whether currently active or not. *Debris avalanches* are very large and remarkably mobile flows of rock debris formed during the collapse of volcanic edifices, and they are commonly associated with volcanic eruptions or magmatic intrusions. In 1980 an intrusion of magma into the interior of Mount St Helens caused the steep northern flanks of the volcano to move outwards at about two metres per day creating a large bulge; after six weeks this collapsed generating a huge debris avalanche. This was accompanied by a lateral volcanic blast and followed by a major vertical explosive eruption. Volcanic landslides and debris avalanches can also be caused by hurricanes or regional tectonic earthquakes, and thus are sometimes unrelated to volcanic activity. Hurricane Mitch in 1998 triggered a major landslide on Volcano Casita in Nicaragua with at least 3,800 fatalities.

Debris avalanches and pyroclastic flows on islands and coastal volcanoes can cause tsunamis when they enter the sea[64]. Tsunamis can cause very large loss of life because of their scale, speed, and their potential for distant impact that can devastate coastal populations. In 1792 a debris avalanche from Mount Unzen, Japan, caused a tsunami with over 14,500 fatalities. Most of the 36,417 fatalities reported during the 1883 eruption of Krakatau in Indonesia were the result of lethal tsunamis generated from pyroclastic flows entering the sea[65]. Moreover, volcanogenic tsunamis can be destructive tens to hundreds of km from where they were generated. Oceanic islands with gentle slopes, like Hawaii, have collapsed to form some of the largest known debris avalanches. Tsunamis associated with these collapses could have affected the coastlines of entire oceans, but these events are very rare.

4.6 Volcanic gases

Volcanic gases can directly cause fatalities, health impacts, and damage to vegetation, livestock, infrastructure and property [e.g. CS7, CS8 and CS10]. Volcanic gases are dissolved in magma at depth in the subsurface but escape during reduction in pressure as the magma moves towards the surface. Whilst the main volcanic gas is water vapour (60-99%), there are many other volcanic gas types and associated aerosols. These may include: carbon dioxide (up to 10%), sulfur dioxide and other sulfur gases (up to 15%), halogens (including fluorine and chlorine, up to 5%), various metals such as mercury and lead (trace amounts) and trace amounts of carbon monoxide. The impact of volcanic gases varies widely and depends on the amount and type of gas emitted, the level at which it is injected into the atmosphere, local topography and the meteorological conditions at the time. Carbon dioxide (CO_2) is denser than air and will flow silently along the ground accumulating in depressions, including cellars. In 1986 a sudden release of CO_2 from Lake Nyos in Cameroon generated a gas flow that moved into surrounding villages with 1800 fatalities as a result of asphyxiation[66]. The volcanic crater lake had became saturated in CO_2 and became unstable so that the lake water overturned releasing several hundred thousand tons of gas. Sulfur gases, notably sulfur dioxide, are toxic in high concentrations and convert in the atmosphere to sulphate particles, a major cause of air pollution[48]. Fluorine and chlorine-bearing gases can also be hazardous and may adhere to the surfaces of volcanic ash. People and animals can be affected by fluoride poisoning if they consume affected water, soil, vegetation or crops [CS8].

4.7 Lava

Lava flows (Figure 8d) usually advance sufficiently slowly to allow people and animals to self-evacuate, but anything in the pathway of a lava flow will be damaged or destroyed, including buildings, vegetation and infrastructure. A few exceptional volcanoes produce lavas with unusual chemical compositions that can flow rapidly. For example, Nyiragongo in the Democratic Republic of Congo has a lake of very fluid lava at the summit and when the crater wall fractured in 1977 lava flowed downhill at speeds of more than 80 kilometres per hour, killing an estimated 282 people[1]. In 2002 lava from Nyiragongo[45] caused great damage, many injuries and fatalities (Figure 12f) [CS8].

4.8 Volcanic earthquakes

Earthquakes at volcanoes are typically small in magnitude. The cumulative effects of repeated small volcanic earthquakes can include damage to man-made structures, as well as ground deformation and cracks. Larger earthquakes can be associated closely in time with volcanic eruptions. However, most volcanoes are in major earthquake zones so many of these larger earthquakes are likely to be a coincidence. There is also evidence that some large earthquakes can very occasionally trigger eruptions and that volcanic eruptions can trigger earthquakes. However, volcanoes tend to be in tectonically active areas, and so many earthquakes are caused by fault movement or hydrothermal fluids, rather than magma movement.

4.9 Lightning

Explosive volcanic eruptions are commonly accompanied by spectacular lightning due to the friction charges that build up in the eruption column. A few fatalities have been reported as a result of volcanic lightning[1].

4.10 Environmental and secondary effects on communities

The effects of volcanic eruptions on communities and the environment are many and varied, as already described above for individual hazards. These are further discussed throughout this report. While evacuation saves lives from hazardous volcanic eruptions, it can be very disruptive for communities. There is typically great uncertainty in how long a volcanic emergency will last and the impact of an eruption will be exacerbated if emergency accommodation or facilities are poor.

Volcanic phenomena can lead to damaging secondary hazards. For example the Nyiragongo eruption in 2002 [CS8] illustrates the impact of an eruption on a major city in the middle of a humanitarian crisis. Some deaths were reportedly caused by an explosion at a petrol station due to inundation by lava. Economic impacts caused by evacuations or closing volcano access to tourists, as well as infrastructure failure, are other examples of secondary hazards on society. Crop failure and livestock losses can cause famine and epidemic disease outbreaks can occur. The environmental effects of the 1783 Laki eruption in Iceland and the 1815 eruption of Tambora, Indonesia, have already been described in section 3.3. An open question is how the modern globalised world will cope with eruptions with a magnitude similar to, or greater than, Tambora (1815) or Laki (1783-4). There is about a 1 in 3 chance of an eruption of this magnitude occurring in the 21st century.

4.11 Fatalities

Historic fatalities provide a valuable source of information to assess the impact of volcanic eruptions and assess the relative importance of different volcanic hazards. There are several sources of data on volcanic fatalities. Here we use an integrated database, which is available from the Smithsonian institution. All fatality data in this report are derived from analysis of this database[1].

Volcanic eruptions have caused 278,880 known fatalities (Figure 13). This is modest compared to other major natural hazards. However, a small number of disasters dominate the record. Five eruptions have caused 58% of recorded fatalities, and just ten eruptions 70% of all fatalities. Such large loss of life in the one event is catastrophic for the communities affected.

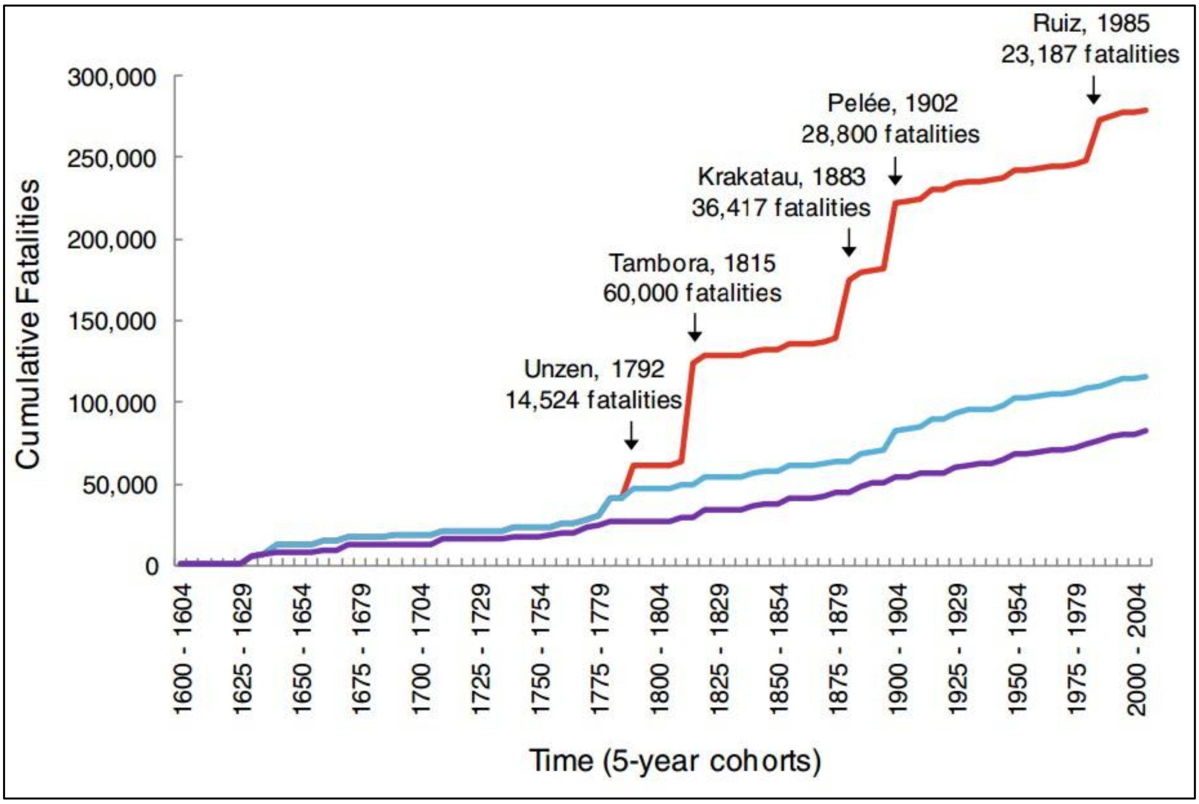


Figure 13: Cumulative number of fatalities directly resulting from volcanic eruptions[1]. Shown using all 533 fatal volcanic incidents (red line), with the five largest disasters removed (blue line), and with the largest ten disasters removed (purple line). The largest five disasters are: Tambora, Indonesia in 1815 (60,000 fatalities); Krakatau, Indonesia in 1883 (36,417 fatalities); Pelée, Martinique in 1902 (28,800 fatalities); Nevado del Ruiz, Colombia in 1985 (23,187 fatalities); Unzen, Japan in 1792 (14,524 fatalities). The sixth to tenth largest disasters are: Grímsvötn, Iceland, in 1783 (9,350 fatalities); Santa María, Guatemala, in 1902 (8,700 fatalities); Kilauea, Hawaii, in 1790 (5,405 fatalities); Kelut, Indonesia, in 1919 (5,099 fatalities); Tungurahua, Ecuador, in 1640 (5,000 fatalities). Counts are calculated in five-year cohorts.

Statistical analysis of fatalities and eruption size from 4350 BC to 2011 (Figure 14) shows that the most likely sized eruption (mode) for number of fatal incidents is actually a modest VEI 3 and for number of fatalities is VEI 4. More than 80% of fatal incidents caused fewer than 100 deaths; however these amount to less than 10% of total fatalities. 85% of fatalities have occurred within the tropics, partially due to high rainfall contributing to extensive lahars and the tendency of populations to live at altitude, on the flanks of volcanoes. Indonesia, the Philippines, the West Indies and Mexico and Central America dominate the spatial distribution of fatalities. These regions have large populations and higher population densities proximal to volcanoes than other volcanically active zones.

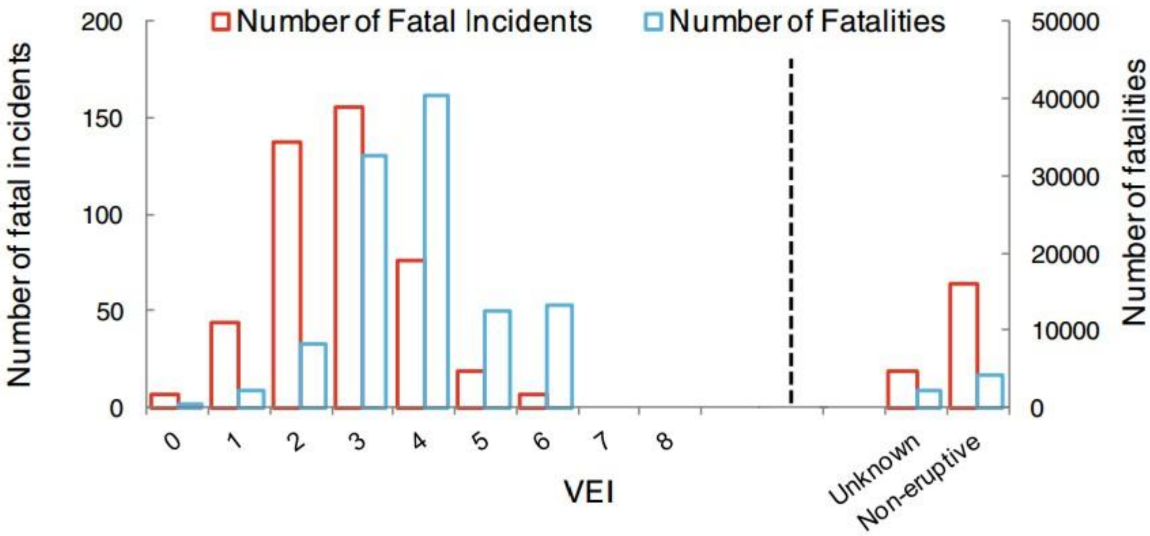
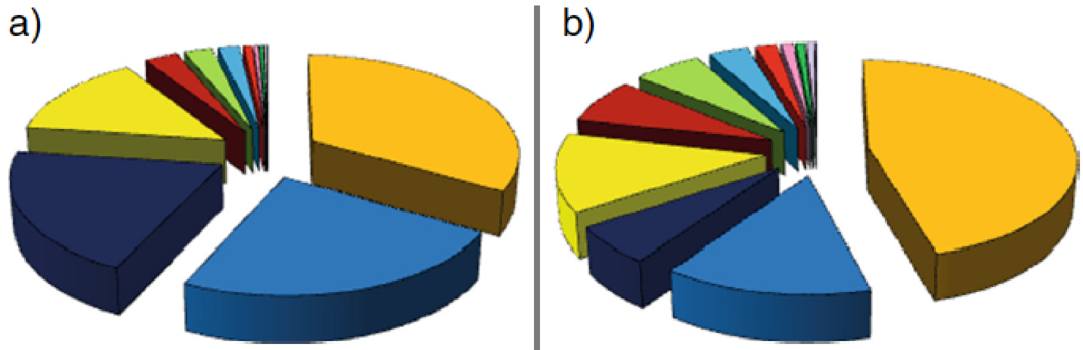


Figure 14:Distribution of fatalities and fatal incidents across VEI levels (not including the five largest disasters from statistical analysis of fatalities and eruption magnitude data[1]. The five volcanic disasters with largest fatalities were discarded in order to investigate the relationship of fatalities with magnitude in an unskewed dataset.

Despite exponential population growth, the number of fatalities per eruption has declined markedly in the last few decades, suggesting a reduction in societal vulnerability and exposure to volcanic hazards through an increase in monitoring and resulting improvements in hazard assessments, early warnings, evacuations, awareness and preparedness at specific volcanoes identified as posing a high risk (e.g. the UNISDR Decade Volcanoes). Volcano Observatories have had a major role to play in this achievement. A conservative estimate is that at least 50,000 lives have been saved over the last century as a consequence of these improvements[1]. Millions of people have been evacuated during volcanic emergencies over the 100 years and likely the number of lives saved is much higher. However, the potential for mass fatalities is still increasing as populations grow, causing an overall increase in exposure to volcanoes and their hazards. The margin of safety for recent mitigation successes has been alarmingly narrow[67]. Future fatalities may arise from eruptions at volcanoes where the risk is either not yet recognised, from large-magnitude eruptions, from unmonitored volcanoes, or from logistical, technical and management challenges in evacuating large numbers of people in time.

Figure 15 shows the distribution of fatalities between the different volcanic hazards and between direct (the hazards themselves) and indirect effects (e.g. famine and disease). Pyroclastic density currents emerge as the most significant hazard with lahars accounting for about half the number of fatalities attributed to pyroclastic density currents. Indirect effects are more pronounced in the greatest disasters. It is likely that fatalities resulting from secondary factors not directly related to primary volcanic hazards are under-represented in the fatalities. For example in the 1991 eruption of

Pinatubo (Philippines) about 500 indigenous Aeta children died of measles in evacuation camps, because their parents distrusted Western-trained lowland doctors and refused help [CS4].



All Fatal Incidents			Largest 5 Disasters Removed	
Fatalities	%	Hazard	Fatalities	%
91,484	33	Pyroclastic Density Currents	50,994	46
65,024	24	Indirect	15,724	14
55,277	20	Waves (Tsunami)	6,813	6
37,451	14	Lahars (Primary)	14,054	13
8,126	3	Tephra	8,126	7
6,801	3	Lahars (Secondary)	6,801	6
5,230	2	Avalanches	3,953	3
2,151	0.78	Gas	2,151	2
1,163	0.42	Floods (Jökulhlaups)	1,163	1
887	0.32	Lava Flows	887	0.79
765	0.28	Seismicity	765	0.69
142	0.05	Lightning	142	0.13

Figure 15: (a) Distribution of fatalities across fatality causes, for all fatal incidents; (b) Distribution of fatalities across fatality causes, with the largest five disasters removed.

5 Monitoring and forecasting volcanic eruptions

Effective monitoring and integrated, effective warning systems are central to protecting citizens and assets affected by volcanic eruptions and increasing resilience in communities living with volcanoes. There are many benefits of volcano monitoring and it can be shown to be cost effective[68]. Costs of monitoring itself are typically between several tens of thousand USD per year for at the lowest level to several million per year at the highest level. There are also costs of any evacuation (temporary housing, food, transport for evacuees), and indirect costs of evacuation (e.g. foregone business, increased health problems), and the costs and benefits of other measures taken outside an evacuation zone, e.g., to save crops or protect power grids downwind. The main benefit is the saving of lives that would be lost if the volcano erupts and those at risk were not evacuated, multiplied by a country's official Value of a Statistical Life, VSL[69]. Other benefits include avoided losses of equipment, goods, and anything else that can be moved out of the way or otherwise protected, and matters like business continuity, continuity of electric power supply that can be maintained if operators are alerted from the monitoring. Since the VSL in most countries is in the order of several hundred thousand to several million USD, saving a few lives alone justifies the monitoring from a cost benefit perspective.

There are very few examples of in-depth assessment of economic losses from volcanic emergencies and evacuations. An evaluation of the economic impact of the eruption of the Soufrière Hills volcano, Montserrat in the first few years[39] estimated costs of dealing with the emergency to the UK government of order £160 million over the first 6 years and total losses to end of 1998 of order £1 billion, much of which relate to unrecoverable losses and uninsured assets. The costs of the Montserrat Volcano Observatory in this period were a few million £. The cost of the 6-month evacuation of around 73,000 people from Basse Terre, Guadeloupe, has been estimated at 60 % of the total annual per capita Gross Domestic Product (GDP) in 1976 or about 342 million USD using 1976 currency rates[42], but the estimate excludes the losses of uninsured and other personal assets.

Volcanic eruptions are typically preceded by days to months of precursory activity, unlike other natural hazards like earthquakes. For example 50% of stratovolcanoes erupted after about one month of reported unrest[70]. Detecting and recognising warning signs provides the best means to anticipate, plan for, and mitigate against potential disasters. More than half of 288 studied eruptions reached their climax within a week of their onset and more than 40% peaked within the first 24 hours of the eruption[20].

The localised character and individuality of volcanoes gives a special importance to dedicated Volcano Observatories (VOs), which play a key role in monitoring, hazard assessments and early warning around the World [CS12]. A volcano observatory may be an institute or group of institutes whose role it is to monitor active volcanoes and provide early warnings of future activity to the authorities and in most cases the public too. The responsibilities of a VO differ from country to country. In some nations, a volcano monitoring organisation may be responsible only for maintaining equipment and ensuring a steady flow of scientific data to an academic or civil protection institution, who then interpret the data or make decisions. In other jurisdictions, the VO may provide interpretations of those data and undertake cutting edge research on volcanic processes. In most cases a VO will provide volcanic hazards information such as setting Volcanic Alert Levels and issuing forecasts of future activity, and in some instances, a VO may even provide advice on when civil actions should take place such as the timing of evacuation. Effective volcanic risk reduction is a partnership between volcanologists, responding agencies and the affected communities.

Monitoring of volcanoes can be done at ground level, from the air and from space (including satellite observations). Changes in ground movement, thermal signatures, gas emissions, presence of ash, and earthquakes provide clues about the movement of magma in the subsurface and detection of an eruption if it occurs. Where monitoring is in place, scientists infer the causative processes and likelihood that they will lead to eruption. Quality data enable more accurate eruption forecasting. Where there is no monitoring VOs do not have the ability to analyse current or past activity, or forecast eruptions. It is important that baseline data are collected so that the normal behaviour of a volcano can be better understood. Periods of unrest can therefore be more easily recognised.

Most volcanic eruptions have a rapid onset, following periods of dormancy, which are commonly much longer than the duration of eruptions[20]. There are, however, examples of persistently active volcanoes, which pose threats to surrounding communities much of the time. Analytical studies of volcanic samples, experimental investigations and theoretical modelling are providing insights into the dynamics of magmatic systems, giving a physical framework with which to interpret volcanic phenomena. Magmas undergo profound changes in physical properties as pressure and temperature vary during magma chamber evolution, magma ascent and eruption. Active volcanic systems also interact strongly with their surroundings, causing ground deformation, material failure and other effects such as disturbed groundwater systems and degassing. These processes and interactions lead to geophysical and phenomenological effects, which precede and accompany eruptions.

5.1 Monitoring

Instrumental monitoring is the basis of early warning, forecasting and scientific advice to decision-making authorities. Monitoring programs at VOs typically include: tracking the location and type of earthquake activity under a volcano; measuring the deformation of the ground surface as magma moves beneath a volcano; sampling and analysing gases and water being emitted from the summit and flanks of a volcano; observing volcanic activity using webcams and thermal imagery; measurements of other geophysical properties such as electrical conductivity, magnetism or gravity. VOs may have ground-based sensors measuring these data in real-time or they may have staff undertaking campaigns to collect data on a regular basis (e.g. weekly, monthly, annually) from sensors that are left in the field or deployed temporarily. Some VOs also have the capability to collect and analyse satellite data.

The ability of a volcano observatory to make short-term forecasts effectively about the onset of a volcanic eruption or an increase in hazardous behaviour real-time is dependent on many factors including having functioning monitoring equipment and telemetry, real-time data acquisition and processing, a long baseline of data to take into account the variability of natural systems. However, it is fundamental to have as good knowledge as possible of the past behaviour of the volcano and a conceptual model for how the volcano works to interpret monitoring data, quantify uncertainty, and thus contribute to efficient risk management. Longer-term forecasts are based mainly upon geological and geochronological data if it has been collected.

The range and sophistication of the detection systems has increased dramatically in the last few decades[71]. Advanced models of volcanic processes are helping to interpret monitoring data. Spectacular advances in computing have led to improvements in power and speed, data transmission, data analysis and modelling techniques.

Monitoring volcanic earthquakes (seismicity) lies at the heart of every volcano observatory. Volcanic earthquakes are typically very low magnitude in comparison to tectonic earthquakes and maximum magnitudes rarely exceed 5. This means they may not be detected on regional and global seismic networks, requiring a dedicated network of seismometers near or on the volcanic edifice. There are several different causes of volcanic earthquakes, which can commonly be distinguished from the diagnostic characteristics of seismic signals[72,73]. One very common kind of earthquake, known as a volcano-tectonic earthquake (VT), results from magma forcing its way towards the Earth's surface by breaking surrounding rocks. Identification of the location of VT earthquakes can help outline magma chambers (Figure 16)[74], and enable the pathways for magma ascent to be identified (Figure 17). In some cases VT earthquakes can track the migration of earthquakes towards the surface[75], enabling forecasts of the start of an eruption. A different kind of VT earthquake occurs up to tens of km away from the volcano, along preexisting tectonic faults that are reactivated by increased pore water pressure as intruding magma compresses surrounding country rock.

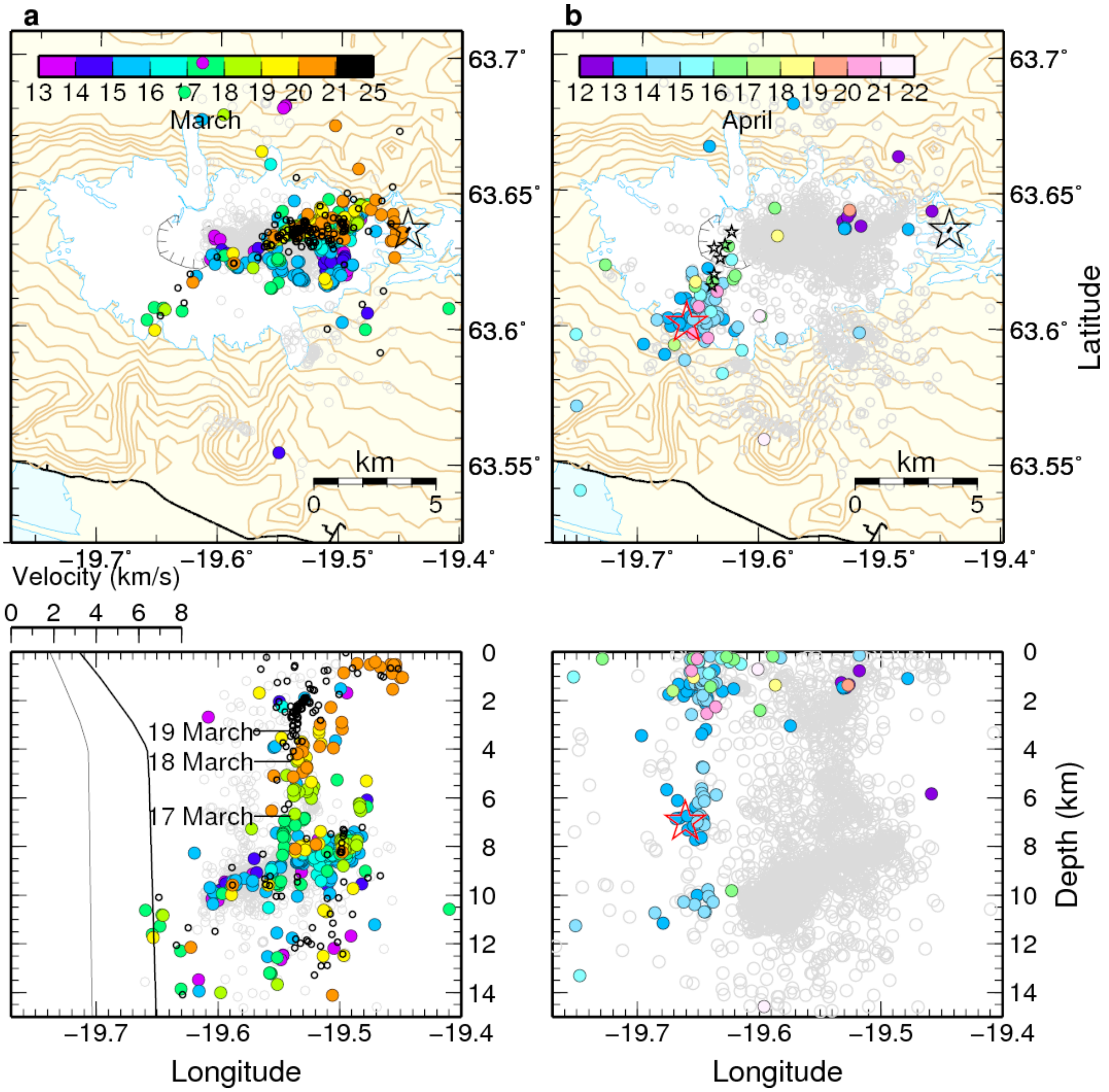


Figure 16: Spatial location of earthquakes before and during the eruption of Eyjafjallajökull volcano, Iceland in 2010. (a) the flank eruption and b) the summit eruption. a) Earthquakes 4-12 March are gray and 13-24 March coloured or black. A flank eruption site is marked by a star. Crustal velocity model is shown below. b) Earthquakes 12-21 April coloured by date. Seismicity 2009 to March 2010 is grey. Red star shows location of the M 2.7 earthquake on 13 April. Further details can be found in[74]. Diagram courtesy of Sigurlaug Hjaltadottir (Icelandic Meteorological Office).

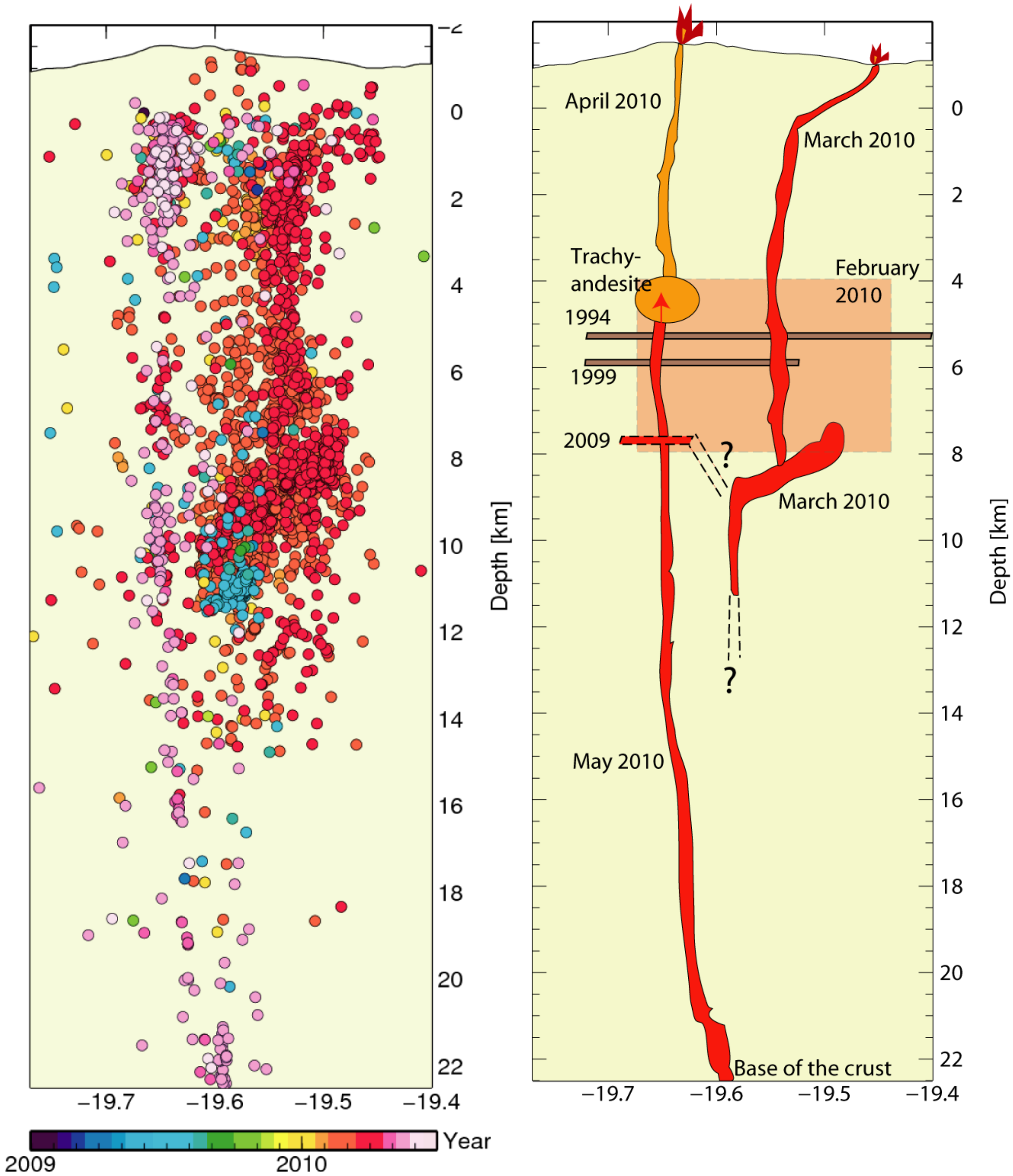


Figure 17: A schematic drawing of magma pathways in Eyjafjallajökull during 2009-2010 based on earthquake distribution (left)67. Vertical scale is stretched. The red transparent box indicates roughly the extent of the February activity (intrusions), south-east of the main clusters. Diagram courtesy of Sigurlaug Hjaltadottir (Icelandic Meteorological Office).

The interaction of volcanic fluids with the surrounding rocks can lead to distinctive earthquakes with relatively low frequency content. These can provide insights into the internal dynamics of the volcanic system and can also provide a useful indicator of an impending eruption. Volcanic earthquakes are often highly repetitive as a result of similarities in both the location and mechanism of the earthquake. Swarms of many thousands of earthquakes can last for many hours and such swarms often occur in the immediate build-up to an eruption. Many volcanoes also display continuous seismic signals, know as volcanic tremor, as well as discrete earthquakes. Changes in the characteristics of these tremor signals can also provide valuable insights into volcanic behaviour.

Seismic signals are also generated by explosions and by resonance of volcanic conduits. Explosion signals can be used to trigger eruption detection systems. Resonance generates characteristically long periods (low frequencies), which can be modelled to understand the geometry of the conduit. Stop-start movement of the magma can lead to highly regular seismic patterns. Ground vibrations are caused by pyroclastic flows and lahars the seismic signals of which are easily recognised. It is even possible to tell the valleys in which the flows are moving at night. In Iceland, the greatest hazard from volcanic activity is jökulhlaup (a flood generated when volcanoes melt glaciers) and often evacuations need to be called. Ground vibrations picked up by seismometers provide early warning (in addition to observations made by hydrological stations). On Mt Ruapehu, New Zealand, seismic signals are used to trigger lahar warning systems on ski areas and for infrastructure users threatened by lahar paths [CS13]. By learning to recognise different kinds of earthquakes and tracking their locations Volcano Observatories can often tell when magma is on the move and issue forecasts and warnings.

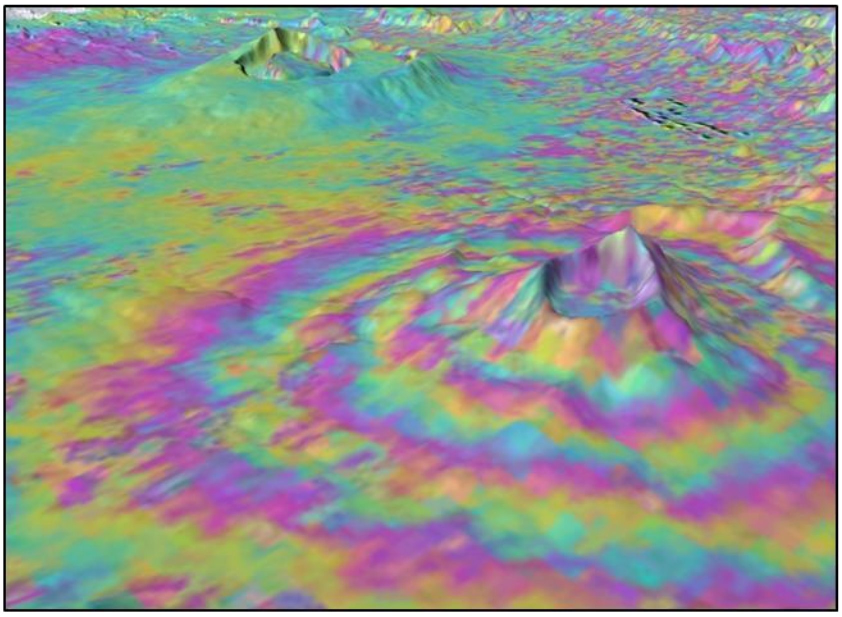


Figure 18: This InSAR image[71] shows a pulse of uplift during 2004 to 2006 at Mount Longonot, Kenya, a volcano previously believed to be dormant. The image, from the ESA satellite Envisat, is draped over a digital elevation model from the Shuttle Radar Topography Mission. Each complete colour cycle (fringe) represents 2.8 cm of displacement toward the satellite. The distance between craters is ~35 km.

Underground magma movement and swelling of magma chambers, which can precede eruptions at many volcanoes, leads to surface ground movements, also known as *deformation*[76]. Movements of a few millimetres over a distance of a kilometre at rates of a few centimetres to a few decimetres per year are typical and can be easily detected by a variety of instruments. The value of deformation using Global Navigation Satellite System (GNSS) is exemplified by the 2007 eruption of Kilauea volcano, Hawaii[77]. Nowadays electronic distance measurements using lasers and networks of GPS stations have largely replaced labour-intensive precise leveling and electronic distance surveys. The change of slope of the ground due to swelling or subsidence can be detected by electronic tiltmeters. Radar images from satellites [CS14] have resulted in a major advance in the ability to detect ground movements (Figure 18). Two images taken at different times by synthetic aperture radar (InSAR) can be subtracted from one another to obtain an interference image, which shows the deformation. Unlike continuous GPS receivers, which measure deformation at specific locations, InSAR data indicate the entire deformation field over a wide area, and the two forms of geodetic measurements are quite complementary. InSAR has revolutionised the ability to monitor deformation at many of the world's volcanoes[31], including those in remote places or those that are otherwise not monitored at all. The method also identifies volcanoes that are dormant but are showing current unrest (Figure 18; CS14)[71,78]. Currently, repeat times of radar satellites are too long to help scientists on the ground in short-term eruption forecasting, but these repeat times will soon be as short as a few days and InSAR will become an important tool for VOs.

Volcanic gas monitoring has traditionally required volcanologists to visit high-risk locations to collect samples from fumaroles, hot springs and volcanic craters. The samples had to be returned to a laboratory for analysis with an unavoidable time delay. While such methods continue and are valuable both for monitoring and research, real-time volcanic gas monitoring nowadays is largely done remotely using ground-based and satellite-based instruments [CS14][79,80]. Different gases are released by magma rising through the Earth's crust, and hence the location of the magma can be inferred by measuring their concentrations through time. Although water and CO_2 are usually the major gases they are also abundant in the atmosphere, making it challenging to make accurate measurements. Therefore volcanic gases that have low background concentrations in the atmosphere are usually measured, in particular sulfur dioxide (SO_2), especially for satellite measurements. However, significant progress is currently being made on measuring CO_2 by both satellite and ground-based methods.

Measurements of volcanic gas composition and flux not only yield key insights into the subsurface volcanic processes but are also a vital tool for eruption forecasting. In the case of Mt. Pinatubo (Philippines) prior to its eruption in 1991, a ten-fold increase in SO_2 emission was attributed to magma ascent and a subsequent, sudden drop in SO_2 suggested that magma was very near the surface and would erupt soon [CS4][40]. Once an eruption has commenced, observations of syn-eruptive degassing provide information on how an eruption is progressing and may give warnings about an imminent increase in explosivity. Gas measurements at Soufrière Hills, Montserrat in 1998 revealed continuing activity of the volcano, even though seismic and geodetic signals had tapered off. The gas measurements were a vital diagnostic tool in hazard assessment in advance of a resumption of lava dome growth in 1999[38]. In early 2008, Kilauea volcano (Hawaii) was emitting unusually high fluxes of sulfur dioxide from the otherwise inactive summit crater. There was no seismicity or ground deformation indicating an imminent eruption (in fact, the summit crater was in a stage of deflation), but the opposite was indicated by gas measurements. Kilauea summit crater subsequently erupted explosively three times within a month. Increased soil degassing of CO_2 was also the first sign of upwards migration of gas-rich magma preceding the 2008 eruption of Etna[80].

Sulfur dioxide emissions from volcanoes are monitored in near real-time by the OMI satellite (http://so2.gsfc.nasa.gov/). The importance of SO_2 as a precursor to warn of an increase in explosivity was shown very clearly during the 2010 eruption of Eyjafjallajökull in Iceland. SO_2 emissions rose dramatically between May 4th and 5th (Figure 19), while ash output did not increase until several hours after the gas emissions (Figure 20). This ash-production phase caused widespread disturbance to European airspace during most of the following week.

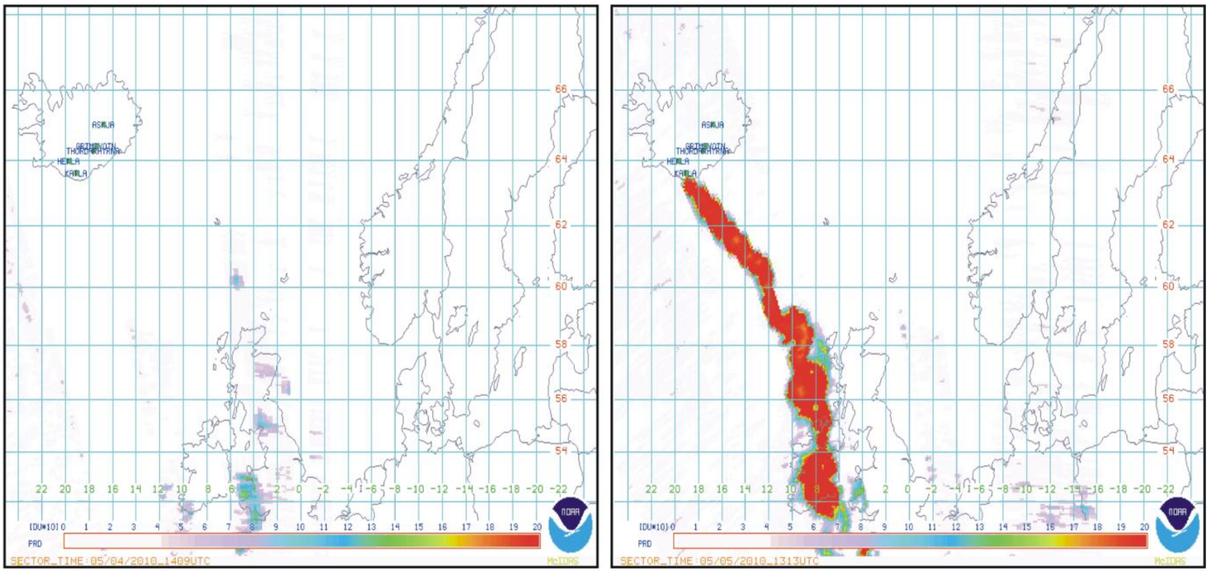


Figure 19:SO_2 emissions measured from satellites during the 2010 eruption of Eyjafjallajökull, Iceland. (a): Low SO_2 emissions measured on May 4 2010, 14:09 UTC (OMI satellite, NOAA). (b) Drastic increase in SO_2 measured on 5^{th} May 2010, 13:13 UTC.

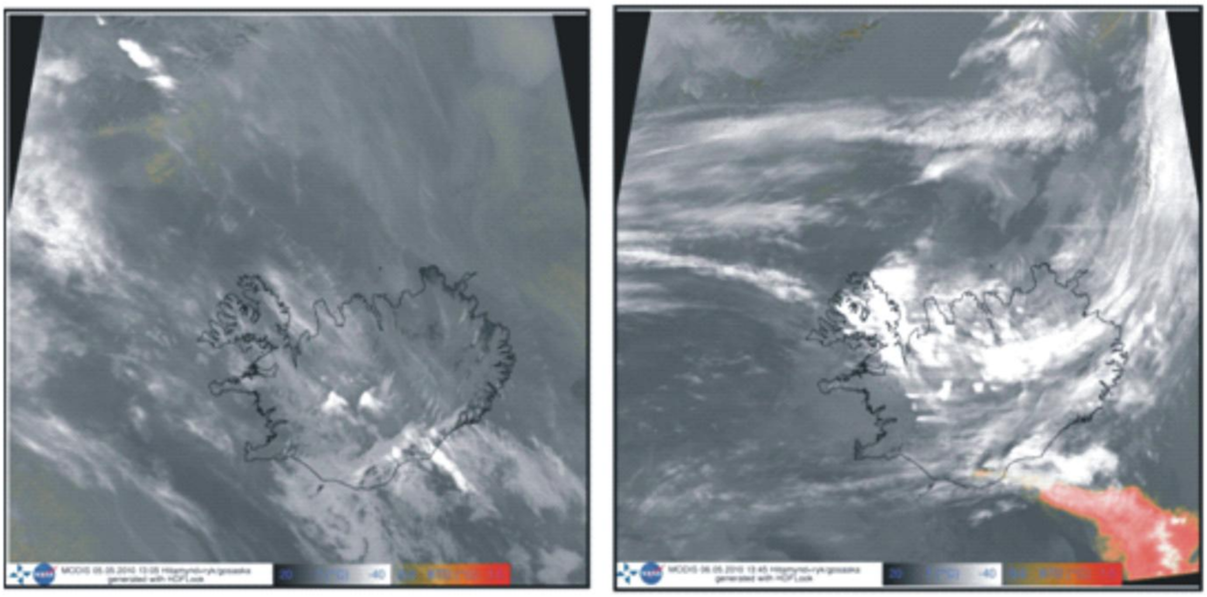


Figure 20: Ash output from Eyjafjallajökull volcano, Iceland in 2010. (a) Low ash output on May 5^{th} 13:05 UTC (MODIS satellite, NOAA) does not coincide with the high SO_2 gas flux (Figure 19b). (b) Ash output has increased when measured on May 6^{th} 13:45 UTC, several hours after the increase in SO_2 output.

Near real-time gas measurements (including satellite and ground-based monitoring) are augmented by studies of volcanic rocks, which trap gases prior to eruption[81], although this is a time-consuming technique currently unsuitable for real-time monitoring. The processing of satellite gas measurements needs to be improved to decrease the significant uncertainties and time delay. There also needs to be wider deployment of new ground-based UV and IR multi-gas sensors for gas measurements. To date SO_2 has been the main focus of gas monitoring because it is so easily detected in the atmosphere. The launch of NASA's OCO_2 and Spain's UVAS missions raises the possibility of detecting large CO_2 emissions and using these observations for early warning.

The three main stalwarts of volcano monitoring (earthquakes, deformation and gas) are augmented by many other kinds of data. These might include: visual observations of volcanic activity (sometimes from imaging networks); acoustics; thermal imaging; environmental measurements such as groundwater levels; other geophysical techniques such as gravity, electrical and magnetic measurements; rock geochemistry and petrology; measurements in rivers, crater lakes and hot springs; ground-based infra-sound[82] and bore-hole strain meters[83]. Much of these data will be collected in real-time by automated sensors. Other data may be collected on a regular basis (e.g. weekly, monthly, annually). Research is ongoing to identify novel methodologies; for example there is current work on using muons (subatomic particles) to image volcanoes[84].

Factors that inhibit other methods being widely and routinely employed on monitoring and forecasting include expense, field logistics and expertise. For example borehole strainmeters may cost of order US$150K to build and install, and require significant processing to interpret. Samples sent back to a laboratory may take days or even weeks to process and require laboratory funding for a rapid response (e.g. petrological characterisation).

One kind of measurement is usually not sufficient for assessing the state of an active or potentially active volcano. Increasingly multiple strands of evidence are necessary for a confident diagnosis. Indeed volcano monitoring can be usefully compared with medical symptoms, one of which on their own might not identify a disease, but where symptoms taken together can. In the explosive eruption of Pinatubo in 1991 it was a combination of earthquake data, SO_2 measurements, minor precursory eruptions and a geologic record of huge eruptions that led to the advice to evacuate large areas a few days before the cataclysmic eruption of 15 June[85]. Pattern recognition is commonly a key element of using monitored data[7,8]. In 1997 the combination of earthquake swarms, deformation measured by tilt meter, spurts of dome growth and explosions allowed the Montserrat Volcano Observatory to recognise regular patterns of activity and forewarn the public and authorities in advance when major escalation of activity was expected[86].

5.2 Volcanic unrest

Almost all eruptions are preceded by periods of *volcanic unrest* [CS15], which can be defined as the deviation from the background behaviour of a volcano that might presage an eruption. Changes may occur in seismicity (the number, location or types of small earthquakes), surface deformation, gas emissions, geochemistry or fumarolic activity. However, there are many cases when such unrest does not lead to eruption. Due to the active tectonic settings of volcanoes, and often the presence of geothermal fields, unrest phenomena can occur without any magma movement. There are still major challenges when assessing whether unrest will actually lead to an eruption or wane with time.

A survey of reports of unrest at 228 volcanoes active in the period 2000-2011[70] indicated that 47% of periods of reported unrest led to an eruption. There is therefore considerable uncertainty about whether an eruption will occur when unrest occurs. The same survey indicated that the duration of reported unrest episodes (both those that lead to eruption and those that don't) is typically an average of about 500 days and can vary from as short as a few days to several years. Unrest prior to eruption at volcanoes that have been long dormant tends to be shorter and averages about one month, but there is a wide range in the durations of precursory unrest. Long dormant volcanoes are also more likely to have large eruptions. Intensification of the unrest sometimes makes it evident that an eruption is very likely, but this is typically only a few days or hours in advance. These traits mean that volcanic emergencies can begin with prolonged periods of unrest without eruption. To minimise the possibility of costly disruption and no eruption, evacuations are commonly only called at a late stage.

Unrest has been documented at hundreds of volcanoes globally in the last few decades[8,31,70,76] and is usually based on changes in seismic behaviour and more recently deformation. The duration of pre-eruptive unrest differs according to volcano type: roughly half of the stratovolcanoes studied erupted after about one month of reported unrest, whereas shield volcanoes had a significantly longer unrest period before the onset of eruption (~ 5 months). For stratovolcanoes there appears to be no link between the length of time between eruptions and the duration of pre-eruptive unrest, suggesting that apparently dormant volcanoes will not necessarily experience extended periods of unrest before their next eruption.

A major challenge in interpreting unrest is that the majority of volcanoes globally are presently not monitored effectively or at all. It is difficult to determine how many of these experience unrest. In 1996, it was estimated that ~200 volcanoes had some form of seismic monitoring, but far fewer are classed as well-monitored. Satellite studies of surface deformation enable us to perform systematic studies of large numbers of volcanoes and can be crucial in identifying the first signs of unrest at unmonitored volcanoes in remote and inaccessible locations. As of 1997, ground-based methods (e.g. traditional surveying, tiltmeters, or GPS) had observed surface deformation at 44 different volcanoes but by 2010, the use of satellite data had increased this number to 110 and the list currently stands at 210[31].

Systematic studies of ~200 volcanoes using satellite data show that after 18 years, 54 had experienced deformation and of these 25 had erupted[31]. In terms of assessing eruption potential, this dataset has strong evidential worth, with roughly half of the volcanoes that deformed over the past 18 years also erupting, compared with only 6% of the volcanoes at which no deformation was observed. Continuous, ground-based monitoring is still required for making short-term evacuation decisions and to validate satellite data, but complementary satellite observations may enable strategic deployment of additional ground-based monitoring systems as needed.

Progress in knowledge of volcanic unrest is hampered by historical isolation of observatories and their data, and, even today, a lack of systematic reporting. To improve the knowledge-base on volcanic unrest, the World Organisation of Volcano Observatories (WOVO) is building WOVOdat, a web-accessible, open archive of monitoring data from around the world[87]. Such data are important for the short-term forecasting of volcanic activity amid technological and scientific uncertainty and the inherent complexity of volcanic systems. The principal goal of WOVOdat, in contrast with databases at individual observatories, is to enable rapid comparisons of unrest at various volcanoes, rapid searches for particular patterns of unrest, and other operations on data from many volcanoes and episodes of unrest. WOVOdat will serve volcanology as epidemiological databases serve medicine. WOVOdat is an example of increasing collaboration between VOs.

5.3 Forecasting and early warning

An ability to forecast the onset of an eruption and tracking the course of an eruption, once it starts, are key components of an effective early warning system and support for emergency management. Recent eruptions, such as the 2010 eruptions of Eyjafjallajökull (Iceland) and Merapi (Indonesia) have benefitted from dense monitoring networks composed of seismometers and deformation instruments, integrated with satellite imagery. Investments in monitoring precursory activity, alongside hazard assessment, mitigation, civil protection, and preparedness has enabled a number of successful evacuations and resulted in a measurable reduction in society's vulnerability to volcanic hazards during the 20th century. One conservative analysis[1] suggests that at least 50,000 lives were saved during the 20th century, and notes that a similar number have already been saved in the three decades that postdate the tragedy at Nevado del Ruiz[2].

Intensive monitoring of recent eruptions has generated integrated time series of data, which have resulted in several successful examples of warnings being issued on impending eruptions [CS4, CS6][7,88]. Forecasting of hazardous volcanic phenomena is becoming more quantitative and based on understanding of the physics of the causative processes. Forecasting is evolving from empirical pattern recognition to forecasting based on models of the underlying dynamics. This has led to the development and use of models for forecasting volcanic ash-fall and pyroclastic flows, for example. However, volcanoes are complex systems where the coupling of highly non-linear and complex kinetic and dynamic processes leads to a rich range of behaviours. Due to intrinsic uncertainties and the complexity of non-linear systems, precise prediction is usually not achievable. These system attributes mean that probabilistic modelling is the most appropriate way to characterise the uncertainties associated with volcanic hazards and risks, so that forecasts of eruptions and hazards can be developed in a manner similar to weather forecasting[89].

Despite wide-ranging technological advances in monitoring, a major challenge for volcano observatories continues to be determination of whether an episode of volcanic unrest will culminate in eruption. It is also almost impossible to predict the exact timing of eruption onset, even where very good monitoring systems are in place. When evacuations are called by authorities but then nothing happens, public trust may be undermined especially if large population and commercial centres are affected, whereas evacuations that are called too late or not at all can lead to tragedy. In Iceland, the warning period for the onset of eruption typically varies between less than an hour and up to several days. Onset of small eruptions may not even be instrumentally detected (e.g. the explosion of Ontake Volcano, Japan on 27 September 2014). Well-informed local populations may self-evacuate if they feel uncomfortable and have emergency housing options, and this may precede official calls.

5.4 Volcano Observatories

A volcano observatory (VO) is an organisation (national institution, university or dedicated observatory) whose role it is to monitor active volcanoes and provide early warnings of anticipated volcanic activity to the authorities and usually the public too [CS12]. The fact that most VOs face similar problems and challenges has led to increasing collaboration between VOs and the formation of the World Organisation of Volcano Observatories (WOVO[90]). There are over 100 members of WOVO. The exact constitution and responsibilities of a VO may differ country-by-country, but a VO is typically the source of authoritative short-term forecasts of volcanic activity and information on volcanic hazards.

There are a variety of models of VOs. Observatories range from sophisticated scientific centres with dedicated buildings, multiple staff, and comprehensive state-of-the art instrumentation to simple observation posts. Some very active high-risk volcanoes may have a dedicated Observatory; the Montserrat Volcano Observatory in the Eastern Caribbean operated by the Seismic Research Centre in Trinidad, and the Osservatorio Vesuviano operated by the Instituto Nazionale Geofisica and Volcanologia, Italy, are examples. Some Observatories, like the Cascades Volcano Observatory (US Geological Survey) monitor several volcanoes in a region. Some national scientific institutions have a mandate for all the nation's volcanoes (e.g. the Philippines Institute of Volcanology and Seismology). The approach in Indonesia with 147 active Volcanoes (by Pusat Vulkanogi dar Mitigasi Bencana Geologi; CVGHM) is to have intense monitoring on a small number of high-risk and very active volcanoes, a permanently staffed observation post with seismometers on 70 volcanoes, and to deploy teams to typical long dormant volcanoes with no dedicated monitoring should they become restless.

VOs play a critical role in supporting communities to reduce the adverse effects of eruptions through: hazard assessments for pre-emergency planning to protect populations and environments; providing early warning when volcanoes threaten to erupt; providing forecasts and scientific advice during volcanic emergencies; and supporting post-eruption recovery and remediation. Capacity to monitor volcanoes is thus a central component of disaster risk reduction for volcanism.

VOs are involved in all parts of the risk management cycle. In times between eruptions VOs may assess hazards as preparation for emergencies and for long-term land-use planning. They are often involved in outreach activities so that authorities and the communities can better understand the potential risk from their volcanoes. Outreach may also involve regular exercises with civil protection agencies and aviation authorities to generate and test planning for eruption responses. During the lead up to an eruption, VOs may provide regular updates on activity which inform decisions on evacuations or mitigation actions to reduce risk to people or to critical infrastructure. For example, power transmission companies may choose to shut off high voltage lines if there is a high probability of ash fall[54]. The extent of involvement of VO in decision-making varies greatly between different countries. A VO is usually responsible for raising the alert and communicating to the relevant authorities (e.g. civil protection and Volcanic Ash Advisory Centres - VAACs) when monitoring data and observations indicate that an eruption is probable in the short term, is imminent, or has commenced. During an eruption, VOs provide up-to-date information about the progression of activity. For an explosive eruption, information might include the duration, the height that ash reaches in the atmosphere and areas being impacted on the ground. This can inform decisions such as search and rescue attempts or provide input to ash dispersion forecasts for aviation. After an eruption has ceased, VOs can aid recovery through advice about ongoing hazards such as remobilisation of ash deposits due to high winds or heavy rainfall. In addition to scientific analysis of the eruptive activity and erupted products, they may also carry out retrospective analysis of emergencies to help improve future response from lessons learnt[2,91].

WOVO, IAVCEI and regional organisations have been active in organising workshops and meetings that promote knowledge sharing, best practice and interactions with disaster risk managers. Two

Volcano Observatory Best Practice workshops, organised by WOVO with support from GVM and IAVCEI, were held in 2011 and 2013 at Erice, Italy. Cities on Volcanoes is a biennial meeting of IAVCEI with a strong focus on hazard and risk, disaster risk reduction and knowledge exchange between scientists, public officials and citizens.

5.5 Volcano Observatories and aviation safety

247 volcanoes have been active, some with multiple eruptions, since the start of commercial airline travel in 1950s. There were at least 129 encounters of volcanic ash by aviation from 1953 – 2009[59], including a number of very near major catastrophic accidents. Two of the most significant encounters occurred in the 1980's which resulted in total engine shut-down, and sixteen more encounters with the 1991 ash of Mt Pinatubo led the International Civil Aviation Organization (ICAO) to set up nine regional Volcanic Ash Advisory Centres or VAAC's [CS9]. They provide volcanic ash advisories to the aviation community for their own geographical area of responsibility (Figure 21).

There are several different alerting systems used worldwide [CS11], each with the aim to update those in local population centres close to the volcano and the aviation community (see section 7.2). The United States Geological Survey (USGS) uses one notification (aviation colour code) specifically for the aviation sector, and another (volcano alert system) for hazards that might affect the surrounding population. ICAO adapted its international aviation colour code system from that of the USGS.

Minimising aviation impact requires rapid notices from VOs and pilots, real-time monitoring, detection and tracking of ash clouds using satellites, modelling to forecast ash movement, and global communication. International working groups, task forces and meetings have been assembled to tackle the problems related to volcanic ash in the atmosphere. The World Meteorological Organization-International Union of Geology and Geophysics (WMO-IUGG) held workshops on ash dispersal forecast and civil aviation in 2010[28] and 2013. ICAO assembled the 2010 – 2012 International Volcanic Ash Task Force (IVATF) as a focal point and coordinating body of work related to volcanic ash at global and regional levels. ICAO's International Airways Volcano Watch Ops Group (IAVW) preceded and continues the work of the IVATF. Globally, there can be many erupting volcanoes that are potentially hazardous to aviation. Therefore, the VAAC's and local volcano observatories must work closely together to provide the most effective advisory system and ensure the safety of all those on the ground and in the air.

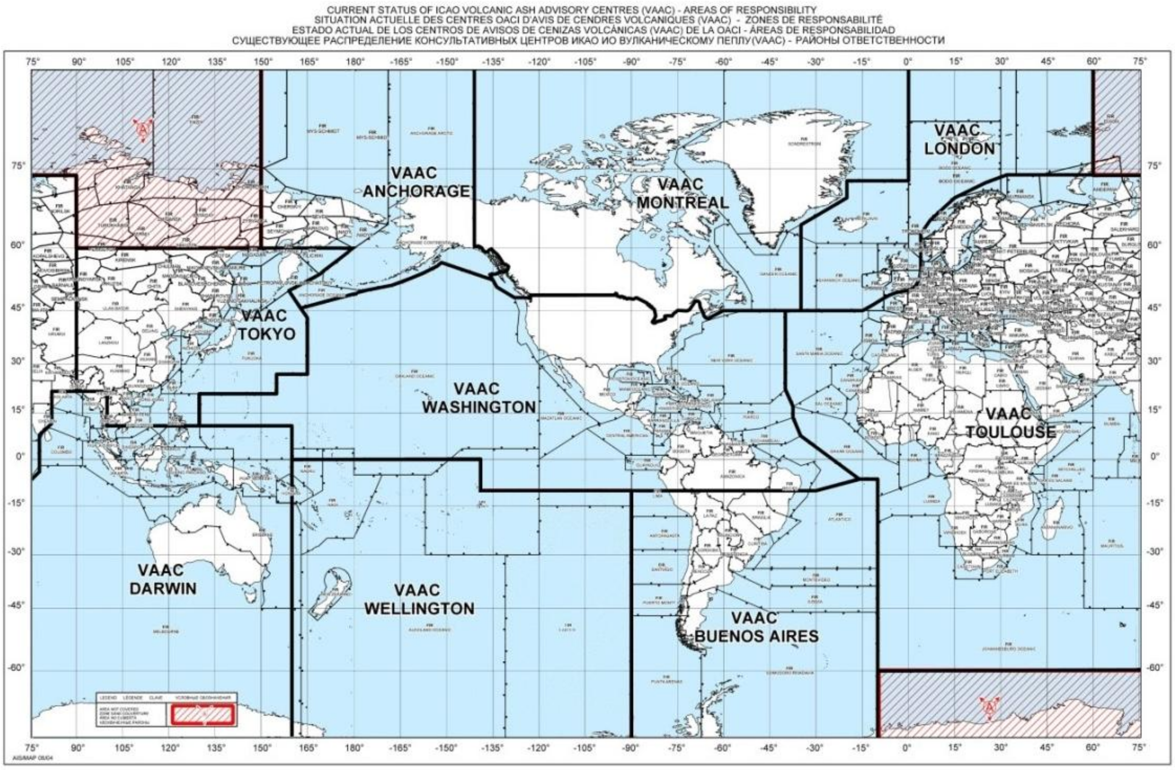


Figure 21: Map showing areas of responsibility of the nine Volcanic Ash Advisory Centres.

VOs play a key role in the system of providing early warning of ash hazard to aviation. Early notification of eruptions is critical for air traffic controllers and airlines so that they can undertake appropriate mitigation of risk to aircraft, such as changing routes. Ideally, VO and the regional VAAC should have regular communication both during and in between eruptive crises. A good example is the Icelandic Meteorological Office (volcano observatory) in Iceland that gives a weekly report on the volcano activity status to London VAAC during quiet periods; while during eruptions the reports are issued every three hours and these reports have also been found to have value for other sectors including civil protection. This VO-VAAC communication channel was significantly improved based on the experience from the 2010 eruption, but it must be noted that not all VOs worldwide have well-defined relationships with their regional VAAC. One of the main roles of WOVO has been to link more VOs with Volcanic Ash Advisory Centres to enhance communication between VOs and the aviation sector. WOVO is also developing discussions on best practice, for example in short-term forecasting and communication of hazard and risk information.

5.6 Global monitoring capacity

Of 1,551 Holocene volcanoes, 596 have recorded historical activity (VOTW4.22). Monitoring activities are largely focussed on historically active volcanoes. A full catalogue called the Global Volcano Research and Monitoring Institutions Database (GLOVOREMID, see CS16) is in development. GLOVOREMID will allow an understanding of global capabilities, equipment and expertise distribution and will highlight gaps. GLOVOREMID began as a study of monitoring in Latin America, comprising 314 Holocene volcanoes across Mexico, Central and South America [CS16]. This database has been populated by the relevant Latin American monitoring institutions and observatories.

Monitoring levels were assigned based on the use of seismic, deformation and gas analyses. The catalogue shows that 36% of Holocene volcanoes and 70% of historically active volcanoes in this region are monitored at a basic level or better. About 27% of historically active volcanoes in Latin America have no monitoring, about 17% have basic seismic monitoring and 57% have seismic networks in place coupled with additional deformation or gas monitoring.

Efforts to expand GLOVOREMID to a global dataset are ongoing, but it is not yet complete. A preliminary appraisal of global monitoring was undertaken for GAR15. Determining the monitoring capacity globally is not an easy task. Many monitoring institutions were approached to aid this understanding and the existing Latin American subset of GLOVOREMID was also used to help populate this dataset, together providing monitoring details for about 50% of the historically active volcanoes. The remaining 50% were investigated through online resources provided by monitoring institutions. This is complicated by the availability of information, outdated information, reduced web presence for some areas and, sometimes, contradictory information. Our GAR15 effort established the monitoring situation of about a further quarter of historically active volcanoes. The monitoring situation at the remaining volcanoes is unknown, but likely to be poor.

For GAR15, we estimated the numbers of volcanoes in three categories: volcanoes without dedicated monitoring systems; those with some monitoring; and those that have adequate monitoring for basic assessments of magma movements and some quantitative assessments of the probability of future volcanic events. The number of seismometers on a volcano is a relatively easy metric to establish and can be used to estimate the level of monitoring at different volcanoes. Although a single seismometer is of limited use in determining the location of earthquakes and for forecasts of volcanic activity, it can be used, often in combination with the larger regional seismic network, to alert the relevant authorities and commence the deployment of further monitoring systems. This may be particularly useful in countries where resources are prioritised at recently active or high hazard or risk volcanoes.

Ideally, a multi-station network of 4 or more seismometers is required to establish accurately the location and size of seismic events beneath a volcano, allowing for swarms of micro-quakes to be detected and for the establishment of the cause of earthquakes - volcano-magmatic, glacier movements, rockfalls and others. As such, the three levels of monitoring derived in this study are:

- No monitoring: No known dedicated volcano monitoring equipment. No dedicated seismometers. No dedicated VO.
- Some monitoring: 1 to 3 or fewer seismometers dedicated to volcano monitoring, and a VO or institution that is responsible for monitoring. Additional monitoring techniques such as deformation and gas analysis may also be in place.
- Adequate monitoring: 4 or more seismometers dedicated to volcano monitoring, and a VO or an institution that is responsible for monitoring and equipment maintenance. Additional monitoring techniques may also be in place.

Of the historically active volcanoes worldwide between 25% and 45% are unmonitored. This large uncertainty exists due to an absence of information for about a quarter of historical volcanoes. Further research needs to be undertaken to better constrain this detail. Some of these unmonitored volcanoes are located in densely populated areas and have histories including large magnitude eruptions. About 14% of historically active volcanoes are described with 1-3 seismometers and the majority of these volcanoes have this seismic monitoring alone. About 35% of historically active volcanoes are considered adequately monitored, with 4 or more seismometers within 20 km distance and most of these volcanoes also have GPS stations, tiltmeters, or other deformation instruments.

5.7 Low-cost systems for monitoring volcanoes in repose

With half of the World's historically active volcanoes having repose of more than 100 years before eruption it is not always practical or cost-effective to have permanent and extensive monitoring networks. Financial constraints are a major obstacle to maintaining monitoring networks at volcanoes in long repose. However, technological advances and international agreements are yielding opportunities for the low-cost monitoring of volcanoes in repose that do not have conventional, permanent ground networks.

Satellite-based Earth Observation (EO) provides the best means of bridging the currently existing volcano-monitoring gap [CS14]. EO data are global in coverage and provide information on some of the most common eruption precursors, including ground deformation, thermal anomalies, and gas emissions. Ideally, EO data must be processed and appropriate products made available and accessible to VOs (often in a nominated national institution) in a timely manner. In addition, training will ensure EO data products can be analysed and used effectively by VOs. Such systematic global provision will come at a modest cost although it will be highly cost-effective. Scientists receiving EO information products about volcanic unrest can then potentially enhance ground monitoring networks and instigate additional mitigation measures with the authorities and populations at risk.

Once an eruption is in progress, continued tracking of these parameters, as well as ash emission and dispersal, is critical for modelling the temporal and spatial evolution of the hazards and the likely future course of the eruption. The need for volcano-monitoring EO data is demonstrated by a number of international projects [CS14]. The costs of satellite monitoring, in particular, are declining through the supply of free data and Free and Open Source Software (FOSS) for image processing and map-making.

6 Assessing volcanic hazards and risk

Knowledge of volcanoes and the ability to anticipate their behaviour is improving. However, the great complexity of volcanoes means that in most circumstances we cannot give precise predictions of the onset and evolution of volcanic eruptions and their consequences. Precise prediction of the time and place of an eruption and its associated hazards is exceptional[7]. Likewise deterministic assessment of footprints for different kinds of volcanic hazard is not a realistic expectation. However, volcanologists are improving their ability to anticipate future volcanic events and their likely footprints. Forecasting the outcomes of volcanic unrest and ongoing eruptions is implicitly or explicitly probabilistic and forecasts are becoming increasingly quantitative[19,71]. This trend reflects the fact that in natural systems and especially volcanoes, multiple eruptive outcomes and consequences are possible over any given time period. Every volcano, as well as the hazards and risks associated with it, are unique in some respects and require dedicated investigation. This diversity has led to different methods being developed and applied in hazard and risk assessment in different places[19,88,89]. Some generic methodologies have proven successful for several eruptions, while for a few high-risk volcanoes significant research efforts have been undertaken and advances include development of novel techniques.

Like other natural phenomena, volcanic hazard and risk are linked to one another through exposure and vulnerability.

6.1 Hazard maps

At many volcanoes, hazards assessments take the form of maps, which may be qualitative, semi-quantitative or quantitative in nature [CS17]. Most are based upon a geological and historical knowledge of past eruptions over a given period of time[92]. A typical study involves mapping young volcanic deposits to generate maps for each type of hazard, reflecting areas that have been affected by past volcanic events. An important limitation though, is that the distribution of previous events (even if known in their entirely), does not represent all possible future events. Increasingly such studies are augmented by computational modelling of the processes involved. Computer simulations are run under the range of conditions thought to be plausible for the particular volcano and commonly calibrated to observed deposit distributions.

The hazards of most widespread concern, as indicated by frequency of occurrence on hazards maps and fatality data[1], are: lahars; pyroclastic density currents: and tephra fall. Currently, tephra hazards (which can have the widest distribution and far-reaching economical impacts) are the best quantified. Lahars and pyroclastic density currents both have more localised impacts, but account for far greater loss of life, infrastructure and livelihoods. These hazard types present greater challenges for modelling, and as a result quantitative hazard analysis for lahar and pyroclastic density currents lags behind that for tephra fall.

Hazard maps take many forms from geology-based maps reflecting the distribution of previous events, to circles of a given radius around a volcano or different zones likely to be impacted by different hazards to probabilistic maps based on stochastic modelling, to administrative maps constructed to aid in crisis management. Hazard maps can also be produced for a region with many volcanoes that consider cumulative hazard from all possible eruption types weighted to frequency and magnitude. Hazards maps can represent specific eruptive scenarios (e.g. dome eruption, explosive Plinian or subplinian eruption), or be based on a scenario from a specific historic eruption of a volcano that is thought to be representative of a likely future eruption or can be hazard specific (e.g. hazard from, tephra fall, or pyroclastic density currents, lahars). These different kinds of map and hazards information are commonly integrated together so that the area around a volcano is divided into zones of decreasing hazard. A common type of integrated (“bulls-eye”) hazard map will have a red zone of high hazard, orange or yellow zones of intermediate hazard (often both), and a green zone of low hazard. Hazard maps used for most volcanoes world-wide today indicate these zones qualitatively or semi-quantitatively, whereas quantitative (fully probabilistic) maps are actually the exception.

The boundaries between zones on a hazard map are typically marked initially by lines on maps based on judgement by scientists about the levels of different hazards. The position of zone boundaries on hazard maps is implicitly probabilistic. Increasingly boundaries are explicitly based on fully quantitative probabilistic analysis. The precise boundary position may be modified to take account of administrative issues and practical matters, such as evacuation routes, as determined by civilian or political authorities. At this point these maps become directly relevant to the planning and decision-making process and more closely aligned to the analysis of risk. Recently, volcanologists are making greater efforts to integrate risk knowledge collaboratively into hazard zone maps. For example a new hazard map Mt. Tongariro was produced in 2012 by GNS Science New Zealand [C13] (Figure 22). The area impacted by the eruptions includes a section of the popular Tongariro Alpine Crossing walking track. Requirements of tourists, concessionaires, and local residents were considered alongside scientific modelling and geological information to produce an effective communication product, which was tailored for use during that specific eruption.

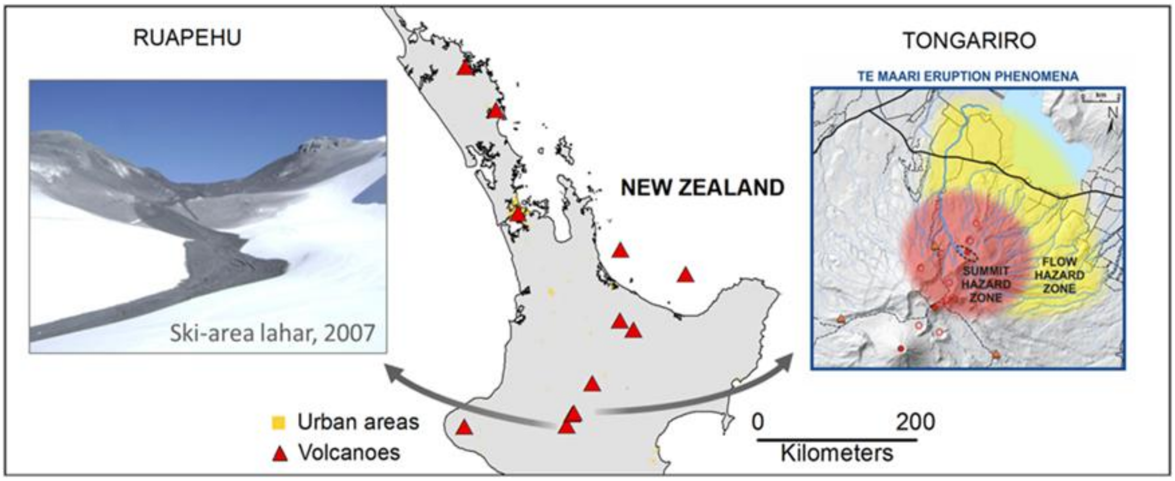


Figure 22: Risk management at two volcanoes in New Zealand. The comprehensive Tongariro hazard map can be found at www.gns.cri.nz/volcano.

Drawing lines on maps to demark safe from unsafe zones sounds easy in principle, but is difficult in practise especially if the threshold that defines the line is itself hard to estimate and the uncertainties in these estimates are large. This problem was very well illustrated during the 2010 Icelandic ash emergency. Initially the operational guidelines for response of air traffic control involved ash avoidance, so computer simulations simply had to forecast where ash would go rather than how much ash there was. However, after a few days of almost complete shutdown of European air space, engine manufacturers effectively announced that engines would not be compromised if the ash concentrations were less than 2 milligrams of ash per cubic metre of air. Forecasting precise atmospheric concentrations, as well where concentrations are above a given threshold, is much more challenging and requires advances in scientific knowledge and modelling methods[28].

In volcanic risk, hazards maps are used for multiple purposes such as raising awareness of hazards and likely impacts, for planning purposes and to help emergency managers mitigate risks. Hazard and derivative risk management maps of volcanoes are produced by Volcano Observatories (or their parent institutions such as geological surveys) and a variety of other organisations (e.g. private sector). Geological surveys or other government institutions typically have official responsibility for providing scientific information and advice to civilian or political or military authorities, who have the responsibility to make policy or decisions such as whether to evacuate. Efforts are underway to classify hazards maps, harmonise terminology and develop discussions around good practices such as how to account for uncertainties, what time interval is taken for the magnitude-frequency analysis of past eruptive behaviour, and what scale of events to consider. There is consensus that the basic foundation on which any hazard analysis should be undertaken is the establishment of an understanding about a volcano's evolution and previous eruptive behaviour through time, based on combined field geology and geochemical characterisation of the products. However, bringing together experts in modelling and statistical analysis, together with field scientists, is then key. Driven by the needs of today's stakeholders there is also a need for future research efforts to advance the science that will aid in the production of a new generation of robust, fully quantitative, accountable and defendable hazard maps.

Academic groups and insurance companies also generate maps, and there is the opportunity for serious, and unhelpful, contention if any of these do not appear to agree with hazard or risk maps from an official source. On the other hand there are several examples where hazard maps produced by official institutions have been enhanced through collaboration. Such cases can benefit from advanced research methods, which may otherwise not be available.

6.2 Probabilistic hazard and risk assessment

There is an increasing impetus to generate fully quantitative probabilistic hazards assessments and forecasts. Forecasting requires the use of quantitative probabilistic models to address adequately intrinsic (aleatory) uncertainty as to how the volcanic system may evolve, as well as epistemic uncertainty linked to the knowledge gap existing on the phenomena or the volcano. As the extent and resolution of monitoring improves, the process of jointly interpreting multiple strands of indirect evidence becomes increasingly complex. The use of new probabilistic formalism for decision-making (e.g. Bayesian Belief Network analysis, Bayesian event decision trees)[19,42,89], could significantly reduce scientific uncertainty and better assist public officials in making urgent evacuation decisions and policy choices when facing volcanic unrest, although these methods have yet to be applied widely. Selection of appropriate mitigation actions using probabilistic forecast models and properly addressing uncertainties is particularly critical for managing the evolution of a volcanic emergency at high-risk volcanoes, where mitigation actions require advance warning and incur considerable costs, including those of evacuation.

There are a variety of probabilistic maps that depend on the nature of the hazard. For volcanic flows (pyroclastic density currents, lahars and lavas) the map typically displays the spatial variation of inundation probability over some suitable time period or given that that the flow event takes place. For volcanic ashfall hazard the probabilistic analysis can be represented using the exceedance of some threshold of thickness or ground loading, volumetric concentration at some specific atmospheric level, or even particle size.

Recent developments mean that ashfall hazard has been considered far beyond individual volcanic or even country settings. In SE Asia, volcanic ashfall is the volcanic hazard most likely to have widespread impacts since a single location may receive ashfall at different times from different volcanoes [CS9]. Probabilistic curves and maps of ashfall thickness can be calculated using volcanic histories and simulations of eruption characteristics, eruption column height, ash volume and wind directions at multiple levels in the atmosphere[93]. In this example risk is expressed via 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 ashfall impacts (vulnerability). By combining probabilistic hazard estimates with freely available exposure data and a proxy for human vulnerability (the UN Human Development Index for a country), each component contributes towards an overall 'risk' score (Figure 23).

This approach offers a synoptic insight into what drives a city's risk. When applied to the Asia-Pacific region, home to 25% of the world's volcanoes and over two billion inhabitants, Tokyo's risk is dominated by the high cumulative hazard (54 active volcanoes lie within 1000 km), Jakarta's risk is dominated by population exposure, and Port Moresby's risk by the vulnerability. A background paper with a much more detailed assessment on ashfall hazard and risk has been prepared for the GVM/IAVCEI contribution to GAR15.

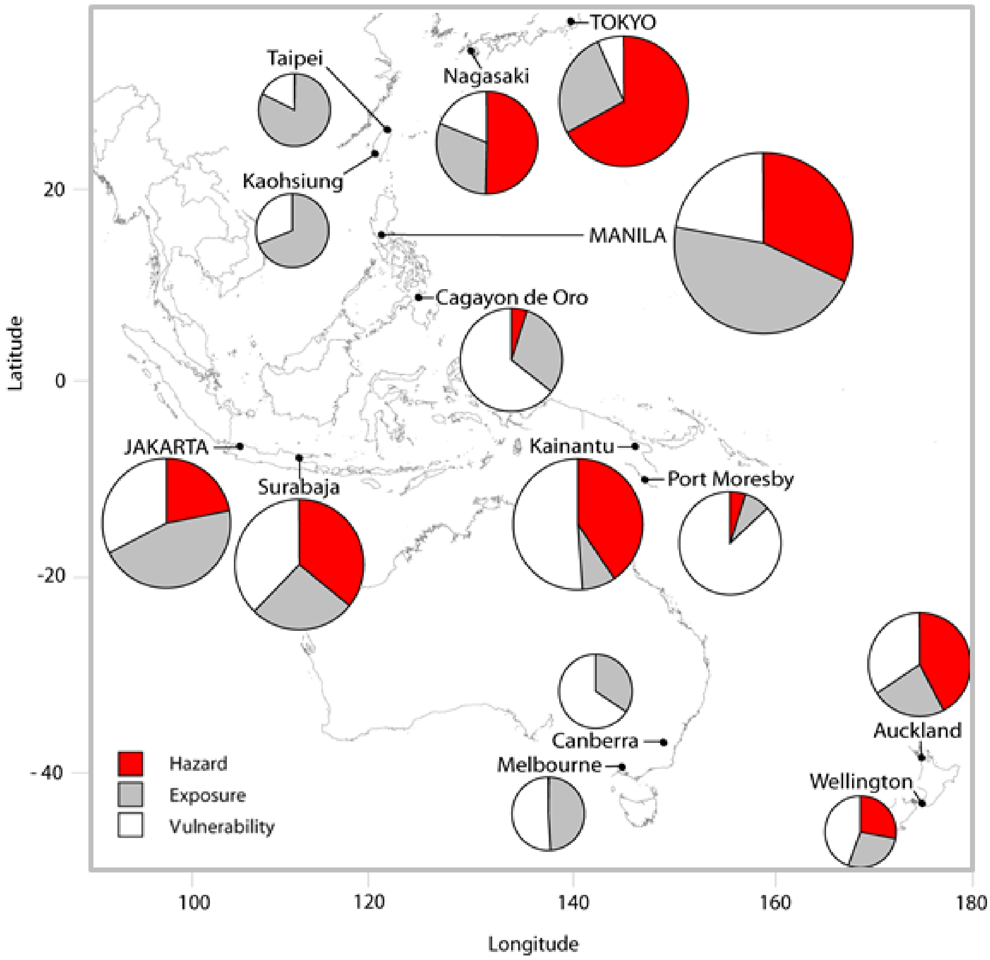


Figure 23: Relative contributions of the three factors comprising overall risk score for cities in the Asia-Pacific region [see Section III].

6.3 Exposure and vulnerability

There can be many different kinds of loss as a consequence of volcanic eruptions including: loss of life and livelihoods[94,95], detrimental effects on health [CS10], destruction or damage to assets (e.g. buildings, bridges, electrical lines and power stations, potable water systems, sewer systems, agricultural land)[15]; economic losses; threats to natural resources including geothermal energy[96]; systemic vulnerability and social capital. Each of these will have its own specific characteristics in terms of exposure and vulnerability[52,53].

Thus moving from hazards to risk requires an assessment of exposed populations and assets, taking account of their vulnerabilities (both physical and social). Vulnerability is a key means by which the impact of volcanic hazards can be amplified or attenuated according to circumstance. Vulnerability is an attribute of individuals and their assets as well as institutions, critical services and cultural or political groupings. Like volcanic hazards, these attributes of vulnerability vary in both space and time[97] and can be expected to affect the outcome for populations at risk in several ways (Figure 24). Risks also usually have to be placed within a suitable time frame appropriate for decision-making and actions. Risk assessments might need to be carried out in near real-time at the height of a volcanic crisis, while long-term planning is normally undertaken over longer timeframes. Thus the nature of the loss and the time scale over which the loss is being considered are critical in characterising vulnerability and exposure. In volcanology there are several examples of analysis of individual facets of vulnerability, particularly health and assets, but rather less on individual and social vulnerability or the dynamics of these components under stress.

In the vicinity of volcanoes, direct loss of life and evacuation of people from high risk areas have been a priority concern. Hazard footprints arising from hazard assessments are traditionally superimposed on census data to identify exposed populations for preliminary potential societal risk calculations. Here we use the metric of numbers of people within 100 km of a volcano. The greatest numbers of people living close to volcanoes are found in Indonesia, the Philippines and Japan [CS1]. However, Guatemala and Iceland have a higher proportion of their total population within 100 km of a volcano (with >90%) and some small island communities may have all their population within 100 km. Hazards footprints can be used to identify exposed assets such as buildings and infrastructure, agriculture, critical systems, supply chains, livelihoods and so on. The scale of assessments (local to global) brings in different uncertainties and assumptions due to availability of data. There is a need for harmonisation of methods and data sources.

Vulnerability is a major determinant of the impact of volcanic hazards and is a key concept for understanding the resilience of a community and its assets. There are both social and physical vulnerabilities, which are commonly linked. Physical aspects of vulnerability include, for example, building quality[52] and to what extent transport systems enable rapid evacuation.

Social vulnerability is defined[98] as ‘the propensity of a society to suffer from damages in the event of the occurrence of a given hazard’. Assessment of social vulnerability is complex as the characteristics of communities and individuals, like volcanoes, vary in both space and time. It is widely acknowledged that marginalised communities, be that geographically, socially or politically, often suffer the most from natural hazards[99–102]. Tourists have also been recognised as a vulnerable group unlikely to be aware of evacuation procedures or how to receive emergency communications when volcanic activity escalates[103]. Like hazards, vulnerabilities can only be assessed within the community and with a strong understanding of the local social, cultural and political landscape. Identifying the factors that lead to social vulnerability is challenging and is only just beginning to be applied for volcanic risk[104].

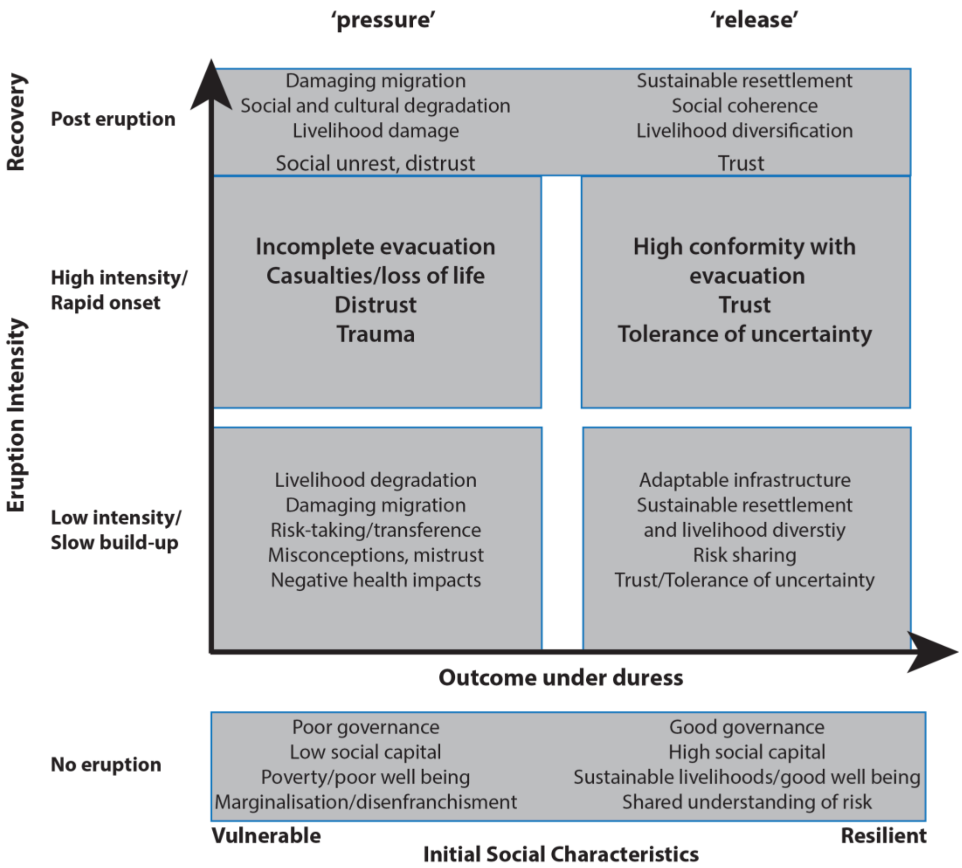


Figure 24: Summary of outcomes associated with the interaction of differing population types with volcanic hazards at differing stages of an eruptive cycle. The 'response' phase of volcanic crises has been sub-divided according to intensity and duration. Low intensity, slow-building or long duration activity (e.g. persistent small explosions or lahars) contains most characteristics of intensive risk for affected populations whereas the higher intensity activity (e.g. Plinian explosions, sector collapse) has impacts more consistent with extensive risk. 'Pressure' and 'release' draws an analogy with the Pressure and Release using a model for vulnerability and disaster risk.

At volcanoes, it is recognised that livelihood is a key factor that plays a role in the vulnerability of societies and individuals. In particular, in equatorial settings large populations live and farm at elevation on volcanic slopes due to the combination of fertile soil and mild climate[105]. Farmers, particularly those at subsistence level need to maintain their crops and livestock in order to secure an income, so even short eruptions can be very damaging. If farmlands are evacuated, the longer the period of evacuation, the more likely it is that attempts will be made to return to evacuated land to care for crops and livestock in at-risk areas. This behaviour has been documented many times around volcanoes (e.g. Philippines[106]; Ecuador[107]; Indonesia[108], Tonga[109]).

If the conditions under which evacuees must live are poor, individuals are more likely to return to their homes in at-risk areas. For example, in Montserrat (Lesser Antilles) evacuated families were living in temporary shelters for months and ultimately years[39], and some sought peace and quiet at their homes in the evacuated zone or continued to farm, resulting in 19 unnecessary deaths in 1997[91]. Concerns about looting also cause people to delay evacuation and return frequently to at-risk areas.

A health and vulnerability study for the Goma volcanic crisis in 2002[46] considered human, infrastructural, geo-environmental and political vulnerability following the spontaneous and temporary evacuation of 400,000 people at the onset of the eruption [CS8]. The area was already in the grip of a humanitarian crisis and a chronic complex emergency involving armies and armed groups of at least six countries. The potential for cascading health impacts (e.g. a cholera epidemic) as a result of such a large displaced population was extremely high. The evacuation of large numbers of people into temporary accommodation for even short periods can lead to significant public and other risks.

The extent to which a population is willing or able to take the appropriate action in the face of a threat is a major factor in vulnerability. The complex pre-existing and dynamic political and cultural landscape is known to impact on likelihood to take action with many other messages competing with emergency and preparedness information. In the cases of the emergencies in 2010 at Merapi [CS7] and in 2002 in the city of Goma [CS8] many people were familiar with previous eruptions and this knowledge led to prompt life-saving actions and positive responses to official advice. In the case of La Soufrière (Guadeloupe) in 1976 [CS5] publically debated disagreement on the future course of the eruption by scientists and officials, a highly disruptive massive evacuation largely perceived as an exaggerated and political application of the precautionary principle, and the non-occurrence of a significant eruption led to a loss of trust in science and public policy, making the population now more vulnerable to future eruptions. Volcanoes that have not erupted historically (e.g. Pinatubo; CS4) or in living memory pose more problems in that volcanic activity and attendant hazards are outside the experience of the exposed population, crisis managers, and policy decision-makers.

The forensic analysis of past volcanic disasters offers an opportunity to identify and investigate risk factors in different situations and also to identify evidence of good practice (http://www.irdrinternational.org/projects/forin/). Long-lived eruptions such as Soufrière Hills volcano, Montserrat, and Tungurahua, Ecuador, also offer opportunities to assess adaptation to extensive risks, for example coping with the cascading impacts of repeated ashfall[110] and developing new risk assessment methodologies.

Like natural hazards, understanding all the factors that contribute to social and physical vulnerability at any moment in time is challenging. Nevertheless, growing knowledge, improved methodologies and an increasing willingness to integrate information across disciplines should contribute to increased understanding of risk drivers. Increasing the opportunities to integrate knowledge and experience from scientists (of all disciplines), authorities and communities at risk should enable us collectively to increase resilience and reduce risk.

6.4 Quantification and representations of volcanic risk

In recent years volcanologists have started to make quantitative assessments of risk. Not all kinds of risk can be easily calculated so the focus to date has largely been on risk to life. The Soufrière Hills Volcano (SHV), Montserrat, has been erupting episodically since 1995, with life-threatening pyroclastic flows generated by lava dome collapse and explosive events. It has provided a testing ground for methods to calculate and track risk during a major volcanic emergency [CS18][111]. Volcanic activity is monitored by the Montserrat Volcano Observatory (MVO). With an international membership, the Scientific Advisory Committee on Montserrat Volcanic Activity (SAC), provides regular quantitative hazard and risk assessments. Advanced quantitative risk analysis techniques have been developed, forming an important basis for mitigation decisions.

Over 18 years, the SAC has used the following sources of information and methods: MVO data on activity at the SHV and other lava dome volcanoes; computer models of hazardous volcanic processes; formalised elicitations of probabilities of future hazards scenarios using structured expert judgement methods[112]; probabilistic event trees; Bayesian belief networks; census data on population numbers and distribution and Monte Carlo modelling of risk levels faced by individuals, communities and the whole island population. The combined methods characterises uncertainty, which is regarded as an essential element for informed and effective decision-making.

Risk assessments are presented to the authorities and public via open reports in a manner that is understandable. Societal casualty risks and individual risk of death are both calculated. MVO and the SAC developed a means of representing risk, which follows methods used for industrial accidents. Societal risk is calculated in terms of the probability (F) of exceeding a given number of fatalities (N) in a specified time. F-N curves have been used successfully in the emergency management on Montserrat. The F-N plot from 2003 (Figure 25) shows the probability of N or more fatalities due to the volcano (red, with uncertainty), the reduced risk if the main at-risk area is evacuated (green), and comparative hurricane and earthquake risks. An individual risk ladder from 2011 is shown (Figure 26) with both residential zone risk levels and work-related risk levels plotted, with uncertainties. Central to the effectiveness of this approach is that comparative values from familiar circumstances are shown for reference.

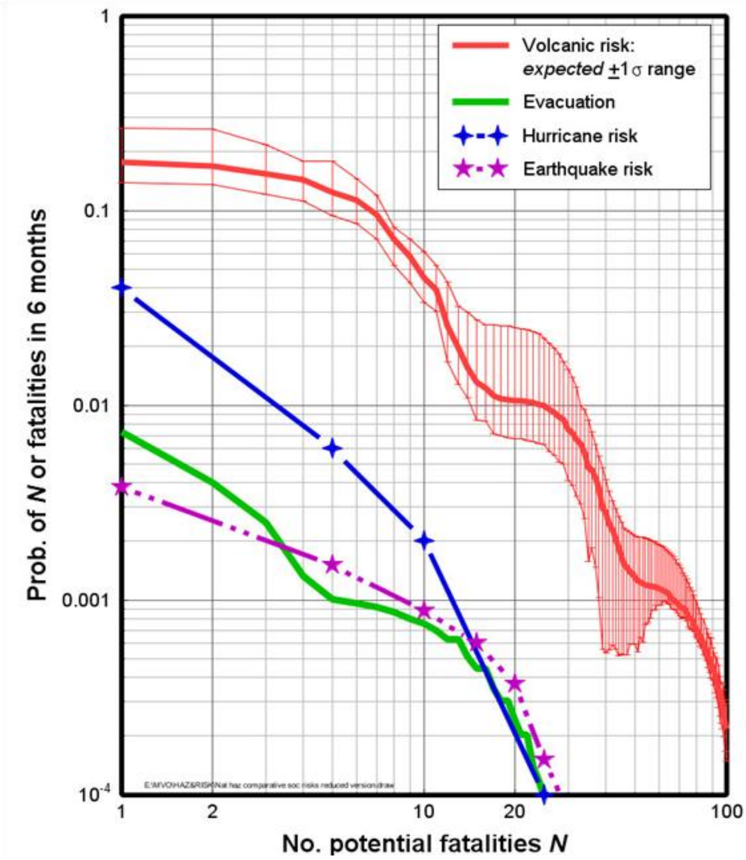


Figure 25: The F-N plot from 2003 for the Soufrière Hills Volcano, Montserrat shows the probability of N or more fatalities due to the volcano (red, with uncertainty), the reduced risk if the main at-risk area is evacuated (green), and comparative hurricane and earthquake risks. The curves are compared with societally accepted risks from regional earthquakes and hurricanes on Montserrat.

These risk assessments have been used to inform critical decisions on Montserrat, including evacuation and re-occupation (Figure 25), and development of management controls on sand mining (Figure 26). In both cases the risks are compared to more familiar risks to aid communication with decision-makers. One very difficult issue is the assessment of the probability that an eruption has ended. This has major societal implications. Although this is the most uncertain area of volcanic risk assessment, end-of-eruption criteria have been proposed for the current eruption on Montserrat. They are systematically evaluated with probabilistic analysis as proxies of the internal behaviour of the volcanic system and to provide support for public decision-making. The Montserrat emergency has lasted over 18 years and so has given the opportunity to assess the hazards forecasts, which form a key component of the risk assessments. The performance of probabilistic event forecasts against actual outcomes has been measured using the Brier Skill Score: more than 80% of life-critical forecasts had positive scores indicating very reliable hazard forecast.

Evacuations may be short term but during some long-lived eruptions evacuations may become regular occurrences as populations continue to live and work alongside a sporadically active volcano (e.g. Tungurahua, Ecuador case study) or become permanent large-scale movements of populations (e.g. Montserrat 1997). Once a permanent evacuation has occurred, risk assessments are needed to manage access into evacuated areas (e.g. White Island, New Zealand), and to manage access and land use in marginal zones (e.g. Montserrat), also to consider the potential for hazards of even greater impact.

Concern about the risk to human health from volcanic ash [CS10] motivated an example of a fully quantitative probabilistic risk assessment on the exposure of population on Montserrat to very fine respirable ash[113]. Here volcanology, sedimentology, meteorology and epidemiology had to be combined together to assess the probability of exposure to ash of different population groups over a 20-year period. The study illustrates the multidisciplinary character of risk assessments, where diverse experts are needed. Figure 27 illustrates some results that led to the conclusion that health risks for most people living on Montserrat was low but that risks were high enough to cause concern for certain more exposed occupations such as gardeners.

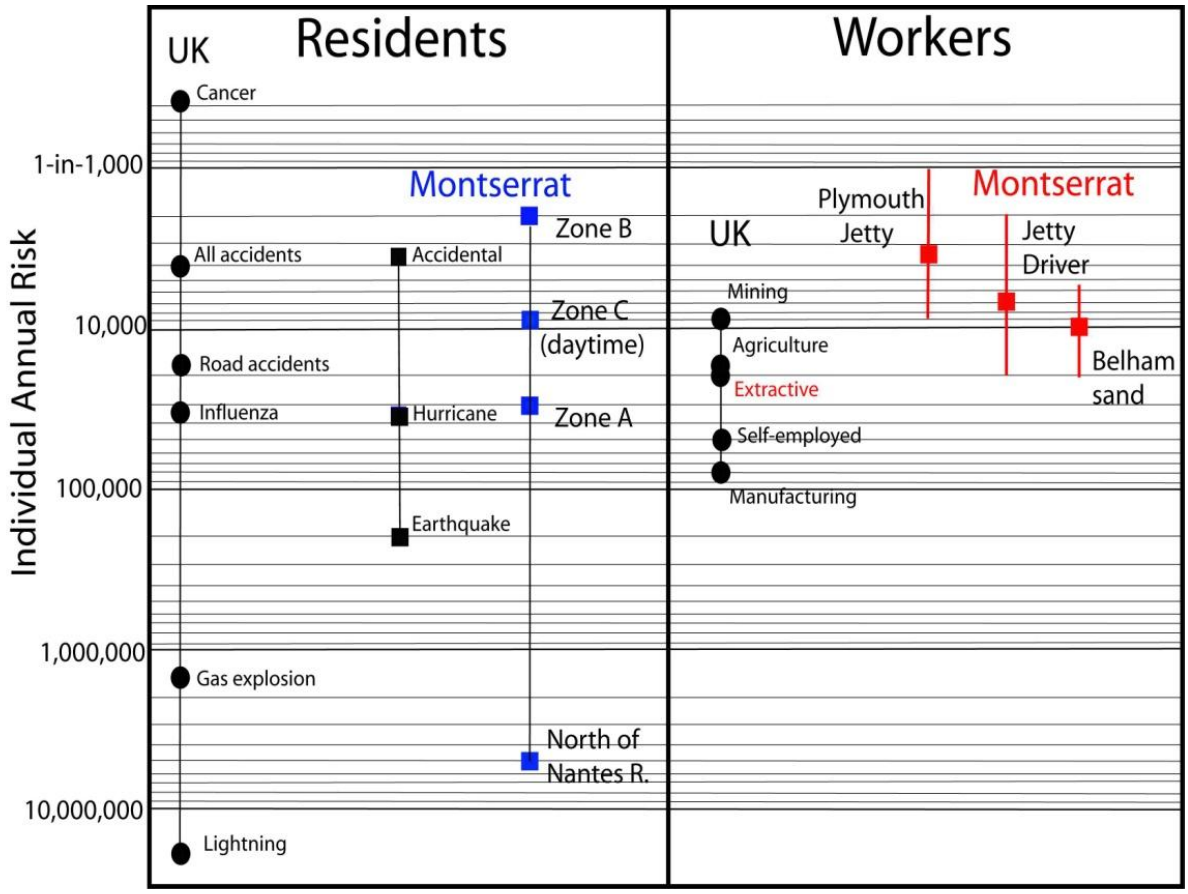


Figure 26: An individual risk ladder from 2011 for the Soufrière Hills Volcano, Montserrat is shown with both residential zone risk levels and work-related risk levels plotted, with uncertainties. Comparative values from familiar circumstances are shown for reference.

Vulnerability is commonly converted to indices to facilitate semi-quantitative approaches to risk. For example the structural vulnerability of roofs to collapse following ashfall (physical vulnerability) can be assessed using an index of different roof types and thresholds for collapse under different conditions[52]. Although semi-quantitative approaches can be used to incorporate assessments of vulnerability into risk assessments, in order to be useful for near real-time emergency response such assessments need to be fine-grained, ideally at a household/building scale.

The physical vulnerability of roofs to collapse following ashfall for example can be assessed using an index of different roof types and thresholds for collapse under different conditions.

In most cases so far, despite the considerable potential and proven value of quantitative risk assessment approaches, volcanic risks have largely been managed without being measured. Small Island Developing States and cities at risk are examples of situations where a quantitative approach will support effective risk management.

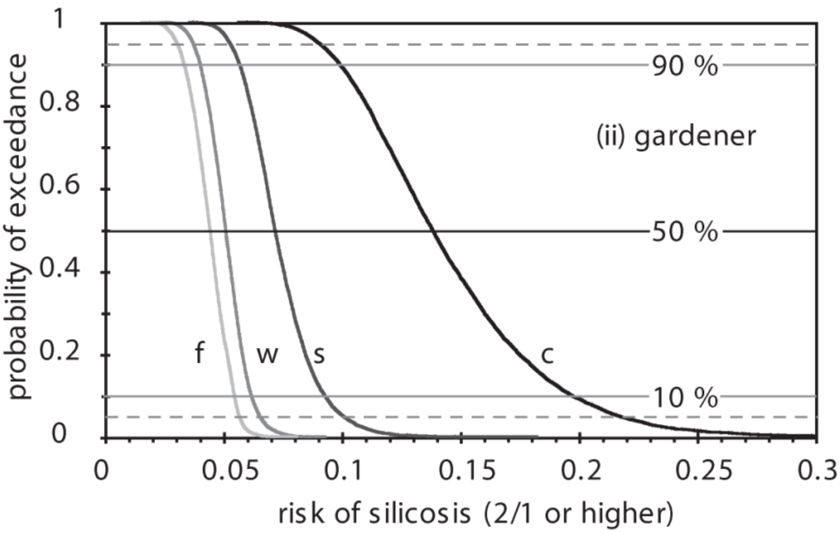


Figure 27: Probability of exceedance curve for risk of silicosis (classification ≥2/1) for gardeners, calculated from simulated cumulative exposures, see Hincks et al. 2005 for key to of curves, which are for specific Montserrat locations). The study involved Monte Carlo sampling of probability distributions for key factors determining exposure to very fine respirable ash. Four curves are shown for different locations on Montserrat. In the location closest to the volcano the risk to gardeners exceeds air quality standards and risk of silicosis is at levels that cause concern to the authorities, resulting in precautionary measures.

6.5 Global and regional assessment

There is also a need for more synoptic assessment of volcanic hazard and risk on global, regional and country scales. This scale of assessment provides a basis for identifying gaps in knowledge, prioritising resources on the highest risk volcanoes, and assessing the overall volcanic risk in regions and countries.

Vulnerabilities to various volcanic hazards can be assessed in a wide variety of ways. The vulnerability of communities is sometimes based on indices such as the Human Development Index (HDI) – a composite measure of development and human well-being, the assumption being that higher levels of development enhance capacity to recover. The Human Vulnerability Index is also used (1-HDI). Vulnerabilities are diverse and complex and a continuing challenge to incorporate effectively into risk assessment and analysis.

As part of this submission to the GAR15, a Volcano Hazard Index (VHI) has been developed to characterise the hazard level of volcanoes based on their recorded eruption frequency, modal and maximum recorded VEI levels and occurrence of pyroclastic density currents, lahars and lava flows. The full methodology is summarised in CS19. The index builds on previous index approaches[114,115]. A separate background paper is a compendium of regional and country profiles, which use these indices to identify high-risk volcanoes.

The VHI is too coarse for local use, but is a useful indicator of regional and global threat. VHI can also help identify knowledge gaps. The VHI can be modified for volcanoes as more information becomes available and if there are new occurrences of either volcanic unrest, or eruptions, or both. 328 volcanoes have eruptive histories judged sufficiently comprehensive to calculate VHI and most of these volcanoes (305) have had historical eruptions since 1500 AD. There are 596 volcanoes with post 1500 AD eruptions, so the VHI can currently be applied to about half the World's recently active volcanoes. A meaningful VHI cannot be calculated for the remaining 1,223 volcanoes due to lack of information. The absence of thorough eruptive histories for most of the world's volcanoes makes hazard assessments at these sites particularly difficult, and this is a major knowledge gap that must be addressed.

The Population Exposure Index (PEI) is an indicator based on populations within 10, 30 and 100 km of a volcano, which are then weighted according to evidence on historical distributions of fatalities with distance from volcanoes. It effectively amalgamates the Volcano Population Index values at fixed distances given in the VOTW4 and uses evidence from historic fatalities to derive a single value. The methodology [CS1] extends previous concepts[116]. Volcano population data derived from VOTW4.0 is used to calculate PEI, which is then divided into 7 levels from sparsely to very densely populated areas to provide an ordinal ranking indicator. A Population Exposure Index provides an indication of direct risk to life and can be used as a proxy for economic impact based on the distance from the volcano. However this does not account for indirect fatalities caused by secondary impacts such as famine and disease or far-field economic losses to aviation and agriculture caused by the dispersion of volcanic ash, gas and aerosols.

In this contribution, VHI is combined with the PEI to provide an indicator of risk, which is described as Risk Levels I to III with increasing risk. The essential aim of the scheme is to identify volcanoes, which are high risk due to a combination of high hazard and population density. 156, 110 and 62 volcanoes classify at Risk Levels I, II and III respectively. In the country profiles plots of VHI versus PEI provide a way of understanding volcanic risk. Indonesia and the Philippines are plotted as an example (Figure 28). Volcanoes with insufficient information to calculate VHI should be given serious attention and their relative threat can be assessed through PEI. The calculation of VHI and Risk Levels from PEI also enables knowledge gaps to be identified and provides a benchmark with which to measure progress in improving knowledge of the status of hazard knowledge on the world's volcanoes.

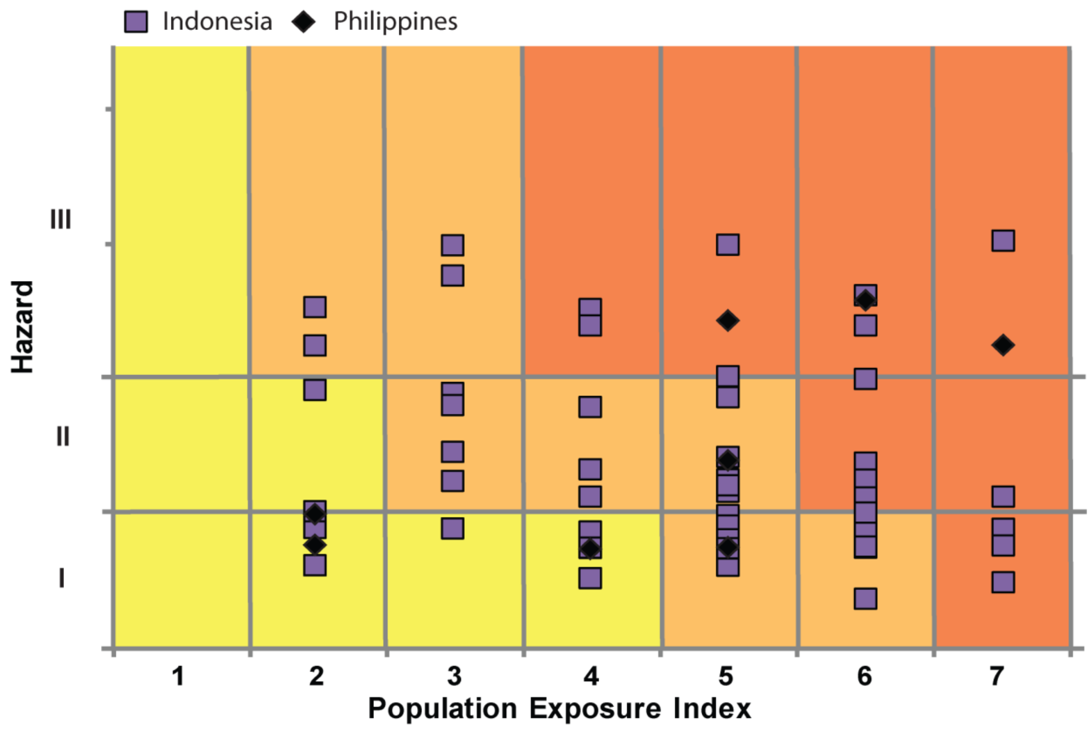


Figure 28: Plot of volcanic Hazard Index (VHI) and Population Exposure Index (PEI) for Indonesia and the Philippines, comprising only those volcanoes with adequate eruptive histories to calculate VHI. The warming of the background colours is representative of increasing risk through Risk Levels I-III.

6.6 Distribution of volcanic threat between countries

In this section the distribution of volcanic threat (potential loss of life) is investigated to help understand how volcanic threat is distributed and to identify countries where threat is high. 'Risk' requires assessment of vulnerability, which has not been assessed here, therefore the term 'threat' is used as a combination of hazard and exposure. Two measures have been developed, combining the number of volcanoes in the country, the size of the population living within 30 km of active volcanoes (Pop30) and the mean hazard index score (VHI). Population exposure is determined using LandScan[117] data to calculate the total population within a country living within 30 km of one or more volcanoes with known or suspected Holocene activity. Countries are ranked using the two measures. Each measure focuses on a different perspective of threat. The full methodology and results are presented in CS20.

Measure 1 is of overall volcanic threat country by country based on the number of active volcanoes, an estimate of exposed population and average hazard index of the volcanoes.

$$Measure\ 1 = mean\ VHI\ x\ number\ of\ volcanoes\ x\ Pop30$$

The sum of Measure 1 for all countries is itself a simple measure of total global volcanic threat. The distribution of threat between countries can be evaluated and countries can be placed in rank order using a normalised version of Measure 1. Table 6.1 shows the distribution of Measure 1 between the 20 highest scoring countries.

Rank	Country	Normalised %
1	Indonesia	66.0
2	Philippines	10.6
3	Japan	6.9
4	Mexico	3.9
5	Ethiopia	3.9
6	Guatemala	1.5
7	Ecuador	1.1
8	Italy	0.9
9	El Salvador	0.8
10	Kenya	0.4

Rank	Country	Normalised %
11	Papua New Guinea	0.4
12	Nicaragua	0.4
13	Colombia	0.4
14	Turkey	0.4
15	Costa Rica	0.3
16	Taiwan	0.2
17	Yemen	0.2
18	Chile	0.2
19	New Zealand	0.2
20	China	0.2

Table 6.1: The top 20 countries with highest overall volcanic threat. The normalised percentage represents the country's threat as a percentage of the total global threat.

Indonesia stands out as the country with two thirds of the share of global volcanic threat due to the large number of active volcanoes and high population density. Table 6.2 shows the distribution of threat by region to provide a broader picture of global distribution of volcanic threat. The results are compared with the ranking of these regions based on known historical fatalities[1].

Measure 1 Rank	Region* (Country)	Fatalities Rank
1	Indonesia (Indonesia)	1 (=)
2	Philippines and China (Philippines, SE China)	3 (-1)
3	Japan (Japan)	6 (-3)
4	Mexico and Central America (Costa Rica, El Salvador, Guatemala, Mexico, Nicaragua)	4 (0)
5	Africa and Red Sea (Cameroon, DRC, Ethiopia, Tanzania)	9 (-4)
6	South America (Chile, Colombia, Ecuador, Peru)	7 (-1)
7	Mediterranean (Italy, Greece, Turkey)	5 (+2)
8	Melanesia (Papua New Guinea, Solomon Islands, Vanuatu)	2 (+6)
9	New Zealand to Fiji (New Zealand, Tonga)	11 (-2)
10	North America (Alaska, Canada, USA-contiguous states)	12 (-2)
11	Atlantic Ocean (Azores, Canary Islands, Cape Verde)	10 (+1)
12	Kuril Islands and Kamchatka (Russia)	14 (-2)
13	Indian Ocean (Comoros, French territories)	15 (-2)
14	Iceland (Iceland)	16 (-2)
15	West Indies (Martinique and Guadeloupe, Montserrat, St. Vincent and the Grenadines)	8 (+7)
16	Hawaii (Hawaii)	13 (+3)

Table 6.2: Regional ranking using Measure 1 and known historical fatalities with the ten largest disasters removed[1]. Following Auker et al. 2013 the regions used here comprise only the countries or territories named, allowing for comparison of ranks with the fatality data.

Measure 1 is an overall measure of threat distribution and may be misleading because individual countries may vary considerably in the proportion of their population that is exposed to volcanic threat as nation states vary greatly in size and in their populations from, for example, China with 1.3

billion people (<1% exposed) to St. Kitts and Nevis in the Caribbean with only 54,000 people (100% exposed). Thus we need a measure of threat that reflects how important volcanic threat is to each country. Volcanic threat is very much higher in small island nations with active volcanoes than in larger countries. Measure 2 was developed to rank the importance of threat in each country that is independent of the country's size, so numbers of volcanoes and exposed population numbers are not included in the calculation. Measure 2 is defined:

$$Measure\ 2 = \frac{Pop30}{TPop}\ x\ Mean\ VHI$$

Table 6.3 lists the top 20 countries according to this measure.

Rank	Country	Rank	Country
1	UK-Montserrat	11	Guatemala
2	St. Vincent & the Grenadines	12	Sao Tome & Principe
3	France – West Indies	13	Spain – Canary Islands
4	St. Kitts & Nevis	14	Grenada
5	Dominica	15	Vanuatu
6	Portugal – Azores	16	Nicaragua
7	St. Lucia	17	Samoa
8	UK – Atlantic	18	USA – American Samoa
9	El Salvador	19	Armenia
10	Costa Rica	20	Philippines

Table 6.3: The top 20 countries or territories ranked by proportional threat: the product of the proportion of the population exposed per country and the mean VHI.

Here the countries identified are those that have very high overall vulnerability to volcanic hazards and are completely different to the rankings using Measure 1. They are a collection of small island states and small countries. Ranking on a broader regional basis using Measure 2 is shown in Table 6.4.

Relative Risk Rank	Region	Relative Risk Rank	Region
1	West Indies	10	Philippines & SE Asia
2	Mexico & Central America	11	Indonesia
3	Atlantic Ocean	12	Japan, Taiwan, Marianas
4	Africa & Red Sea	13	Iceland & Arctic
5	New Zealand to Fiji	14	Alaska
6	Melanesia & Australia	15	Hawaii & Pacific
7	Mediterranean & West Asia	16	Kamchatka & Mainland Asia
8	Middle East & Indian Ocean	17	Canada & Western USA
9	South America	18	Antarctica

Table 6.4: Ranking by region using Measure 3. Note the Kuril Islands region is not included.

Again the ordering of regions is completely different with the West Indies at the top using Measure 2 and near the bottom using Measure 1.

There is no suggestion which of these different country and regional rankings should be preferred. They are simply providing contexts and answers to different perspectives and questions. If the issue is to identify where most volcanic threat is concentrated then SE Asia and East Asian countries like Indonesia, the Philippines and Japan have a large share of the total global volcanic threat. If the question is which countries and regions, irrespective of size, are most vulnerable to volcanic hazards then the West Indies and small nation states are indicated, where the potential losses could be most significant in the context of the country's size.

7 Volcanic emergencies and disaster risk reduction

Volcanic eruptions vary in type, frequency and magnitude, and occur over quite variable periods of time (days to years). Compared to other natural hazards such as the passage of a hurricane, volcanic emergencies can be prolonged with potentially a series of impacts caused by different primary and secondary volcanic hazards. Importantly though, volcanic unrest may precede an eruption giving some early warning if a monitoring capability and responding institutions are in place. Likewise, monitoring data can be used to forecast imminent increases in hazardous activity once an eruption has begun. Volcanic eruptions do not respect national borders and frequently impact several different countries in different ways. Scientists, regulators and emergency managers need to coordinate their activities with other nations in such situations adding another layer of complexity to emergency activities. Establishing that an eruption is over can be challenging and the end of an eruption does not necessarily imply a lack of hazard. Some secondary hazards (e.g. lahars) may continue for years post-eruption thus requiring continued mitigation and response efforts, and some volcanoes are persistently active so the risks arising from primary and secondary volcanic hazards have to be continually managed. In the majority of cases, volcanic emergencies have to be managed in the face of considerable uncertainty.

The official responsibility for volcanic risk management and risk reduction at a societal level usually lies with government agencies, but to be effective also relies on the engagement of communities (including the private sector and NGOs) and individuals. Evacuations are called by these authorities following short term forecasts and early warning from scientists. During volcanic eruptions evacuations may be short-lived or prolonged, both affecting lives and livelihoods. In some cases towns, villages, land and infrastructure may be completely destroyed requiring resettlement and resulting inevitably in a long and protracted period of recovery. Based on priorities and capacities, each individual has a different tolerance to risk and this may in some cases differ substantially from the tolerances considered acceptable for society by civil authorities. For example, some may self-evacuate long before official calls to do so, others may resist evacuation in order to maintain assets or care for livestock.

7.1 Role of scientists

The primary role of scientists (volcanologists) in risk management and risk reduction is to provide timely and impartial information, volcanic hazards assessments, and both long and short-term eruption forecasting to the civil authorities so they can make effective risk-based decisions, for example, about evacuation. In practice, especially if a volcano has been dormant for a long period and accounting for staff turnover among the responding authorities, the scientists may need to provide basic knowledge about the potential hazards and impacts of volcanic eruptions based on lessons learnt at previous eruptions. Good scientific decision-making, effective hazards assessments and forecasts depend not only on good leadership, but also on the capabilities of scientists, the availability of reliable data and often on supportive national and international scientific networks [CS4, CS7]. To turn good science into effective disaster risk reduction requires good communication, strong long-term relationships, cooperation and coordination amongst stakeholders, effective public engagement and ultimately on the capacity of communities to respond.

Volcano Observatories are by necessity connected to place since volcanoes don't generally move and likely areas of impact are known in advance if appropriate geological studies have been carried out. This means scientists and technicians are active within the communities they serve enhancing the potential for long-term relationship building, knowledge exchange, good communication and joint activities in resilience building and risk reduction.

The 1976 volcanic emergency at La Soufrière, Guadeloupe was a pivotal event in highlighting the challenges of effective communication and the issue of trust in scientists, especially under conditions of uncertainty brought about by limited monitoring [CS5][42]. Here a polemical publically-expressed lack of consensus by scientists led to a loss of trust. There was no comprehensive monitoring network prior to the 1976 crisis, limited knowledge of the eruptive history of the volcano, large uncertainties in the interpretation of available scientific data, and awareness of devastating Caribbean eruptions in the past. Following the controversial management of the 1976 eruption (a large-scale evacuation of the capital city with no subsequent major eruption), a major effort in disaster risk reduction began in the area around La Soufrière. A dedicated Volcano Observatory was established and new methods in hazard and risk assessment are being developed alongside cost-benefit analysis in support of pragmatic long-term development and risk mitigation.

Since this episode, other high profile volcanic eruptions showed that some of the issues experienced in Guadeloupe tended to recur, but there were also examples of very good scientific practice. The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), the professional body for volcanologists, published a protocol on the behaviour of scientists working in volcanic emergencies[118]. The protocol highlights some key issues and offers guidelines as to how international scientists could support rather than hinder in-country scientists before, during and after eruptions. One of the key principles of this 'IAVCEI protocol' is that there should be a 'single message' established by the official in-country scientific institution (e.g. Volcano Observatory), often in consultation with others. This might take the form of notices or reports compiled by multiple scientists or agencies. Any disagreement should be handled among scientists themselves and be incorporated in the advice (e.g. within measures of uncertainty) if appropriate. Whenever potentially conflicting material is produced, with or without the knowledge of an official institution (e.g. Volcano Observatory), it undermines in-country scientists and their relationships with authorities and the public. This can result in ineffective risk reduction measures by the authorities and hence puts lives at stake.

Litigation is emerging as a major concern for scientists providing advice on volcanic risk, following the conviction of seven scientists in the L'Aquila earthquake trial in Italy. Governments will likely need to provide re-assurance to scientists who are willing to serve the community in emergencies. The ongoing debate on the implications of the L'Aquila trial within the scientific community may well lead to new protocols and guidelines for scientists working on volcanic emergencies. We note that the conviction of 6 of the scientists was overturned in appeal.

7.2 Alert levels

One of the main functions of a Volcano Observatory is to provide early warning to communities and authorities. Early warnings are needed both for hazards on the ground and airborne hazards. Volcanic Alert Levels[119,120] are commonly used as a means to rapidly communicate the status of volcanic activity to those who need it around the volcano, in a simple and understandable manner. They differ in the number of levels, the types of labels used (e.g., using colours, numbers, words or symbols), and their emphasis on unrest vs. eruptions. Some systems incorporate or are closely associated with response actions (e.g., evacuation), depending on the roles and responsibilities between scientists and authorities in each country. There is variation in the amount of forecasting language included in alert level systems. Alert level systems need to be effective for local communities and emergency responders, as well as for the scientists who typically set the levels (CS13). There is also an established International Aviation Colour Code system which, although optional, is specifically intended to aid communication between volcano observatories and Volcanic Ash Advisory Centres.

The use of an alert level system is exemplified by the 2010 eruption of Merapi [CS6]. Merapi (2948 m summit elevation) is one of the most active volcanoes in Indonesia. The 2010 Merapi eruption affected 2 provinces and 4 regencies and led to evacuation of about 400,000 people[3]. Indonesia applies 4 levels of warnings for volcano activity (Figure 29). From the lowest to highest: at Level I (Normal), the volcano shows a normal (background) state of activity, at Level II (Advisory) visual and seismic data show significant activity that is above normal levels, at Level III (Watch) the volcano shows a trend of increasing activity that is likely to lead to eruption, and at Level IV (Warning) there are obvious changes that indicate an imminent and hazardous eruption, or a small eruption has already started and may lead to a larger and more hazardous eruption. At Level III people must be prepared for evacuation and at Level IV evacuations are required.

	ALERT LEVEL	DATES	RADIUS	ERUPTION
DECREASING	NORMAL	15-9-2011		
	ADVISORY	30-12--2010		
	WATCH	3-12-2010		
		4-11-2010	20 KM (11:00 UTC)	4 Nov. 17:05 UTC (16,5 km)
INCREASING		3-11-2010	15 KM (08:05 UTC)	3Nov. 08:30 UTC (9 km)
	WARNING	25-10-2010,	10 KM (11:00 UTC)	26-10-2010, (10:02 UTC)
	WATCH	21-10-2010		
	ADVISORY	20-9-2010		
	NORMAL	17 -9-2010		

Figure 29: The chronology of warnings and radius of evacuations used during the 2010 eruption of Merapi, Indonesia (time increases from the bottom of the diagram upwards, see CS7. The four alert levels are indicated by colour: green (I); yellow (II); orange (III); and red (IV).

During the crisis, there was rapid escalation of seismicity, deformation and high rates of initial lava extrusion [CS6][3]. All monitoring parameters exceeded levels observed before and during during previous eruptions of the late 20th century. This raised concerns of an impending much larger hazardous event. Satellite monitoring (radar) provided an additional and valuable tool to establish the rapidly changing topography at the summit of the volcano. Consequently, a Level IV warning was issued and evacuations were carried out within 10 km of Merapi's summit. The exclusion zone was then extended to 15 and then to 20 km as the eruptive activity escalated. Each evacuation was followed within hours by devastating pyroclastic density currents that travelled to increasing distances. This very effective anticipation of hazard and risk was possible due to the combination of effective real-time monitoring, effective in-country institutions with strong relationships, communications and a well-practiced response system, good interaction with communities and good international scientific support networks. About 300 people died because they either would not or could not evacuate, but between 10,000 and 20,000 were saved by warnings and evacuations.

7.3 Effective communication and relationships

Communication is a critically important aspect of volcanic risk reduction [CS21]. It has been shown repeatedly that networks of responding institutions with recognised roles and responsibilities (in the form of response protocols) must be established well before volcanic unrest and eruption if there is to be an effective response. Ideally, regular activities and exercises between a Volcano Observatory, the authorities and communities at risk are needed to maintain relationships, trust, knowledge and to develop a common language. Volcanic eruptions are complex and may have multiple outcomes so all potentially affected sectors (from industry to households) need to develop some understanding of the implications for their area of responsibility in advance. Volcano Observatories often have a significant educational role in terms of discussing hazards and their potential impacts with authorities and the public, ideally this is targeted to different audiences. Scientific data products and knowledge need to be provided in formats of value and of use to stakeholders, so often both scientists and non-scientists need to think in different ways in order to identify what is needed at different times and in different situations. For example, authorities may appreciate maps but the public may prefer 3D imagery. The development of user-friendly scientific products is an iterative process requiring long-term dialogue and mutual understanding.

During an emergency situation decisions must be made quickly and under pressure so this is too late to be learning about hazards and risks, and getting to know key stakeholders, their roles, responsibilities and needs. Ideally, a nation will establish an 'emergency committee' capable of handling a range of risks but with specific experts identified for volcanic hazards and risks and this committee will meet regularly during a crisis situation to facilitate communication across sectors.

To be effective the authorities responding to an emergency must be confident in evaluating specialist advice. However, most decision-makers are unfamiliar with the scientific limits of forecasting volcanic behaviour and with the scale of disruption and damage that eruptions can produce. At the same time, scientists may be unfamiliar with how the demand for, and use of, scientific information is shaped by the needs of the user and by the political and institutional contexts in which decisions are made[121–123]. So, an ongoing dialogue between scientists and officials is essential in order to maintain mutual understanding. Commonly there is rapid turn-over of officials and decision-makers due to changes of government or structures of governance so this need for raising awareness is necessarily permanent.

The media and in particular social media are playing an increasing role in informing and updating populations on any event that takes place. The media can be an effective risk management tool, but again interaction with the media requires planning and management for example through press offices or even dedicated media centres and the distribution of materials specifically for media uptake. Some information in the media will be erroneous and so the media needs to be handled proactively to reduce misinformation. Engagement with the media can take up considerable amounts of time during an emergency for both scientists and authorities, particularly if an eruption has cross-border impacts and needs to be planned in advance. During the 2010 eruption of Eyjafjallajökull volcano in 2010, the demand for information from scientists and the authorities was so extreme that two media centres were established in Iceland and regular press briefings and releases were organised and issued. Communications through the media and internet, and with local communities (through local media, community groups and public meetings) were ultimately very effective, but it was recognised that tourists are one group that is challenging to reach[103], especially if they do not actively seek information (e.g. from tourist information centres). A recent initiative in Iceland calls on tourists to register their mobile phone numbers so they can receive SMS texts in case of volcanic unrest.

7.4 International collaboration

There has been a long history of international collaboration around volcanoes and volcanic eruptions. In part this is because experience and lessons learnt from one emergency can often be applied to some extent at the next and sharing of this experience is considered critical to effective global progress in volcanic disaster risk reduction. The internet together with open access journals and reports are now facilitating this sharing of experience. International partners can also provide equipment, specialist expertise and extra hands during a crisis. There are several examples of international scientific collaboration that have led to effective disaster risk management sometimes through the application of novel techniques (e.g. CS4, CS7 and CS8). Opportunities for scientists to engage across regions and internationally in collaborative and coordinated cross-disciplinary research have helped to support progress and to ensure research is integrated into operations [e.g. CS16]. Regional scientific collaborations in the Pacific region, Europe and Latin America to support science and Disaster Risk Reduction in volcanic hazards are proving highly effective and productive initiatives.

The Volcano Disaster Assistance Programme (VDAP) of the US Geological Survey has for almost three decades supported scientists and institutions in many countries during volcanic emergencies [CS22]. VDAP adopts a strict policy of only coming in when invited through formal government mechanisms. VDAP has assisted at some of the major eruptions of the last few decades, including those of Pinatubo, Philippines in 1991, Soufrière Hills Volcano Montserrat in 1995, and Merapi, Indonesia in 2010. Consortia of international scientists have also supported some volcanic emergencies [CS8].

Experience has also shown that it is essential that an identified scientific group within an affected country lead the scientific response and are not undermined or contradicted by external scientists. The IAVCEI protocol[118] went some way to addressing this concern (section 7.1), but it remains possible for a scientific institution dealing with the demanding operational aspects of an eruption response to be overlooked by researchers keen to take advantage of a unique and time-limited research opportunity. Both opportunistic research and an effective operational response are needed but research before, during and after a crisis must be carried out with the knowledge and engagement of the official scientific institution. This ensures that there is no duplication, enhances the potential impact of the research and may enable negotiated access to additional datasets and research networks. For a VO, engagement with researchers can facilitate access to novel methods, provide more data to aid operational activities or conceptual understanding, and may facilitate the timely communication of scientific progress.

The global network of VAACs operating under ICAO guidelines [CS11] provides a strong framework within which communications with volcano observatories can be practised and standardised reports can be produced. There is as yet no other formal standardised reporting system of global extent for volcanic unrest and eruption. The notices issued to the aviation sector are not available at the global scale although there is now a clearly recognised demand for a global resource identifying the status of the world's volcanoes and potential threats to aviation and other sectors. The accessibility of such knowledge and enhanced awareness of volcanic unrest and activity is essential to improve preparedness for and mitigation of risks and to reduce losses. The Smithsonian Institution currently compiles weekly and monthly reports from volcano observatories and intends to increase this frequency to daily reports. Crucial to this effort of daily reporting will be voluntary contributions of observatory reports and forecasts of activity, and later validation of data and information by observatory staff.

Volcanic eruptions do not respect national boundaries and can thus impact adjacent nations equally but the presence of different regulatory frameworks, either for civil aviation or development can lead to inconsistent response and planning. The 2010 eruption of the Eyjafjallajökull volcano in Iceland, provided significant challenges across Europe. For example, the UK government had no planning in place for volcanic eruptions but the existing relationships (and regular exercises) between the London VAAC and the Icelandic Met Office (volcano observatory) and between the British Geological Survey and the University of Iceland enabled a rapid ad-hoc response at government level. As the eruption progressed, a Memorandum of Understanding was signed between responding scientific organisations in the UK and Iceland to ensure the open sharing of data in support of emergency response and to support capacity building in both countries. This underpins ongoing collaborative activities.

7.5 Training and capacity

Some volcano observatories are fortunate enough to be linked to national institutions or a university that can provide training opportunities and career progression but a common challenge at volcano observatories is to ensure that scientists and technicians are not overwhelmed by operational and technical demands and have sufficient time to develop their research and skills. Training and capacity building is one area where external support can be very useful, but of course it should respond to a needs-analysis led by the observatory itself.

Collaborative research projects can be extremely valuable for volcanologists and may lead to the application of new methodologies, ideas and techniques at volcano observatories. However, they can also be a great drain on observatory resources and so should include provision for the engagement of observatory scientists in the research as partners and the potential need for technician time and expertise should not be forgotten. Turning any research into a long-term operational capacity at a volcano observatory may be challenging given that observatory resources are already stretched and such activities also require funding. Training in the use of new equipment or technology, or in new methodologies (e.g. social science approaches) may be very welcome and can also be included in research project budgets. Research projects may leave monitoring equipment but the need for continued maintenance in the field, data acquisition and real-time interpretation can for example be a prohibitive long-term cost.

Volcano observatories typically take part in regular exercises to test operational responses with VAACs, civil authorities and communities. Such exercises can simply test existing communication lines or can test responses to more complex situations (e.g. scenario planning). The lessons learnt from such exercises are critical to building capacity, increasing resilience and continually improving preparedness and response.

Merapi [CS7] is well known for a capacity building program named *wajib latih* (mandatory training) required for people living near the volcano. The aim of this activity is to improve hazard knowledge, awareness and skill to protect self, family and community. In addition to the *wajib latih*, people also learn from direct experience with volcanic hazards, which at Merapi occur frequently. However, the 2010 Merapi eruption showed that well-trained and experienced people must also be supported by good management, and that training and mitigation programs must consider not only "normal" but also unusually large eruptions[124]. Another example of building capacity [CS13] is provided by improvements to lahar warnings and hazard information for visitors to the ski areas on Mt Ruapehu, New Zealand (Figure 22). The assessment of multiple simulated events indicated potential actions aimed at improving future responses, such as increasing ski area staff training and improving hazard signage[125]. The communication tools were improved by repeating these activities annually and tracking perceptions of visitors through time in response to real events[120].

Cost-benefit analysis[126] is proving an increasingly valuable tool to support constructive dialogue between scientists and civil authorities on the merits of volcano monitoring and the management and mitigation of volcanic risks where it is currently minimal or lacking. Effective monitoring may, for example, help avoid unnecessary and costly evacuations and may support good risk management practice in the private sector. In some cases, existing monitoring capabilities can be harnessed to help monitor volcanoes (e.g. earthquake monitoring, groundwater monitoring, air quality monitoring).

7.6 Risk management

Risk management is usually led and implemented by relevant government authorities at different levels (national to local) with active response to disasters led by civil protection or civil defence and partners across sectors. Risk mitigation requires recognition of risk and allocation of budgets for mitigation measures, again at national to local scales. Effective management and mitigation of risk includes establishment and practice of early warning systems, the maintenance of effective political, legal and administrative frameworks, land use planning and efforts to influence the behaviour of populations at-risk.

There are a variety of different disaster risk management options open to authorities. Attempts to reduce the hazard are rare, reflecting that this is in most cases not possible, but there have been some examples of engineering measures such as lava flow diversion and lahar barriers that have had some effect. Exposure can be reduced directly in the short-term through evacuation of people and can be reduced long-term by development of new assets in geographic areas of lower risk and by transferring existing assets to areas of lower risk. Vulnerability of individuals and communities is complex and diverse, reflecting in part ability to cope with disruption to lives and livelihoods and to understand and respond effectively to warnings. Improving the resilience of communities and society as a whole may include increasing awareness of hazards, effective planning at individual to national scale and enhancing capacity to adapt in the face of risks. Effective early warning and forecasts from volcanologists can, in combination with effective emergency management, good communication and participatory approaches, contribute to timely evacuation and hence reduction in exposure and vulnerability. In long-lived eruptions and at frequently erupting volcanoes there is a need to adapt and live alongside volcanoes, requiring careful identification of evolving risks alongside effective risk management. The need for different sectors to work together requires long-term relationships, trust and a common language to ensure effective communication[127].

During a volcanic crisis, civil authorities and scientists are under immense pressure and must make decisions in short time-frames and often with limited information. Decisions about evacuation, for example, may be based on pre-defined thresholds and probabilities. The example of the 1976 eruption in Guadeloupe [CS5] in section 7.1 shows what can go wrong when an evacuation is called with minimal preparation or planning. One effective way for civil authorities and scientists to work together to support risk management is to combine hazards and risk assessments with cost benefit analysis. There are trade-offs involved in taking mitigating action in the interests of public safety that can be analysed within the economic decision framework of cost benefit analysis[125,128] and this has been applied at Naples (CS3). Another example of an analysis of the costs and benefits of evacuation has been carried out at Auckland, New Zealand (CS2). Cost-benefit analysis of evacuation does raise some difficult issues, such as the value of human life, but can be used to support any aspect of decision-making not just evacuation, such as land use planning and the establishment of monitoring capability. Importantly it can be done before any crisis develops and allows difficult topics to be considered outside an emergency situation.

Experience and lessons learnt inevitably improves risk management and this is particularly evident around volcanoes with long-lived eruptions. The Tungurahua volcano in Ecuador erupted in 1999 after decades of inactivity. Thousands were forcibly evacuated for 3 months leading to acrimony between the authorities, the community and scientists. A more collaborative approach to risk management was quickly adopted in which community volunteers (now 25 of them) became key players in the official communication network. They use VHF radios to share volcano observations with the Volcano Observatory on a daily basis, and also manage sirens and facilitate local evacuations (with support from Civil Defence). The network has been sustained largely on a voluntary basis thanks to commitment from all parties for over 14 years and has resulted in several effective evacuations since 2000 (CS23). The communities themselves take account of the most vulnerable individuals in their evacuation planning and many have alternative agricultural land and homes (allocated as part of the risk management procedures) to which they can retreat during periods of elevated volcanic activity.

Threat to livelihoods has been identified as a critical risk driver in many cases and during volcanic eruptions there have been many cases of farmers returning to evacuated land to care for livestock and harvest crops[91], or business owners returning to retrieve capital assets. Safeguarding livelihoods by providing alternative land or opportunities can significantly contribute to disaster risk reduction. This is linked to planning and development both of which need to be closely connected to disaster risk reduction activities.

Long-lived eruptions also demonstrate the critical difference between intensive and extensive risk. Intensive risk may be extreme and short-lived leading to evacuation and disaster risk management activities. In long-lived eruptions, however, populations though may be exposed to low levels of semi-continuous ash fall for weeks or months, which do not result in specific risk management or risk reduction measures. Volcanic ash fall can have many impacts on infrastructure, agriculture, environment, water, transport and also on psychological well-being but these are not characterised holistically and thus may not lead to an identifiable economic impact.

In practice, in many places, individuals have their own risk tolerance thresholds and will tend to act upon that. One significant challenge for individuals relying on such an approach in close proximity to an active volcano is a tendency to require visual or audible signals before action, even though it is well known that dangerous hazards such as pyroclastic density currents and lahars may give no audible signal and may go unnoticed if one is not watching the volcano[91]. Even a large explosion may go unheard on the flanks of a volcano but will be heard clearly much farther away.

More participation of communities in risk assessment, risk management and risk reduction can have considerable benefits to the community[94,95] and can influence the psychological and sociological aspects of risk, it can also benefit scientists (increase in trust) and civil authorities (more efficient and timely response). For example there is evidence that uncertainties may be better understood and there is more acceptance of risk reduction actions taken in the face of uncertainty.

7.7 Planning and preparedness

A milestone in international collaboration for natural disaster risk reduction was the approval of the "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters" (International Strategy for Disaster Reduction, 2005: Hyogo Framework for Action 2005-2015). This document, which was approved by 164 UN countries during the World Conference on Disaster Reduction in Kobe, January 2005, clarified international working modes, responsibilities and priority actions for the following 10 years. Here we discuss volcanic risk through the prism of these five HFA priorities for action:

1. Ensure that disaster risk reduction is a national and local priority with a strong institutional basis for implementation.
2. Identify, assess and monitor disaster risks and enhance early warning.
3. Use knowledge, innovation and education to build a culture of safety and resilience at all levels.
4. Reduce the underlying risk factors.
5. Strengthen disaster preparedness for effective response at all levels.

Priority for Action 1 states that each nation has the prime responsibility for preventive measures to reduce disaster risk, and is expected to take concrete actions. This principle can be interpreted as the need to establish an institution or mandate an existing institution to monitor active volcanoes within each country. Ideally every active volcano should have a dedicated monitoring system, but this ideal is unrealistic due to the large resources implied, especially for countries with many active volcanoes. Thus some prioritisation is needed where high-risk volcanoes are identified. Our assessment of monitoring capacity indicates significant improvements around the World in the last 10 years, but some high-risk volcanoes remain unmonitored or poorly monitored and major geological knowledge gaps exist. There is still a lack of a comprehensive data on monitoring capacity, which prevents documenting progress and identifying gaps. This principle also encourages community participation in all aspects of disaster risk reduction.

Priority for Action 2 states that emphasis should be put on making and regularly updating risk assessments at local to national scale, establishing and/or enhancing early warning systems, capacity building and anticipation of regional and emerging risks. There is also emphasis on data sharing, information systems, space-based earth observation and dissemination. There would be great benefits if more effort were put into these areas. Volcanic risk organisations like WOVO, IAVCEI and GVM provide platforms for assuring quality of information, identifying best practice and protocols in data collection, standardisation of terminology, and harmonised approaches to database construction and hazard mapping for example. The consideration of risk at different scales from local to global is of key importance and there are implications for approaches used at different scales. This principle also encourages people-centred early warning and we have presented several examples of good practice in this area between VOs and communities at risk.

Priority for Action 3 focuses on using knowledge, innovation and education to enhance DRR at all levels and across disciplines and regions. To a large extent international cooperation to assist in volcanic emergencies is working well in volcanology. The US Geological Survey's VDAP has been exemplary in supporting countries that need assistance and there are several examples of bi-lateral and multi-lateral assistance responses. There are also examples of workshops, short courses and technical training activities organised within the volcanological and Observatory communities at national, regional and global levels that promote technical training, knowledge transfer and sharing of good practise. However, there is a case that international cooperation should be defined in broader terms than this principle suggests. A model of high-income jurisdictions helping low income countries does not fully reflect the need to support integrated efforts for disaster risk reduction. IAVCEI and GVM provide mechanisms for grassroots actions and coordinated international collaboration. Some volcanic emergencies cross borders so there is a need to support co-operation between countries. Support is needed for the international community to work together to create and maintain databases, collate information, work towards agreed standards and international authenticated methodologies and procedures, and share best practices.

Priority for Action 4 addresses the need to reduce identified risk factors encouraging partnerships, integration across sectors, risk sharing, land-use planning and development among other things. Identification of key risk factors in Action 2 will greatly facilitate the ability to reduce risk. There is certainly great potential for volcanologists to have a greater input into risk reduction activities across sectors, but especially in land use planning and development. Long term risk assessments can be carried out over large geographic areas if there has been investment in geological and geochronological studies and hazard modelling.

Priority for Action 5 states that greater preparedness will lead to better response at all levels. There is strong evidence that good planning, well-prepared emergency services and a well-informed population with trusted advice from volcanologists and decisions made by the authorities based on this advice will greatly reduce the impact of a volcanic emergency. In densely populated areas around a volcano there is a need for regular review of hazard mitigation strategy, including spatial planning, mandatory disaster training, contingency planning and for regular evacuation drills.

Like many other countries, the UK and Iceland are actively responding to the HFA guidelines in their planning. In Iceland with many active volcanoes there are mature plans to raise awareness and prepare for future eruptions [CS24]. The eruptions of Eyjafjallajökull in 2010 and Grimsvötn in 2011 drew attention to how an eruption in one country with active volcanoes could affect many other countries. The UK government department handling civil protection in the UK, the Civil Contingencies Secretariat (CCS) of the Cabinet Office, introduced volcanic risks into the National Risk Register (NRR) for the first time [CS25]. In order to enhance UK preparedness for most types of eruption in Iceland and their distal impacts, two scenarios were included in the NRR based on past events: a small-moderate explosive eruption of several weeks duration (the Eyjafjallajökull eruption) and a large fissure eruption of several months duration (the 'Laki' eruption of Grimsvötn volcano). Hazard assessments based on these scenarios inform contingency planning across government (e.g. transport, health, environment) and at local authority level so the UK should be more resilient to future eruptions in Iceland.

Traditionally, consideration of volcanic risk has focused on loss of life. However, other potential losses such as livelihoods, critical infrastructure, buildings, health, agriculture and environment all benefit from rigorous hazard and risk assessment approaches.

8 The way forward

Our background paper highlights the wide range of hazards posed by volcanoes and describes their diverse impacts on communities. As with other hazards an approach based on science and technology has developed to anticipate these hazards, increase societal resilience and reduce risk. Many volcanic hazards are localised around a particular volcano and each volcano is to some extent unique. Thus dedicated volcano observatories are at the frontline of emergency management and disaster risk reduction. Observatories and their linked scientific institutions can help communities prepare for future eruptions, can provide early warning and forecasts when a volcano threatens to erupt, and will be at the centre of emergency management during an eruption. There is also increasing recognition that, while science and technological monitoring are vital components of disaster risk reduction for volcanoes, scientists can also contribute to risk management and mitigation, and support the decision-making of individuals and authorities. Building resilience and living with an active volcano requires good communication between scientists, decision-makers, emergency services and the public, effective planning and exercise of emergency responses, development of trust, and understanding of cultural factors that affect community responses. Our study also highlights gaps in knowledge, best practices and shortfalls in capacity.

The benefits of preventive measures are increasingly recognised, locally, at the level of national governments and among international donors and the Hyogo Framework for Action 2005-15 provides an excellent blueprint for disaster risk reduction. Here, we identify three key pillars for the reduction of risks associated with volcanic hazards worldwide and list recommended actions with the underlying principle that volcanologists based in a specific country are the best to lead any national needs-analysis:

Pillar 1: Identify areas and assets at risk, and quantify the hazard and the risk.

Without knowledge and characteristics of hazard and risk, it would not be meaningful to plan and implement mitigation measures. Many of the World's active volcanoes have only rudimentary records at best. Also many of the data that do exist are not in a standardised form and lack quality control. These knowledge gaps can only be closed by systematic geological, geochronological and historical studies and support for international collaborative activities attempting to address issues around data collection, analysis methods and databases.

Action 1.1 The hazard level of many volcanoes is highly uncertain, mostly reflecting the paucity of geological knowledge and in many cases a low frequency or absence of historical eruptions. Those volcanoes with a combination of high uncertainty level and high population exposure index (in this study) should be prioritised for geological studies that document recent volcanic history for a hazard assessment context. Recommended studies include stratigraphy, geochronology, petrology, geochemistry and physical volcanology. Such studies greatly enhance the ability of volcanologists to interpret volcanic unrest and respond effectively when activity begins. In some cases, findings are likely to increase the currently known risk. This work requires government funding to resource geological surveys and research institutions as primary funds are not likely to come from the private sector. However, where there are commercial activities associated with active volcanoes, such as geothermal energy, tourism or insurance potential it would be reasonable to ask for contributions to this base-line work.

Action 1.2 Probabilistic assessment of hazard and risk that fully characterises uncertainty is becoming mandatory to inform robust decision-making. Deterministic approaches cannot fully characterise either hazard or risk, are limited and further can be highly misleading. Assessments and forecasts are typically combinations of interpreting geological and monitoring data and various kinds of modelling. Probabilistic event trees and hazard maps for individual volcanoes are best made by local or national scientists, and we recommend that these be made in advance for high-risk volcanoes. However, some data from beyond the specific volcano in question are also needed for these trees and maps, especially if the volcano in question is poorly known.

Action 1.3 Global databases can serve as references for local scientists, providing analogue data and distributions of likely eruption parameters. Creation and maintenance of global databases on volcanoes, volcanic unrest and volcanic hazards, and quality assurance on data, hazard assessment methods, forecast models, and monitoring capacity are best done through international co-operation. Funding compilation of such databases does not fit easily into national and regional research funding and needs stronger international support.

Action 1.4 Forensic assessments of volcanic hazards, their impact and risk drivers are needed during and after eruptions. Such studies are essential to improve knowledge of hazards and vulnerability in particular and to improve and test methodologies such as forecast modelling based on real observational data. National Governments should be encouraged to support their institutions to include timeline-based analysis of their actions and subsequent impacts, and to report successes and shortcomings of crisis responses. A great deal of valuable information about volcanic disasters is in the form of unpublished and often anecdotal information, so formal publication of post-hoc assessments of emergency responses should be encouraged. Evaluations of "lessons learnt" from past disasters are likewise important to improve future responses and avoid repetition of mistakes.

Action 1.5 Risks from volcanic ashfall associated with a particular volcano or region can be characterised by detailed probabilistic modelling, taking into account the range of physical processes (atmospheric and volcanic) and associated uncertainties. There is also a need to better understand the impacts of volcanic ash, and define thresholds of atmospheric concentration and deposit thickness for various levels of damage to different sectors. We recommend that further analysis be performed for all high-risk volcanoes, to enable more conclusive statements to be made about expected losses and disruption and to support resilience and future adaptation measures.

Pillar 2: Strengthen local to national coping capacity and implement risk mitigation measures.

Mitigation means implementing activities that prevent or reduce the adverse effects of extreme natural events. In a broad perspective, mitigation includes: volcano monitoring, reliable and effective early warning systems, active engineering measures, effective political, legal and administrative frameworks. Mitigation also includes land-use planning, careful siting of key infrastructure in low risk areas, and efforts to influence the behaviour of at-risk populations in order to increase resilience. Good communication, education and community participation are critical ingredients to successful strategies. All these measures can help minimise losses, increase societal resilience and to assure long-term success.

Action2.1 Many active volcanoes are either not monitored at all, or have only rudimentary monitoring. Some of these volcanoes are classified in this study as at high risk. A major advance for hazard mitigation would be if all active volcanoes had at least one volcano-dedicated seismic station with continuous telemetry to a nominated responsible institution (Volcano Observatory) combined with a plan for use of satellite services. This matches a strategy from space agencies to monitor all Holocene volcanoes and make data available (http://www.congrexprojects.com/2012-events/12m03/memorandum). For volcanoes in repose there are two suggested responses, namely implementation of low-cost systems for monitoring and raising awareness of volcanic hazards and risk among vulnerable populations. Provision of funding to purchase equipment must be complemented by support for scientific monitoring, training and development of staff and long-term equipment maintenance. We recommend this action as a high priority to address volcanic risk.

Action 2.2 Volcanoes identified as high-risk should ideally be monitored by a combination of complementary multi-parameter techniques, including volcano-seismic networks, ground deformation, gas measurements and near real-time satellite remote sensing services and products (e.g. satellite-based geophysical change detection systems). We recommend that all high-risk volcanoes should have basic operational monitoring from all four domains. This should be maintained, interpreted and responded to by a nominated institution (Volcano Observatory). Donations of equipment and knowledge transfer schemes need to be sustainable long-term with respect to equipment maintenance and consumables. Supporting monitoring institutions and sustaining local expertise is essential.

Action 2.3 Technological innovation should strive towards reducing costs of instrumentation and making application of state-of-the-art science as easy as possible so more volcanoes can be monitored effectively. For example, satellite observation offers a new and promising approach to monitoring the World's volcanoes in isolated or remote locations as well as providing additional information to augment ground-based Observatory monitoring systems. However, lower costs, easier access, technological training, and better and more timely sharing of data are needed to realise the potential. Many of the new models derived from research of volcanic processes and hazardous phenomena for forecasting can be made into accessible and easy to apply operational tools to support Observatory work and decision-making. More such tools are needed to aid decision-making in general. There is also a lack of model comparison and validation to standards that might ensure robust application. More resources need to be put into converting research into effective tools.

Action 2.4 Volcanic hazards, monitoring capacity, early warning capability and communication by volcanologists are key risk factors. The behaviour, attitudes and perceptions of scientists, decision-makers and communities also influence risk. Reducing risk is thus possible with better assessment and awareness of the hazards, effective communication by scientific institutions and authorities, well-practiced response protocols, participatory activities with communities and a greater awareness by all of key risk factors and how they can be managed/reduced. We recommend open, transparent interaction and communication with effective exchange of knowledge. In addition well thought out plans for emergencies are essential in all sectors of society.

Pillar 3: Strengthen national and international coping capacity.

Efforts should be made to increase coping capacity to address a wide range of hazards, especially relatively infrequent events like major volcanic eruptions. Many countries are enhancing their own disaster preparedness as suggested in the Hyogo Framework for Action. New resources have been made available. In addition, a number of countries have over the last decade also assisted developing countries where the risk associated with natural hazards is high. A key challenge with all projects from donor countries is to be assured that they are needs-based, sustainable and well anchored in the host countries' own development plans. Another challenge is coordination, which often has proven to be difficult because the agencies generally have different policies and the implementation periods of various projects do not overlap. A growing number of (recipient) countries want 100% ownership of their DRR activities.

On the other hand some volcanic emergencies cross borders and there may be hazards and attendant risks at regional or global scales. The threat to aviation from airborne volcanic ash is an example, another may be threats to health and agriculture from ashfall. A volcanic summit may lie in one country but valleys at risk from lahars and pyroclastic flows may lie across a border. Co-ordinated planning, mitigation and response from two or more countries are needed in these situations.

Action 3.1 Exchange visits, workshops, Summer Schools, and international research collaboration are good ways to share experience and expertise in volcano monitoring, appraisal of unrest, assessment of hazard and risk, and communication. Topics could include hazard mapping, physical volcanology, real-time interpretation of multi-parameter data, process modelling especially with respect to practical hazards assessment and forecasting tools, remote sensing and risk assessment. Cross-disciplinary training is particularly useful: earth science - remote sensing - social science-atmospheric science – technology. The value of interdisciplinary science is becoming more evident and an understanding of methodologies available in other disciplines can greatly strengthen effective collaboration. Volcanoes often have cross-border impacts so collaborative regional networks of countries can work together to build capacity, carry out research, carry out coordinated monitoring and planning, and make effective use of leveraged resources.

Action 3.2 There needs to be much more effort to integrate volcanic hazard and risk assessments with development and land use planning activities, preferably before eruptions occur so issues around livelihood, evacuation and potential resettlement are considered as part of resilience building and risk reduction activities.

Action 3.3 Free and easy access to the most advanced science and data will greatly enhance the ability to manage and reduce volcanic risk. Access to knowledge is globally very uneven between the developed and developing nations. For volcanic hazards, easy access to high-resolution digital elevation data and remote sensed data, together with appropriate training would significantly improve the scientific capacity of many countries. We encourage ISDR to promote open access of scientific knowledge to all and support the deployment of advanced technologies and information wherever it is needed. Equally important, ground-based data need to be shared among VOs and with the EO community (for validation purposes). Progress toward this goal has been slow but steady and some VOs already make their data freely available. Great effort and expense goes into both ground-based and satellite-based data, but the volcano community is still far from full utilisation of those data. As spatial, temporal, and spectral resolution of satellite data continues to improve, satellite and ground-based data simply must reach and be integrated by observatories in near real-time. For applications beyond minute-to-minute monitoring, WOVOdat, the GVM Task Force for Volcano Deformation, and several other initiatives are developing searchable archives with useful derivatives from raw ground- and satellite data monitoring data

Action 3.4 Index based methods to characterise hazard, exposure, risk and monitoring capacity used in this study are straightforward, intended to provide a basic broad overview of volcanic hazard and risk across the world. The Volcanic Hazards Index and Population Exposure Index should not be used to assess or portray hazard and risk in detail at individual volcanoes, which is the responsibility of national institutions and volcano observatories. Nonetheless, combinations of the two at many volcanoes will enable improved and more robust global and regional assessments and identification of knowledge gaps.

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CS3 Tephra fall hazard for the Neapolitan Area
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CS4 Eruptions and lahars of Mount Pinatubo, 1991-2000
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CS5 Improving crisis decision-making at times of uncertain volcanic unrest (Guadeloupe, 1976)
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CS1. Populations around Holocene volcanoes and development of a Population Exposure Index

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A way of ranking the risk to life from volcanoes is to establish how many people live in their vicinity. In addition to being an indicator of lives under threat, population exposure is a proxy for threat to livelihoods, infrastructure, economic assets and social capital. This report uses two indicators of population density around volcanoes to assess the current global exposure and as a risk indicator for individual volcanoes, and discusses this in combination with the Human Development Index (HDI) as a proxy for vulnerability.

Background

Ewert and Harpel (2004) introduced the Volcano Population Index (VPI), which estimates the number of people living within 5 and 10 km radii of volcanoes (VPI5 and VPI10). These population statistics, and VPI30 and VPI100 (population within 30 and 100 km of Holocene volcanoes) are reported in the VOTW4.0 (2013) database (www.volcano.si.edu; Siebert et al. (2010)). The Population Exposure Index, (PEI), was developed by Aspinall et al. (2011) for a study of volcanic risk in the World Bank's GFDRR priority countries. Here, populations within 10 and 30 km radii were estimated and combined using weightings that reflect how historic fatalities vary with distance from volcanoes.

The VPI was developed on the basis that most eruptions are small to moderate in size (VEI ≤3), with footprints of less than 10 km. The VPI therefore represents the population exposures for most eruptions. Indeed, eruptions of VEI2 occur at a rate of approximately one every few weeks, and VEI3 several times a year (Siebert et al., 2010). Eruptions of larger magnitudes (VEI≥4) are less frequent, but often cause fatalities at distances well beyond 10 km (Auker et al., 2013). Hazard footprints from such eruptions commonly extend to tens of kilometres. The PEI thus complements the VPI, accounting for the high threat from large eruptions and potentially distal hazard types. An advantage of PEI is that only a single indicator parameter captures the exposure of populations around each volcano with the various VPI populations all contributing to the index and weighted according to historical evidence on the distribution of fatalities with distance. Here we develop and apply an amended version of the PEI, which correlates quite well with VPI_{10}.

Population

The location and total population within circles of radius 10, 30 and 100 km of each volcano is derived from the VOTW4.0 (2013) database. Due to overlapping radii from multiple volcanoes, these population figures cannot simply be summed, therefore country-level data counting populations in the vicinity of multiple volcanoes only once were calculated by the Norwegian Geotechnical Institute (NGI) using the Oak Ridge National Laboratory LandScan 2011 dataset of Bright et al. (2012).

Holocene volcanoes are located in 86 countries. The total population within 100 km of these volcanoes is over 800 million (Table 1). With 142 volcanoes Indonesia has the greatest total population located within all distance categories (>8.6 million at 10 km, >68 million at 30 km and >179 million at 100 km). After Indonesia, the Philippines and El Salvador have the largest populations living within 10 km, both at >2 million.

Total population within 10 km	Total population within 30 km	Total population within 100 km
29,294,942	226,267,790	801,833,245

Table 1: The total global population living within given radii of volcanoes, derived using volcano location data from VOTW4.0 and 2011 LandScan data. Populations within each country were calculated and summed: no population was counted twice.

Indonesia, the Philippines and Japan have the greatest numbers of people living with 100 km of their volcanoes (Figure 1; left). The populations of small volcanic island nations, such as Tonga and Samoa, are almost all resident within 100 km. The percentage of the population living within 100 km of volcanoes is therefore calculated for those countries with an area of more than a circle of 100 km radius (Figure 1; right). These populations may be affected by volcanoes in bordering countries.

Capital cities are frequently located close to volcanoes. The capitals of American Samoa, Wallis and Futuna islands, Montserrat, Dominica, Guadeloupe, Saint Kitts and Nevis and Nicaragua all lie within 10 km of volcanoes. A further 20 capitals lie between 10 and 30 km; 32 lie between 30 and 100 km.

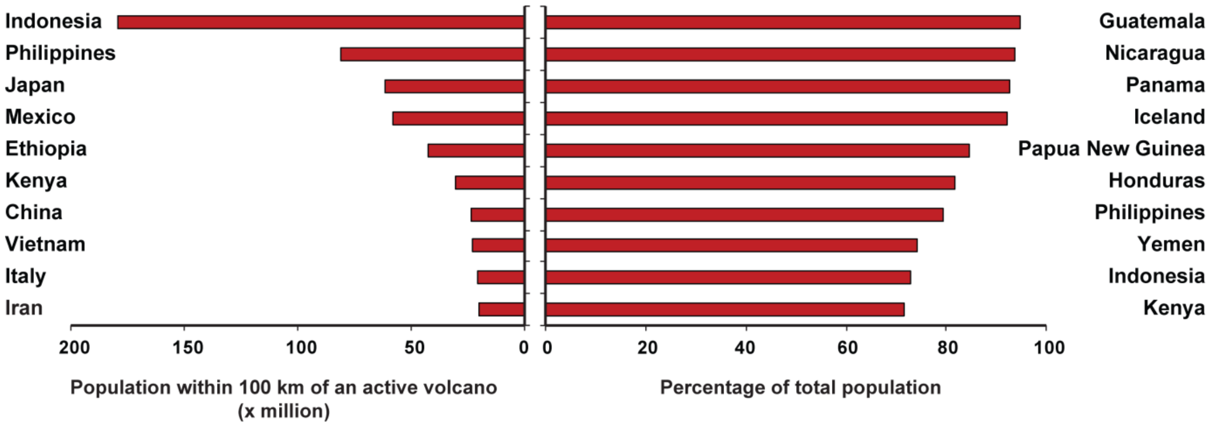

Figure 1: The top 10 countries for population within 100 km of a volcano (left) and the top 10 countries (area over 31,415 km^2) for percentage of the total population (right).

Countries without Holocene volcanoes within their borders may also have populations within 100 km of a volcano (Table 2).

Country	Population within 30 km	Population within 100 km
Jordan	48,278	5,690,340
Israel	1,056	1,884,367
Lebanon	0	3,141,870
Laos	0	26,512
Cambodia	0	1,409

Table 2: Countries with populations living within 100 km of volcanoes beyond their borders. No populations in these countries live within 10 km of volcanoes.

The largest populations within 10 km of volcanoes are those around Michoacán-Guanajuato, Mexico (>5.7 million), Tatun Group, Taiwan (>5 million) and Leizhou Bandao, China (>3.2 million) (Table 3). These and many other volcanoes with high populations in their vicinity have poorly understood eruptive histories; the age or magnitude, in some cases both, of their last eruption are often unknown. Poorly constrained eruptive histories make hazard assessment at these volcanoes difficult.

The volcanoes with largest populations within 100 km differ considerably from those with largest populations within 10 km, illustrating variation in population distribution (Table 3). Indeed, Small and Naumann (2001) explored regional trends in population density around volcanoes, showing a globally-averaged decrease in population density with increasing distance from volcanoes, dominated by tropical areas such as SE Asia and Central America. The opposite relationship is present in Japan and Chile. Eight of the ten most populous volcanoes at 100 km are located in Indonesia and Mexico; of these, only Chichinautzin and Popocatépetl have eruptions of VEI≥4 recorded in the Holocene.

The eruptive histories of almost half of the most populated volcanoes are poorly constrained (Table 3). The Holocene records for three volcanoes: Salak; Perbakti-Gagak; Tangkubanparahu (all Indonesia), solely contain VEI ≤2 eruptions, suggesting there is a low probability of significant effects beyond 10 km. However, large eruptions of M or VEI ≥4 often have long recurrence intervals, for which the Holocene may not be statistically representative. The volcanoes with largest proximal populations that have produced VEI≥4 eruptions in the Holocene are shown in Table 4.

Radius	Volcano, Country	Population within given radius	Year of last eruption (VEI of last eruption)	Maximum recorded Holocene VEI and modal Holocene VEI	Pleistocene record of M≥4 events
10 km	Michoacán-Guanajuato, Mexico	5,783,287	1943 (VEI 4)	VEI 4. Modal 3.	
	Tatun Group, Taiwan	5,084,149	4100 BC (VEI 1)	VEI 1.	
	Leizhou Bandao, China	3,230,167	? (VEI ?)	Unknown	
	Kars Plateau, Turkey	3,067,709	1959? (VEI 2?)	VEI 2?	
	Malang Plain, Indonesia	2,397,210	? (VEI ?)	Unknown	
	Campi Flegrei, Italy	2,234,109	1538 (VEI 3)	VEI 5. Modal 4	Yes
	Ilopango, El Salvador	2,049,583	1879 (VEI 3)	VEI 6.	Yes
	Hainan Dao, China	1,731,229	1933 (VEI ?)	Unknown	
	Jabal ad Druze, Syria	1,487,860	? (VEI ?)	Unknown	
	San Pablo Volcanic Field, Philippines	1,349,742	1350 (VEI ?)	Unknown	
100 km	Gede, Indonesia	40,640,105	1957 (VEI 2)	VEI 3. Modal 2.	
	Salak, Indonesia	38,154,252	1938 (VEI 2)	VEI 2. Modal 2.	
	Perbakti-Gagak, Indonesia	36,630,568	1939 (VEI 1)	VEI 1. Modal 1.	
	Tangkubanparahu, Indonesia	32,855,731	2013 (VEI 2)	VEI 2. Modal 1.	Yes
	Hakone, Japan	30,282,197	1170 (VEI ?)	VEI 3. Most unknown.	Yes
	Papayo, Mexico	28,677,002	? (VEI ?)	Unknown	
	Chichinautzin, Mexico	28,030,794	400 (VEI 3)	VEI 4. Modal 3.	Yes
	Iztaccíhuatl, Mexico	27,276,280	? (VEI ?)	Unknown	
	Arayat, Philippines	27,216,491	? (VEI ?)	Unknown	
	Popocatépetl, Mexico	26,509,510	2013 (VEI 2)	VEI 5. Modal 2.	Yes

Table 3: The top ten volcanoes by population size within the given radii and details of their last recorded eruptions. As magnitude affects the extent of the hazard footprint, the maximum recorded Holocene VEI and model VEI are given, and the occurrence of a Pleistocene record (in the LaMEVE database) of M≥4 eruptions is shown.

Rank	Volcano, Country	Rank	Volcano, Country
1	Popocatépetl, Mexico	6	Merapi, Indonesia
2	Chichinautzin, Mexico	7	Galunggung, Indonesia
3	Fuji, Japan	8	Tengger Caldera, Indonesia
4	Kelut, Indonesia	9	Pinatubo, Philippines
5	Taal, Philippines	10	Izu-Toba, Japan

Table 4: The top ten volcanoes by population size with a Holocene record of VEI ≥4 eruptions.

Population Exposure Index

A multitude of factors determine a population's vulnerability to volcanic hazards. Most volcanoes have the potential for a spectrum of eruption magnitudes and styles, with consequently varied footprints. In most cases, hazard and threat decreases with distance from the volcano. This is particularly true of pyroclastic density currents and lahars (the cause of almost 70% of all directly caused fatalities (Auker et al., 2013)), which are commonly confined to valleys. A maximum distance for consideration of population exposure of 100 km likely captures the majority of these hazards. However, the effects of the largest eruptions may extend beyond this distance.

The location and population within 10, 30 and 100 km of each volcano is derived from VOTW4.0. These populations are weighted on the basis of the area of each ring, and the number of fatal events recorded since 1600 AD within each distance category, using data from VOTW4.0 and the Smithsonian fatalities database described and analysed in Auker et al. (2013). Fatal incidents attributed to direct hazards (e.g. pyroclastic density currents, lahars, lava flows) are included, whilst indirect fatalities (e.g. famine) are excluded.

The fatality weighting is calculated based on the numbers of fatal incidents from direct hazards at each extent. The distance of fatalities from the volcano is only available for 27 of the 533 fatal incidents listed in Auker et al. (2013). These numbers differ from those used in Aspinall et al. (2011) due to the slight change in selection criteria. 17 fatal incidents are recorded at 0 – 9 km, 6 fatal incidents at 10 – 29 km, and 4 fatal incidents at 30 – 100 km, giving proportional weightings of 0.63, 0.22 and 0.19 respectively.

The increase in area of each circle moving away from the volcano decreases the population density for any given population size. The area of the 10 km radius circle is nine times smaller than that of the 30 km circle, and 100 times smaller than the 100 km circle, giving weightings of 0.91, 0.08 and 0.01, respectively. These two sets of weights are combined and scaled, yielding a weighting of 0.967 for the 10 km ring, 0.03 for the 30 km ring, and 0.003 for the 100 km ring.

For each volcano, the population within each distance category is multiplied by the appropriate weighting, and the three figures are summed. These final weighted populations are then assigned one of seven index scores, from 1 to 7 (Table 4; amended from the scale of 0 to 3 of Aspinall et al. (2011). We refer to these seven index scores as the Population Exposure Index (PEI).

Weighted Summed Population	Population Exposure Index
0	1
<3,000	2
3,000 – 9,999	3
10,000 – 29,999	4
30,000 – 99,999	5
100,000 – 300,000	6
>300,000	7

Table 5: Population Exposure Index (PEI), amended after Aspinall et al. (2011).

There are inherent uncertainties in the population statistics and in the accuracy of volcano locations. The fatality weighting may be refined through further study of the historic record and improvement in the evidence on distances of fatalities.

Global PEI

The PEI is calculated for all volcanoes in VOTW4.0. Over 40% of volcanoes have a PEI of 2; with the exception of PEI 7 there is an approximately even spread across all other PEI classes. The division of the total global population within 100 km (Table 1) across PEI classes is also examined (Table 6). 60% of the population living within 100 km are located around just 4% of volcanoes: the PEI 7 volcanoes. About a quarter of volcanoes are PEI ≥5, yet 96% of the total population are located here. The data indicate that most exposure (>95%) to volcanic hazards is distributed in volcanoes with PEI values of 5 to 7.

Population Exposure Index	Number of Volcanoes (%)	Percentage of Total Weighted Population
1	197 (12.7%)	0%
2	642 (41.4%)	0.4%
3	157 (10.1%)	1.0%
4	178 (11.5%)	3.5%
5	188 (12.1%	11.4%
6	128 (8.3%)	23.8%
7	61 (3.9%)	59.9%

Table 6: The number of volcanoes in each PEI category globally and the percentage of the total number of volcanoes. The percentage of the total weighted population is also provided.

There are 61 PEI 7 volcanoes, of which 16 are in Indonesia. Africa and the Red Sea and Mexico and Central America have 11 PEI 7 volcanoes each, with all other regions having <10. Indonesia, Mexico and Central America and Africa and the Red Sea have the greatest numbers of PEI ≥5 volcanoes. The regions with the greatest proportions of PEI ≥5 volcanoes are Philippines and SE Asia (70%), Mexico and Central America (64%), and Indonesia (55%). Alaska, Antarctica, and the Kuril Islands have no PEI ≥5 volcanoes (Figure 2).

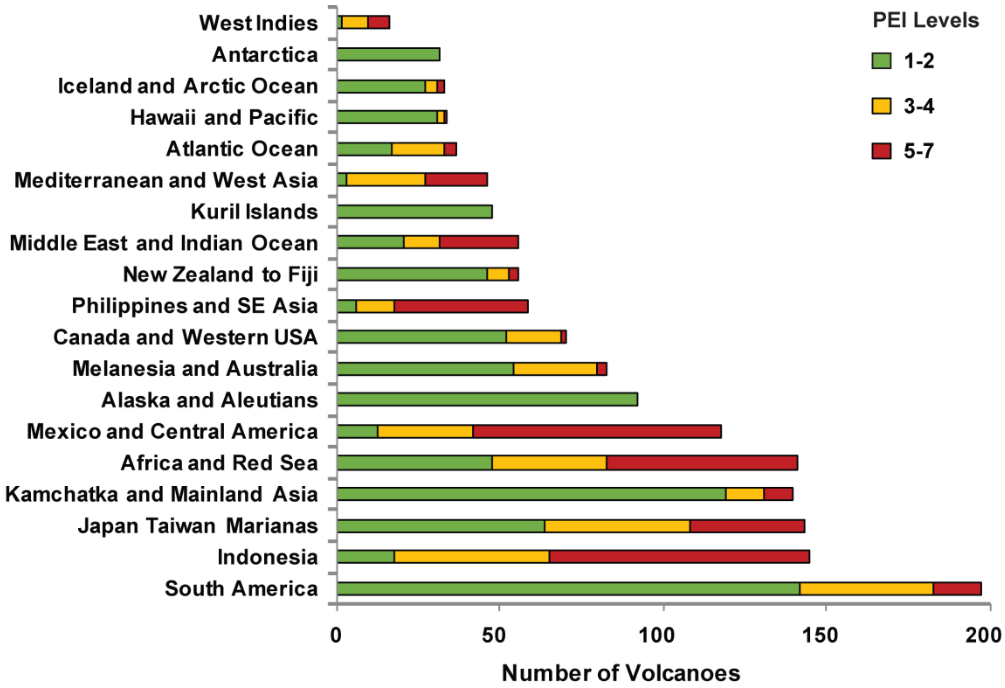

Figure 2: Number of volcanoes per region and their PEI classification.

PEI and VEI

Eruptions of M or VEI ≥4 are less frequent than smaller events, but have the potential for greater losses over larger areas. 864 volcanoes have no recorded eruptions of known VEI. Of the remaining 687, 438 have no eruptions of VEI >3; 249 volcanoes have one or more eruptions of VEI ≥4, of which 61 have a PEI of 5 - 7. There is clearly the potential for far-reaching hazards to affect large populations.

PEI and HDI

The Human Development Index (HDI) combines details of life expectancy, education and income to provide a measure of social and economic development, calculated by the United Nations Development Programme (United Nations Development Programme (UNDP), 2013) and categorised as Low, Medium, High or Very High. HDI is available for most, though not all countries; notable exceptions are overseas territories and island volcanoes. HDI and other metrics such as Gross Domestic Product (GDP) provide an indication of the wealth and development of a country. A low HDI does not always reflect the resources dedicated to disaster preparedness and response; however, there is a general relationship between the wealth of a country and the losses sustained in disasters (Toya and Skidmore, 2007). Toya and Skidmore (2007) and references therein explained that populations of wealthier nations have greater expectations regarding safety and are therefore more likely to use expensive precautionary measures to improve safety. They found that disaster losses and the underlying socio-economic fabric within a country are also correlated.

530 volcanoes are located in countries of Very High HDI (dominantly in Japan, Chile and the USA, which account for 391 of these volcanoes; Figure 3). Countries of Low HDI have fewer volcanoes (218), though there is a broad negative correlation between HDI and PEI. Significant examples include Ngozi in Tanzania (Low HDI), which has a PEI of 7 and a Holocene eruption of VEI 5; and Masaya in Nicaragua (Medium HDI) which also classifies at PEI 7 and has a Holocene record of eruptions of VEI 5 and 6 and frequent eruptions of VEI 1 and 2. The 142 volcanoes of Indonesia dominate the distribution of PEIs amongst the 355 volcanoes in medium HDI countries.

Fewer than 20% of volcanoes in High and Very High HDI countries are PEI≥5, and over 60% are classed as PEI 1 or 2. Notable examples of PEI 7 volcanoes in Very High HDI countries are Vesuvius and Campi Flegrei. Both border Naples in Italy and have Holocene records of VEI 5 eruptions and the potential to generate far-reaching hazards. The Auckland Field in New Zealand (Very High HDI) is also PEI 7, due to its situation under the city of Auckland. The low relief of this volcanic field makes large explosive eruptions with volcanic flows that extend to tens of kilometres unlikely.

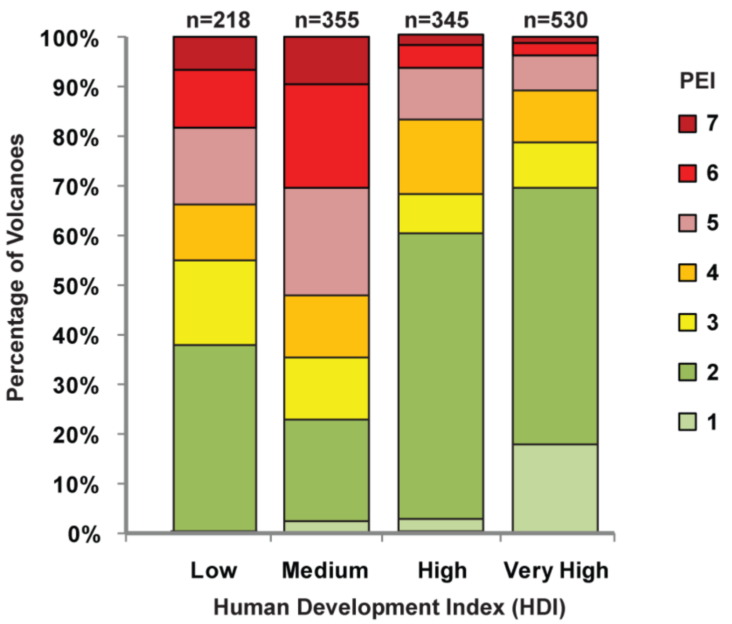

Figure 3: The four categories of the HDI and the proportion of volcanoes in each PEI band.

Combining PEI and HDI provides an indicator of the number of people in harm's way and societal and economic capacity to handle disasters. Volcanoes with large proximal populations in relatively low HDI countries may be more vulnerable and suffer greater relative losses. However, factors such as local prioritisation of resources or experience with natural hazards may counter this, and PEI and HDI do not account for differences in eruption styles or recurrence rates. Three main regions have high HDI x PEI rankings: Africa, SE Asia (dominated by Indonesia and the Philippines) and Central America (Figure 4).

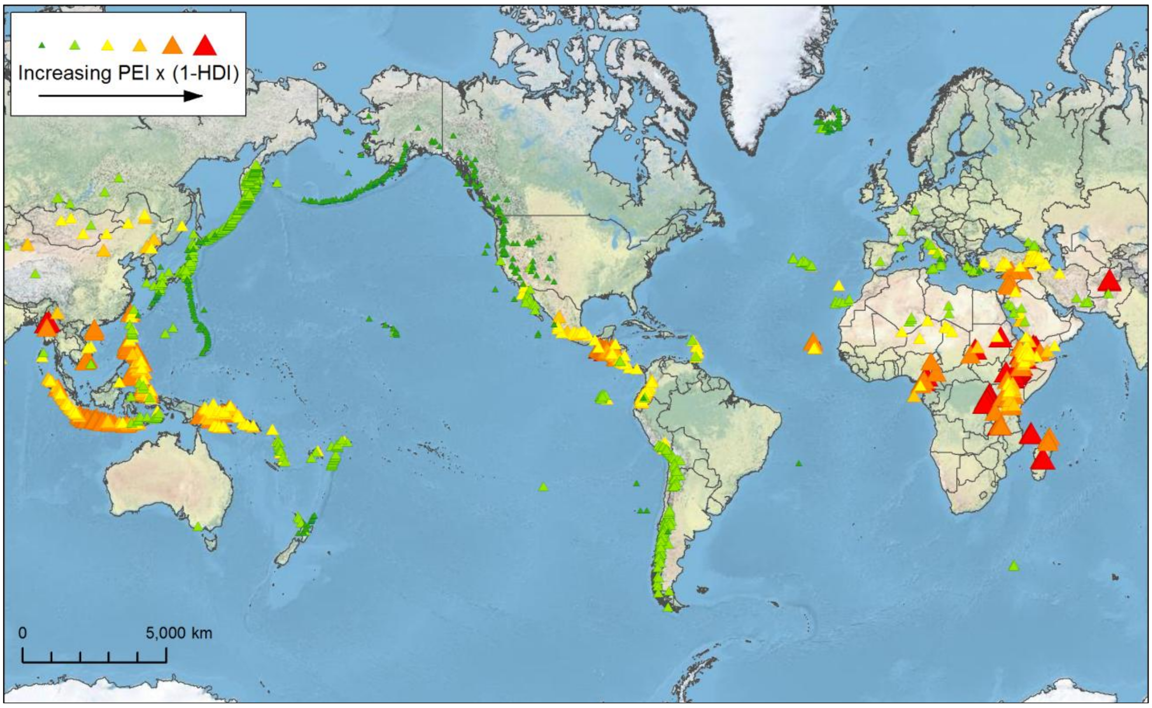

Figure 4: Global distribution of volcanoes coloured and scaled by PEI x (1-HDI), illustrating the locations of volcanoes with high proximal populations and lower HDI scores.

Implications and use of PEI

The VPI and PEI enable volcanoes close to large populations to be identified. The PEI's weighting of populations at different extents aims to capture the factors that control the number of people exposed.

We show that the majority of people exposed to volcanic hazards live around the 61 PEI 7 volcanoes. Indonesia has the greatest number of PEI 7 volcanoes (16), and subsequently the greatest total number of people living within 100 km of volcanoes. PEI and HDI are generally negatively correlated, suggesting larger populations are situated close to volcanoes in developing countries, compared to developed. 61 volcanoes have recorded VEI ≥4 Holocene eruptions and a high PEI (PEI 5 – 7). Similarly large eruptions from these volcanoes have the potential to cause significant disruption and loss. Many other high PEI volcanoes may produce VEI ≥4 eruptions over longer time scales.

The PEI may be used as a basis for disaster risk reduction resource management decisions. However, population exposure is not the only component of volcanic threat, and use of a hazard index for volcanoes provides a fuller picture. The PEI is also not a substitute for in depth assessments of exposure and vulnerability at specific volcanoes. Indeed it is certain that volcanoes with the same index value may have very different exposed populations. Topographic factors in particular will have a large role in determining exposure. For example, many volcanoes have craters or flank collapse scars open in one direction that will channel flows and produce directed hazards that threaten populations on one side of the volcano to a far greater degree than the other. Also, populations close to river valleys and on flood plains are very vulnerable to lahars and pyroclastic flows, and populations in the dominant downwind direction are more exposed to ash fall hazards. Full assessment based on local factors may lead to different conclusions about priorities.

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CS2: An integrated approach to Determining Volcanic Risk in Auckland, New Zealand: the multi-disciplinary DEVORA project

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Auckland, New Zealand, is home to 1.4 million people - over a third of New Zealand's population - and accounts for ~35% of New Zealand's GDP (Statistics New Zealand, 2014). The city is built on top of the Auckland Volcanic Field (AVF), which covers 360 km^2, has over 50 eruptive centres (vents), and has erupted over 55 times in the past 250,000 years, producing a cumulative volume of ~2 km^3 of tephra, lava, and other volcanic deposits[1] (see Figure 1). The field is likely to erupt again: the most recent eruption, Rangitoto, was only 550 years ago. Most AVF vents are monogenetic, i.e., they only erupt once. This means that it is very likely that the next vent will erupt in a new location within the field. Despite considerable scientific efforts, no spatial (where) or temporal (when) patterns have been identified; indeed, the oldest (Pupuke Volcano) and the youngest (Rangitoto) vents are located next to each other. As such, it is wholly unknown where or when the next eruption will be. The size of the next eruption is also difficult to address, as the last eruption, Rangitoto, accounts for nearly half of the erupted volume of the field, and it is unclear whether this eruption is an anomaly or signals a change in the eruptive behaviour of the field. These difficulties of assessing location, time, and size of next eruption pose a considerable problem for emergency and risk managers. The main challenges facing Auckland and other populated areas coinciding with volcanic fields include:

- Uncertainty of where and when the next eruption will take place;
- Communicating to the public how an eruption of unknown location will impact them and how they can best prepare;
- Planning for an event which hasn't occurred in historic time;
- Foreseeing and appropriately planning for the range of possible impacts to the built environment, local, regional and national economy and psyche.

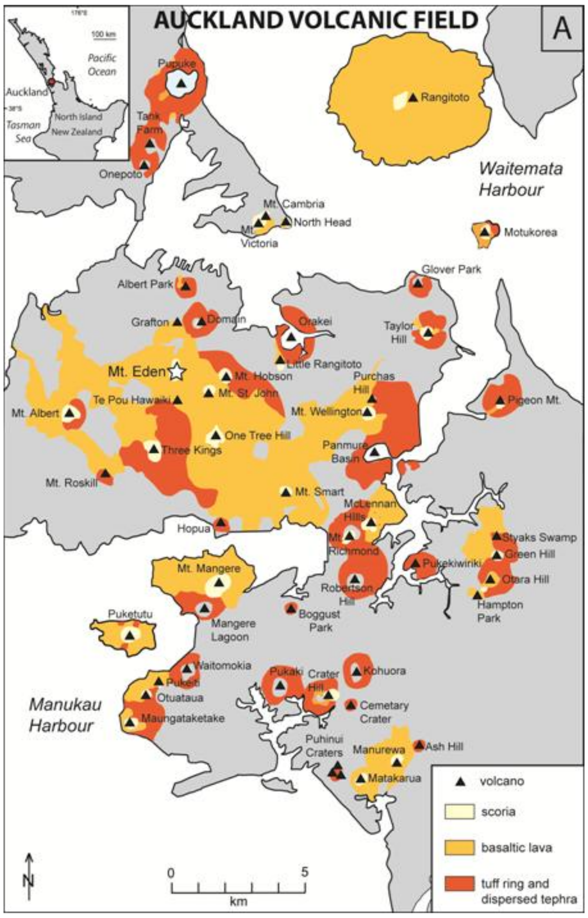

Figure 1: (A) Map of Auckland Volcanic Field (©modified from Lindsay et al. (2011); star indicates location of Mt Eden. (B) View of Mt Eden looking to the north highlighting the complete overlap of AVF and city (© Auckland Council).

[1]Equivalent to volume of 800,000 Olympic size pools.

(Ministry of Civil Defence and Emergency Management, 2008)The DEtermining VOlcanic Risk in Auckland (DEVORA) program is a 7 year multi-agency research program launched in November 2008. DEVORA was established following Exercise Ruaumoko, a 2007-2008 national Cabinet-lead Civil Defence exercise simulating an AVF eruption, in part to address knowledge gaps revealed by the exercise (Ministry of Civil Defence and Emergency Management, 2008). It is co-led by GNS Science (New Zealand's geologic survey) and the University of Auckland, with associated researchers at Massey University and the University of Canterbury. It is funded by these organisations, the Earthquake Commission (national government), and Auckland Council (local/regional government). The DEVORA program has a mandate to investigate the geological context of the AVF, volcanic hazards, and risk posed by the AVF, as reflected by the three themes organising the program (Figure 2), listed below along with key questions:

1) Theme 1: Geological Model
    - Where is AVF magma coming from?
    - Why does it leave its source?
    - What controls the path of magma in the crust?
    - Where will the magma reach the surface?
    - What is the crust underlying the AVF made of?
    - Why is the most recent eruption the largest?
    - How fast will magma travel to the surface?
    - When will we detect the ascending magma?

2) Theme 2: Probabilistic Volcanic Hazard Model
    - What is the distribution in time of past eruptions affecting Auckland?
    - What is the likelihood and size of future eruptions affecting Auckland?
    - What are likely styles and hazards of future eruptions?
    - Where are we in the lifespan of the AVF?
    - How do we usefully calculate probabilistic volcanic hazard for Auckland?
    - What is the probabilistic volcanic hazard?
    - How intensive should the monitoring be to provide adequate warning of an AVF eruption?

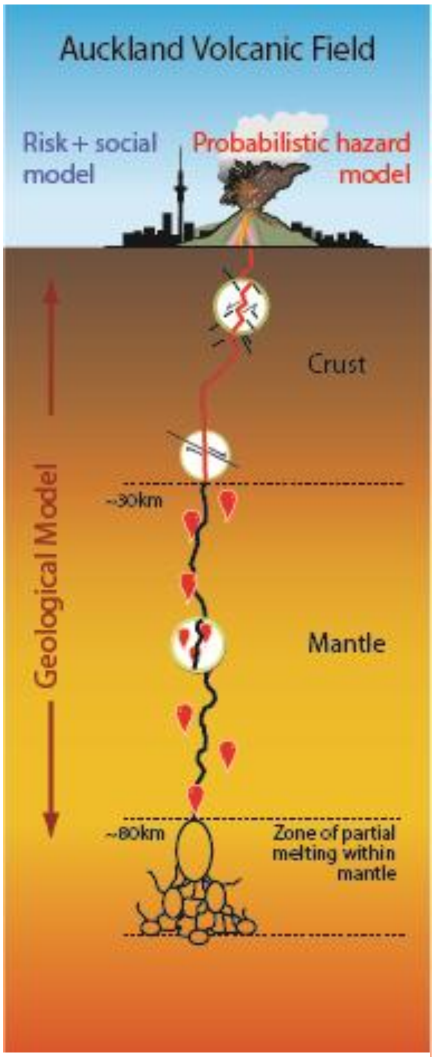

Figure 2: Scope of DEVORA themes.

3) Theme 3: Risk and Social Model for Auckland
    - Who and what are exposed to volcanic hazards in Auckland?
    - How will each hazard affect people and infrastructure?
    - How will people and organisations cope in an eruption?
    - What are the flow-on effects nation-wide from an eruption affecting Auckland?
    - How can we calculate risk to people and infrastructure?
    - What are the risks to people and infrastructure?
    - How can these risks be reduced?
    - How can people and organisations prepare to respond effectively to warnings?

To ensure that DEVORA outputs are useful not just scientifically but practically, government representatives sit on the DEVORA steering committee, which charts and directs DEVORA efforts. Furthermore, there is an annual research forum open to Auckland Council and Civil Defence staff and representatives from critical infrastructure and utility organisations. Here, recent findings and ongoing research are presented. This strengthens communication between scientists and decision makers, and enables policy to be informed by the most recent scientific findings. Indeed, the Auckland Volcanic Field Contingency Plan, the policy document which details response arrangements should an AVF eruption occur, has been recently reviewed and updated in close consultation with DEVORA scientists. Additionally, through DEVORA, University of Auckland students and the Auckland Civil Defence team participate in an annual informal mock eruption exercise. A longitudinal study is planned to compare public risk perception in 2008 and now, and will evaluate effectiveness of the DEVORA and associated programs in improving public understanding of AVF hazards and risk.

As of the first quarter of 2014, 7 Masters and 11 PhD projects have been at least partially supported by DEVORA, over 180 presentations have been given at scientific conferences, and over 80 papers have been accepted or published in a range of peer-reviewed scientific journals. Sample titles of published papers include:

- *Asthenospheric control of melting processes in a monogenetic basaltic system: a case study of the Auckland Volcanic Field, New Zealand* (McGee et al., 2013);
- *Age, distance, and geochemical evolution within a monogenetic volcanic field: Analysing patterns in the Auckland Volcanic Field eruption sequence* (Le Corvec et al., 2013);
- *Longevity of a small shield volcano revealed by crypto-tephra studies (Rangitoto volcano, New Zealand): change in eruptive behaviour of a basaltic field (Shane et al., 2013);*
- *Amplified hazard of small-volume monogenetic eruptions due to environmental controls, Orakei Basin, Auckland Volcanic Field, New Zealand* (Németh et al., 2012);
- *LiDAR-based quantification of lava flow susceptibility in the City of Auckland (New Zealand) (Kereszturi et al., 2012)*;
- *Some challenges of monitoring a potentially active volcanic field in a large urban area: Auckland Volcanic Field, New Zealand (Ashenden et al., 2011)*;
- *The communication of uncertain scientific advice during natural hazard events (Doyle et al., 2011)*;
- *Evacuation planning in the Auckland Volcanic Field, New Zealand: a spatio-temporal approach for emergency management and transportation network decisions* (Tomsen et al., 2014).

The breadth and scope of the DEVORA program has produced not only invaluable scientific outputs that advance scientific understanding of volcanic fields, but also important and applicable information for government policy makers and risk and emergency managers. As such, DEVORA is a model for the production of scientific research for science and society, resulting in strengthened ties between scientists and practitioners. Although the location, timing, and size of the next eruption is unknown, and an AVF eruption will be unwelcomed due to its highly disruptive nature, Auckland and New Zealand will be as best prepared as possible given the high uncertainty of such an event.

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CS3. Tephra fall hazard for the Neapolitan area

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The Neapolitan area is one of the highest volcanic risk areas in the world, both for the presence of three potentially explosive and active volcanoes (Vesuvius, Campi Flegrei and Ischia), and for the extremely high exposure (over a million people located in a very large and important metropolitan area). Even though pyroclastic flows and lahars represent the most destructive phenomena near the volcanoes, tephra fall poses a serious threat on a wider spatial scale. Excess of tephra loading can cause building collapse, disrupt services and lifelines, and severely affect agriculture and human health. On a larger spatial scale, tephra fallout may cause a major disruption of the economy in Europe and in the Mediterranean area (Folch and Sulpizio, 2010, Sulpizio et al., 2012).

The volcanic *hazard* is the way in which scientists quantify such a kind of threat. The hazard is usually expressed in probabilistic terms in order to account for the vast irreducible (aleatory) and reducible (epistemic) uncertainties. In the past several papers focussed on the assessment of tephra fallout hazard from Neapolitan volcanoes (e.g. Barberi et al. (1990), Cioni et al. (2003), Costa et al. (2009), Macedonio et al. (1990)). These studies have combined field data of tephra deposits and numerical simulations of tephra dispersal (often considering tens of thousands of wind profiles to account for wind variability) to produce maps for the expected tephra loading in case of a specific scenario (e.g. considering one specific kind of eruption), or of a few reference scenarios at both Mount Vesuvius and Campi Flegrei.

This kind of map is still frequently used in volcanology, however they do not represent the real volcanic hazard, because they do not consider the probability of occurrence of the specific scenarios considered, and they neglect a large part of the natural variability, such as the possibility to have eruptions of different size and from different vents. The latter is particularly important for the Campi Flegrei caldera, where the largest source of uncertainty comes from the forecast of the next eruption location. From a more technical point of view, these studies do not properly incorporate all known aleatory and epistemic uncertainties. This aspect is of primary importance in order to get a reliable volcanic hazard assessment.

The need to have a realistic volcanic hazard analysis is not only important from a scientific perspective, but it is of paramount importance for risk mitigation. Any sound (and defensible) risk assessment and mitigation plan has to be based on a reliable volcanic hazard analysis. In practical terms, the costs and benefits of any possible mitigation option have to be weighted and compared with the probability of occurrence of the wide range of possible threats, i.e., with the volcanic hazard. Any decision making based on single scenarios without considering their probability of occurrence cannot lead to any rational and defensible risk mitigation plan, in particular for high risk areas.

The need to use the best available science for helping society to mitigate the high volcanic risk in the Neapolitan area pushed volcanologists to develop innovative tools for volcanic hazard analysis in probabilistic terms, the so-called Probabilistic Volcanic Hazard Analysis (PVHA). The attempt is to move toward hazard assessment formats that are similar to other kinds of hazards, such as, for example, the seismic hazard. Following the results of Costa et al. (2009), Selva et al. (2010) assessed tephra fallout hazard at Campi Flegrei attempting to overcome some of the limitations described above. In particular they accounted for the most important sources of uncertainty and natural variability in the eruptive processes due to many different possible scenarios (represented by a discrete number of eruptive scales, and vent positions), and statistically combining the contribution to the final PVHA from all the possible scenarios, making use of the law of total probability.

In order to provide information to the engineers to move from hazard to risk assessment we need to shape the hazard output in a way that can be easily combined with the fragility curves that represent how a building can be damaged as a function of the different intensities of the different volcanic threats (e.g. Spence et al. (2005), Zuccaro et al. (2008), Zuccaro and Leone (2011)).

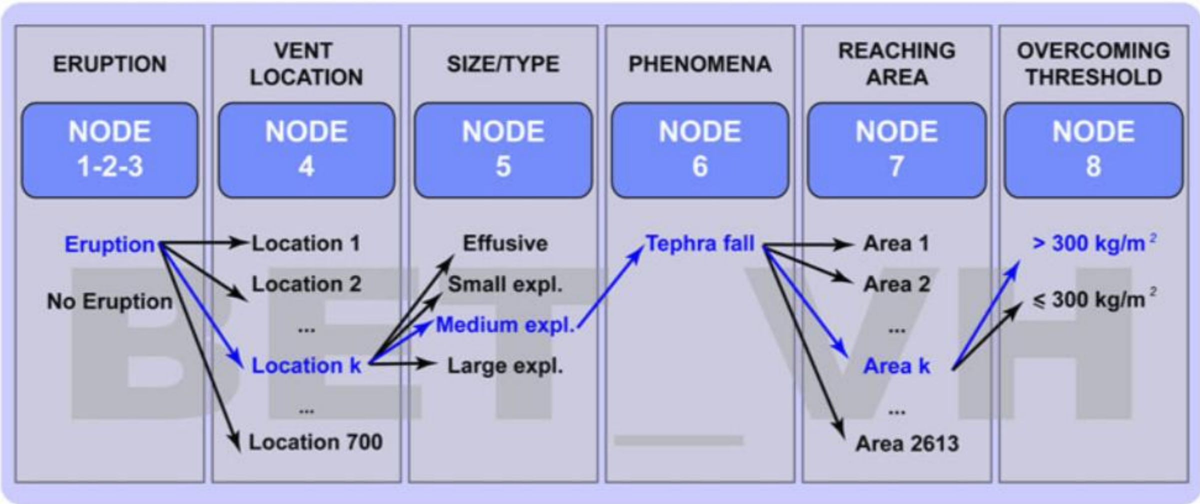

Figure 1*: Event tree of the model BET_VH for a specific volcano to evaluate the PVHA for tephra fallout above 300kg/m^2*

One of the currently adopted methodologies is based on the BET_VH tool (Marzocchi et al. (2010); https://vhub.org/resources/betvh) that performs a proper statistical mixing of the different possible scenarios, further extending the work made by Selva et al. (2010). Such an open source tool, being based on Bayesian inference modelling, properly accounts for the aleatory (intrinsic) and epistemic (linked to our limited knowledge of the eruptive process) uncertainty, propagating these two all along the different factors of PVHA. PVHA and related uncertainties are described by a probability density function instead of by a single value. This gives the interested stakeholders an idea about the confidence of the probabilities we are providing. The analysis for the volcanic hazard posed by tephra is based on an *event tree* (see Figure 1). An event tree is a branching graph representation of events in which individual branches are alternative steps from a general prior event, state, or condition, and which evolve through time into increasingly specific subsequent events. Eventually the branches terminate in final outcomes representing specific hazards (or risks) that may occur in the future. In this way, an event tree attempts to graphically display all relevant possible volcanic outcomes in progressively higher levels of detail. Points on the graph where new branches are created are referred to as nodes. In BET_VH all uncertainties can be assessed at each level, namely on the eruption occurrence, on vent position, on the eruptive scale, on the production of tephra and on its transport, dispersal and deposition by the wind. The BET_VH tool has been used in other volcanic areas to produce a full PVHA for tephra fallout and other volcanic hazardous phenomena (Sandri et al., 2012, 2014).

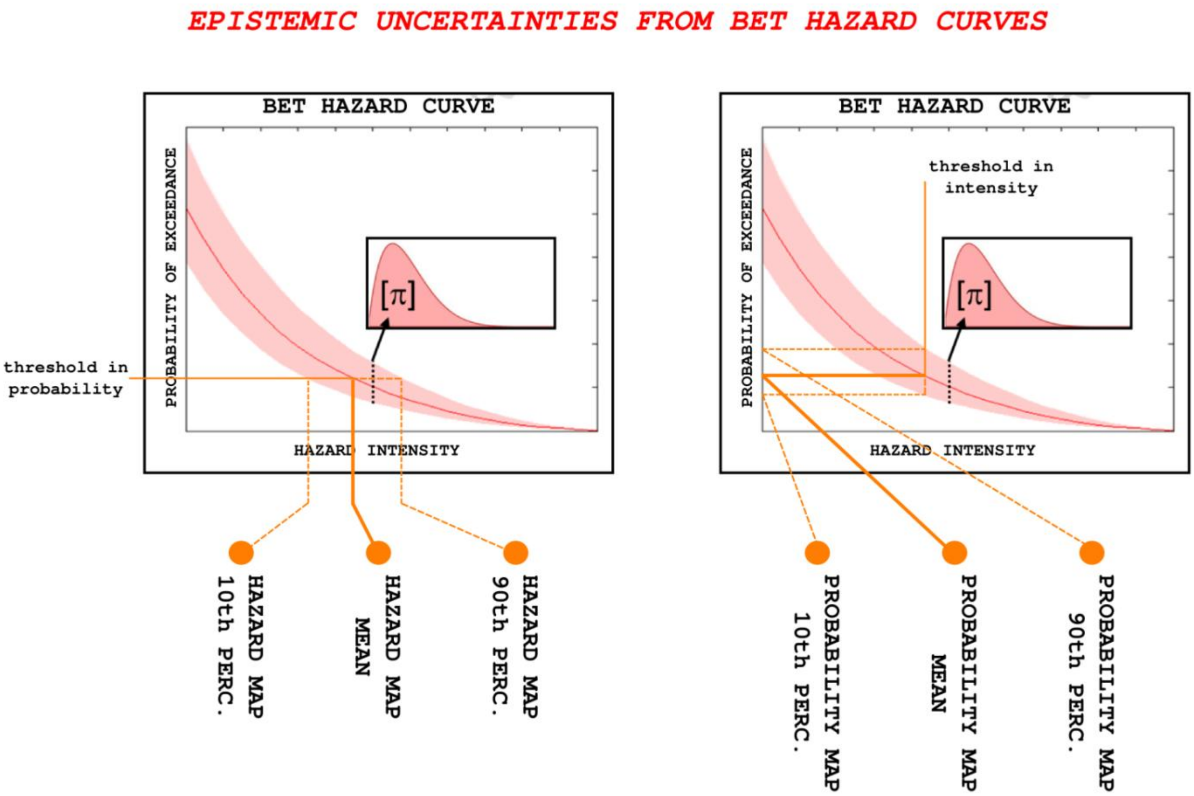

***Figure 2**: Example of hazard curve for a given target cell of the gridpoint. On the x-axis reports the different threshold of the intensity measure (tephra load in our case). On the y-axis reports, the computed exceedance probability of such intensity thresholds in a given time window and a given target position. The shaded area shows the 10-90-th percentiles confidence interval of the hazard curve. Cutting the curves horizontally (left panels), we obtain the hazard intensity for a given exceedance probability value (basic ingredient of hazard maps). Cutting them vertically (right panel) we obtain the exceedance probability for a given intensity value (basic ingredient of probability maps). Given hazard curves at each position in a target area, maps can be produced at different levels of confidence (e.g., mean, 10th and 90th percentiles), showing the effects of epistemic uncertainties on either hazard (left panel) and probability (right panel) maps. (Modified from Selva et al. (2014)).*

An ongoing improvement of the method aims at performing the production of fully probabilistic hazard curves (see Figure 2), estimating the exceedance probability of a set of thresholds in tephra load, based on the method proposed for seismic hazard by Selva and Sandri (2013) Indeed, hazard curves represent the most complete information about the hazard, and they allow volcanologists to produce proper hazard maps at different levels of probability (SSHAC 1997), as shown in Figure 2. The proposed method can be used in both long- (years to decades) and short- (hours to weeks) perspectives (e.g. Marzocchi et al. (2008), Selva et al. (2014)). For the volcanoes threatening the Neapolitan area, several papers have already taken some steps in the direction of estimating some of the node probabilities reported in Figure 1 for both long- and short-term hazard. For Vesuvius, Marzocchi et al. (2004), (2008) estimated the factors probabilities of the first five nodes of the event tree of figure 1, while Macedonio et al. (2008) provided an estimation of the best guess probabilities for nodes 7 and 8. For Campi Flegrei, the probability distributions for the first five nodes have been respectively estimated by Selva et al. (2012a), Selva et al. (2012b) and Orsi et al. (2009), while Costa et al. (2009) provided an estimation of the best guess probabilities for nodes 7 and 8 in two possible vent locations (Eastern and Western parts of the caldera). Merging all these factors in a full comprehensive volcanic hazard analysis for tephra fall is one of the main goals of the ongoing research.

The results obtained so far include the PVHA for tephra fallout conditional to the occurrence of specific eruptive scenarios, i.e. the probability maps conditional to the occurrence of eruptions of specific sizes at Vesuvius (e.g. Macedonio et al. (2008)) and Campi Flegrei (e.g. Costa et al. (2009)). Figures 3 show some of these maps. A significant improvement for Campi Flegrei was achieved by the proper mixing of all the possible eruptive sizes and vents, conditional to the occurrence of an eruptions, performed by Selva et al. (2010), computed by accounting for the different possible vent locations Selva et al. (2012b), eruption sizes (Orsi et al., 2009), and the probability distribution for the nodes 6, 7 and 8 (see Figure 4). In this respect, this kind of approach is particularly useful for large and potentially very explosive calderas, such as Campi Flegrei, for which the position of the vent is critical and it imposes a large uncertainty on the final PVHA.

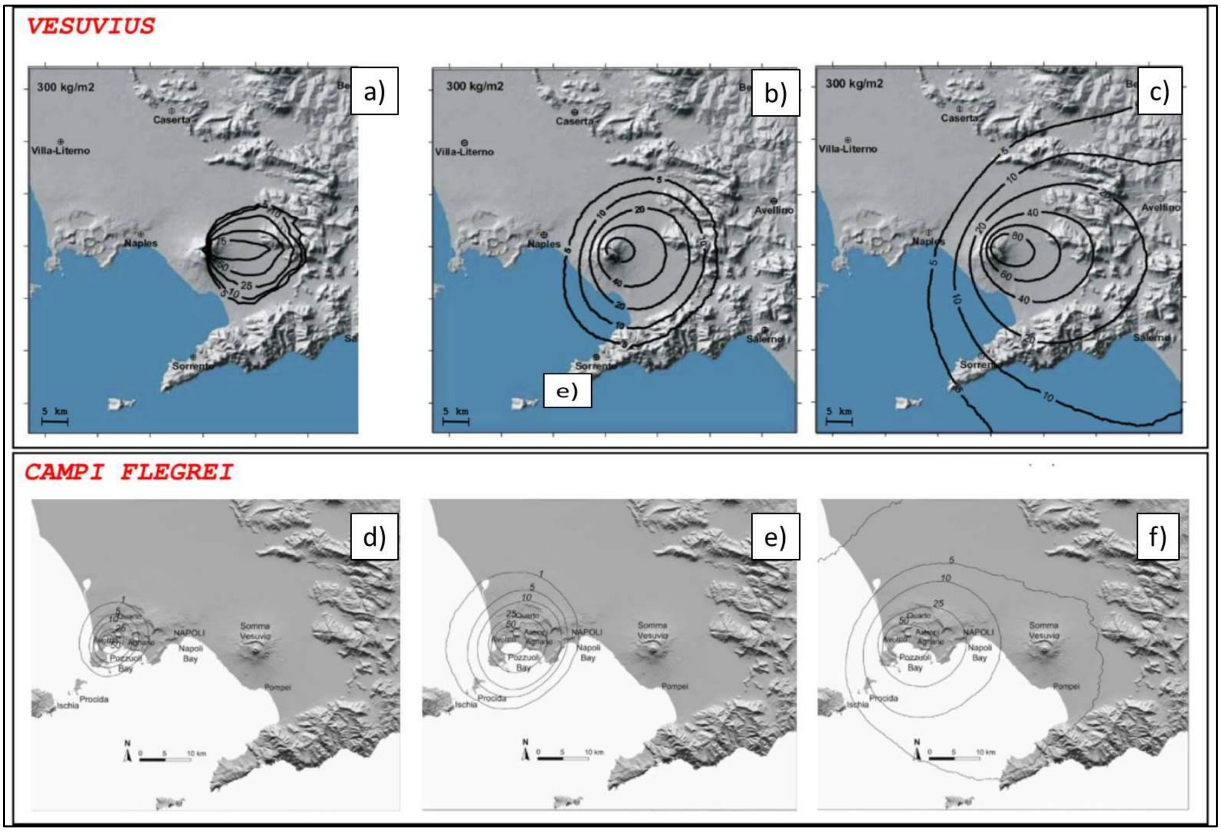

***Figure 3**: Results for tephra fallout probability of overcoming 300 kg/m^2 given the occurrence of an eruption of size Violent Strombolian (a), Subplinian (b) and Plinian (c) at Vesuvius (Macedonio et al., 2008), and of size low (d), medium (e) and high (f) explosive, from the eastern vent (Averno-Monte Nuovo) at Campi Flegrei (Costa et al., 2009). Each map shows the hazard footprint of the event, enabling the user to assess areas under threat.*

Despite the recent significant steps ahead in achieving a full and comprehensive PVHA for tephra fall, much more work has still to be done. In two ongoing Italian projects (ByMur, 2010-2014, DPC-V1, 2012-2013), there have been attempts to provide further improvements in long-term PVHA for Vesuvius, Campi Flegrei and Ischia, by accounting for all the factors concurring to the full hazard. A preliminary merging of the full PVHA for tephra fallout posed by both Vesuvius and Campi Flegrei on the municipality of Naples is shown in Figure 5 (Selva et al., 2013). The variability of eruptive parameters within each size class must also be modelled, to evaluate its importance and impact on the final PVHA. The production of hazard curves, as mentioned above, is a necessary step if PVHA results are to be included into quantitative risk assessment procedures. The assessment of the epistemic uncertainty on the hazard curves represents the most complete results that we aim to achieve (Figure 4). The final PVHA for the municipality of Naples is planned to be ready for the end of the project ByMuR and it will consist of a hazard curves, at different level of confidence regarding epistemic uncertainties, for each cell of the grid covering the municipality of Naples.

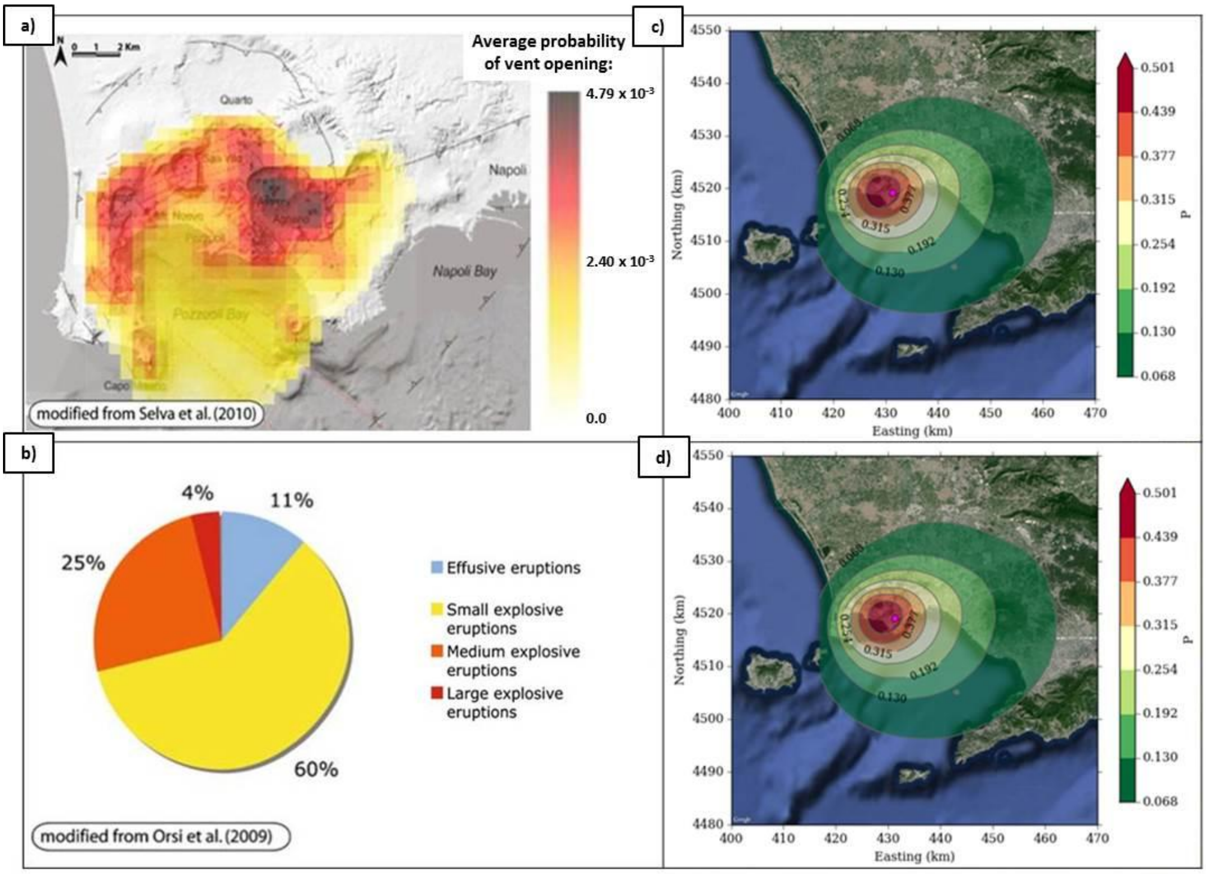

Figure 4*: a) mean probability of vent opening at Campi Flegrei (the notation '4.7E-03' means 4.7 x 0.001=0.047); b) mean probability of possible eruptive sizes at Campi Flegrei; c) mean probability of tephra fallout and of tephra loading larger than 0 kg/m^2; d) as for c) but relative to a tephra loading larger than 300 kg/m^2. The maps reported in panels a) and b) have been obtained by Selva et al. (2010) integrating the outcome of all possible scenarios – all possible size (panel b) and all possible vent opening (panel a) – with their own probability of occurrence.*

Regarding short-term PVHA in the Neapolitan area, two research projects (the Italian DPC-V2, 2012-2014, and the EC MEDSUV 2013-2015) aim at providing quantitative improvements for Vesuvius and

Campi Flegrei in order to reach its operational implementation for tephra fallout. This would represent a tool of primary importance during potential volcanic unrest episodes and for ongoing eruptions, being able to be updated frequently and accounting for the rapidly evolving situation and providing crucial information for crisis management. Theoretically, short-term PVHA should be based on sound modelling procedures stemming from frequently updated meteorological forecast and information about the crisis evolution (Selva et al., 2014). In addition, the relevance of epistemic uncertainties arising from the forecast of the future eruption dynamics and wind conditions, and from the tephra dispersal model, should be estimated.

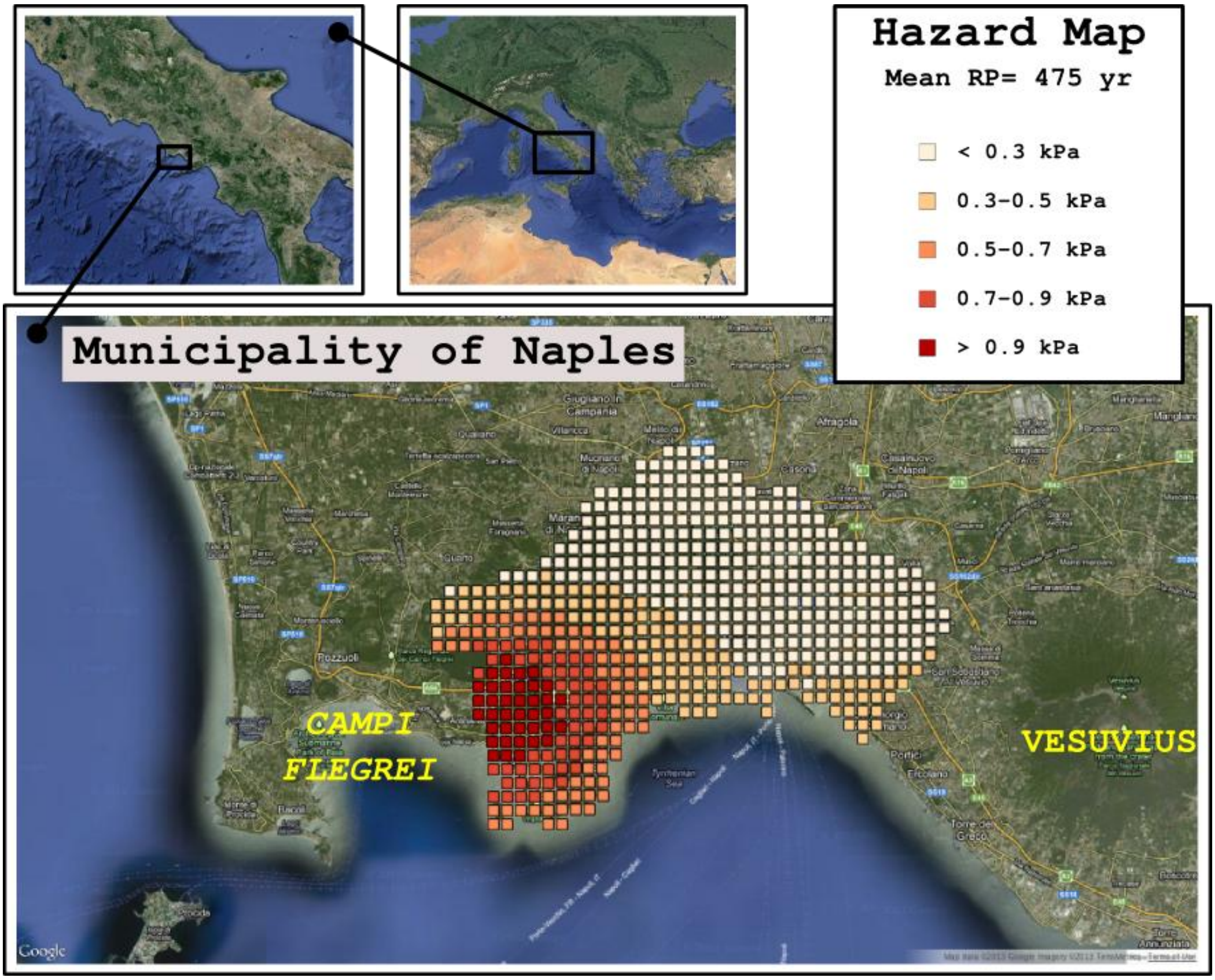

Figure 5: Hazard map (mean) for tephra loading with a return period of 475 years (exceedance probability threshold equal to 0.1 in 50 yr), considering both Vesuvius and Campi Flegrei on the municipality of Naples. In the legend 1 kPa stands for 1000 Pascal (or 0.1 bar).

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CS4. Eruptions and lahars of Mount Pinatubo, 1991-2000

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Mount Pinatubo (Philippines) – asleep for ~ 500 years – began to stir in mid-March 1991, and produced a giant eruption on 15 June 1991, 2nd largest of the 20th century. Only that of remote Katmai-Novarupta, Alaska in 1912 was larger. About 20,000 indigenous Aeta lived on the volcano, and ~1,000,000 lowland Filipinos lived around it. Two large American military bases, Clark Air Base and Subic Bay Naval Station, added about 40,000 Americans to those at risk. With centuries' of volcanic gas (supply) accumulated in tens of cubic kilometres of molten rock (magma), and with so many innocent people nearby, a disaster was waiting to happen.

Thick deposits from pumice-rich pyroclastic flows formed the lower slopes of the volcano and told a history of infrequent but very large eruptions -- larger than any eruption in the history of modern volcano monitoring. Scientists warned that a giant eruption was possible, perhaps even likely, but none had ever been monitored, much less successfully forecast. For two months after the volcano began to stir, small earthquakes and other signs fluctuated without clear, systematic trends. The volcano was teasing the scientists, and the public was profoundly sceptical.

Against the odds, a team of scientists from the Philippine Institute of Volcanology and Seismology (PHIVOLCS), assisted by the US Geological Survey, correctly forecast a giant eruption. Evacuations that had been recommended earlier were now enforced and expanded. Over the course of a few days, small precursory eruptions escalated to a spectacular climax on 15 June that swept the whole volcano, killing virtually everything in its path. Avalanches of searingly hot ash and pumice (pyroclastic flows) filled valleys and swept over ridge crests. Tens of centimetres of ash, with weight nearly doubled by rain from simultaneous Typhoon Yunya, caused many roofs to collapse. Loss of life was relatively modest considering the population at risk and the enormous size of the events (~400 died during the eruption, and ~500 Aeta children died in evacuation camps from measles). Warnings, coupled with strong visible clues from pre-climactic eruptions, had saved nearly all of the Aeta population, plus an unknown number of lowlanders. Some damage was unavoidable, but much was also averted, especially damage to military assets and commercial jets.

What factors worked for successful mitigation of the eruption risk?

- Pinatubo, and other long-dormant volcanoes, give plenty of warning signs. The challenge is to read them correctly, and to time the warnings to be early enough for evacuation but not so early that people give up and return home. With no precedent monitoring of such a large eruption elsewhere, and no prior monitoring of Pinatubo, the scientific team just barely managed to install enough instruments, collect and interpret the data, educate those at risk, and to give the right warnings at the right time. Fortunately for all, the volcano gave scientists two months in which to work and in early June gave signs that the eruption was just days away.
- PHIVOLCS had a quick-response team that started work at Pinatubo in earliest April, and captured critical early data. The US Geological Survey also had a team of volcano scientists

and technicians, experienced, fully equipped and ready to help. The latter team had been formed after the disaster at Nevado del Ruiz in Colombia just a few years earlier, and was supported by USAID's Office of Foreign Disaster Assistance. Together, the two teams accomplished what neither team by itself could have accomplished. When Nature presents an enormous challenge, rapid, joint, international responses may be necessary.

- Although public and even official scepticism was a huge challenge, trust between key scientists and officials offset that scepticism. The longer a volcano has been quiet, the less people know about it, and the more sceptical they will be. Scientists (led by the late Raymundo Punongbayan of PHIVOLCS) and officials – some who had known each other for years and some who were new-found friends – prepared for the crisis as a team and developed the trust that was needed for critical mitigation decisions. Trust in other circles – e.g., between missionaries and the indigenous people – also helped greatly.
- That the Philippines already had protocols and procedures for evacuations ahead of typhoons and floods, and even for volcanoes elsewhere in the Philippines, also helped to offset local unfamiliarity and scepticism about Pinatubo. The hierarchy of national, regional, provincial, municipal, and village civil defence worked well. A similar hierarchy of command and hazard preparedness within the military had equally beneficial effects.
- Especially because of Pinatubo's long quiescence before 1991, very few people around Pinatubo understand anything about volcanoes and their hazards. The same had been true in Armero, downriver from Nevado del Ruiz, and unfamiliarity with volcanic hazards cost residents of Armero their lives. A hard-hitting video made by the late Maurice Krafft for the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) was wonderfully graphic, showing quickly in images what words could not describe. This video saved many lives. Video worked where words would have failed. *(Ironically and at the same time, Maurice and his wife Katia, dissatisfied with the footage of pyroclastic flows in this video, stopped by Unzen Volcano to get better footage, and they and 41 others were sadly killed).*
- Scientists are by training cautious about making forecasts. Invariably, they wish for more data. But during a crisis, advice must be given no matter how high the uncertainties. Ray Punongbayan and his colleagues set aside their normal caution, explained the uncertainties, and gave their best guesses. They made forecasts where others might have feared to tread. Obviously, caution and an all-out search for reliable data are important, but when Nature signals that a hazard is imminent, scientists must speak out.
- Those at risk can be diverse, and require an equal diversity of communication approaches. Some of those at risk responded best to "Trust me. Follow me." Others challenged us to convince them of the hazard. Military officers and engineers understood probability trees; others drew more from the IAVCEI video.
- Many – indeed most – of those at risk waited until the last possible moment before evacuating. Yes, many were sceptical. And yes, few people wanted to evacuate even if they knew they should. Although the plan called for evacuations at Alert Level 4, very few moved because the hazard wasn't yet in their face. Two messages by example helped. First, scientists moved themselves from the centre of Clark Air Base to the far perimeter of the base, and base commanders took notice. Second, when Americans from Clark Air Base left town, Filipinos in neighbouring towns also took notice.

Beginning during the eruption, and continuing for a more than a decade thereafter, rain-triggered volcanic mudflows (lahars) buried large areas around the foot – including many towns up to 40 km away – with an average of 5-10 m of sand and gravel. Unlike floods that come and go, lahars come … and stay. Of roughly 6 million cubic meters of deposit on the volcano slopes, more than half was washed into the surrounding lowlands over the next 10 years. The scale of the hazard far exceeded normal sediment control measures. More than 200,000 people were "permanently" displaced, though by 2014 some have returned and built new homes on top of the lahar deposits. Within just a few years, costs of lahar damage and mitigation exceeded the ~ USD 2B damage from the eruption itself.

Again, in spite of the enormous scale of the lahar hazard, only about 400 were killed by lahars. Scientists set up high-tech warning systems with radio-telemetered rain gauges and flow meters. For lahars, the PHIVOLCS-USGS team was joined by a team from the University of the Philippines and University of Illinois-Chicago. Kelvin Rodolfo of the university team introduced the Indonesian word “lahar” which, because it is foreign, became a good educational tool. Police set up manned lahar watchpoints. More videos were shown. Time and again, warnings were sounded, towns were evacuated, and most people survived. In addition to warning systems, engineers built an elaborate set of levees (dikes) and sediment catchment structures. Early structures were too optimistic, getting filled or overrun quickly, but eventually, the increasing scale of the engineered structures matched the decreasing scale of hazard. Some of the waste was inevitable, as there was public pressure to act even before the full scale of the problem was understood. Some additional waste might be charged to politics and corruption. Debate about whether to spend for dikes or spend for relocation of towns was generally cut short, either by normal human reluctance to abandon one’s home, or by lahars themselves. Much of the engineering mitigation was financed by the central government; overseas development aid financed additional studies and construction in selected watersheds.

Estimated costs for the pre-eruption scientific response (mainly, helicopter time and equipment that was destroyed and had to be replaced) were approximately USD 1.5 million; for preparation of scientists over the preceding decade ~15 million and for pre- and syn-eruption evacuations ~USD 40 million. Compare these costs to roughly 10,000 lives saved and hundreds of millions of dollars of damage averted. Clearly, maintenance of quick response teams and the warnings they gave were cost effective.

The cost-effectiveness of lahar mitigation was not as clear. Costs of scientific response were roughly USD 2M and lahar control structures plus temporary and relocation housing cost at least USD 700M of government outlays. Damage to the town of Bacolor, sandwiched by sediment control levees, should also be counted as a cost of mitigation. Savings might include other towns, e.g., Bamban, Guagua, San Marcelino, Botolan, and the large city of San Fernando, but saving them from lahars has caused substantial flooding in subsequent years. A proper cost-benefit analysis of Pinatubo lahar mitigation would be of great interest.

Preparation time for the eruption was short, the scientific team was tight and spoke with one voice, and a relatively small number of political, civil defence, and military leaders made most of the decisions. The subsequent lahar crisis was much more complicated, with more scientists, more decision makers, and more time. Before the eruption, there was no time for debate; during the lahar period, there was lots of time for debate – between scientists, among engineers and policymakers, and between citizens of one town and the next. The result was that mitigation measures during the lahar period were more controversial, and probably more expensive than they needed to be, but in the end most people and towns were protected. It wasn’t perfect, and some bitterness still remains, but the overriding fact is that most people at risk survived and have been able to rebuild their lives.

Figure 1. Mount Pinatubo prior to the paroxysmal explosive eruption of 15 June 1991 (top) and after the eruption (bottom). Much of the edifice disappeared and became a caldera depression with a lake and many active steam vents.

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CS5. Improving crisis decision-making at times of uncertain volcanic unrest (Guadeloupe, 1976)

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Defining the problem

Scientists monitoring active volcanoes are increasingly required to provide decision support to civil authorities during periods of unrest. As monitoring techniques and their resolutions improve, the process of jointly interpreting multiple strands of indirect evidence becomes increasingly complex (Sparks and Aspinall, 2013). During a volcanic crisis, decisions typically have to be made with limited information and high uncertainty, on short time scales. The primary goal is to minimise loss and damage from any event, but social and economic losses resulting from false alarms or evacuations must also be considered (Woo, 2008). It is not the responsibility of scientists to call an evacuation or to manage a crisis; however, demands are increasing on them to assess risks and present scientific information and associated uncertainties in ways that enable public officials to make urgent evacuation decisions or other mitigation policy choices.

The 1975-1977 volcanic unrest at La Soufrière (Guadeloupe)

An increasing number of earthquakes were recorded and felt at La Soufrière one year prior the eruption, which began with an unexpected explosion on 8 July 1976. In the subsequent 9-month period, the volcano ejected about 2 million tonnes of old, cold volcanic ash and rocks in 26 explosions (Feuillard et al., 1983, Komorowski et al., 2005, Beauducel, 2006, Feuillard, 2011). Various volcanic gases (H_2O, minor CO_2, H_2S, SO_2) were also released during the eruption and led to moderate environmental impact with short-term public health implications (Figure 1), due to the presence of chlorine and fluorine in the vapour. A report that “fresh glass” was present in an ash sample, implying new magma was close to the surface, led to a major controversy among scientists that was widely echoed in the media (Fiske, 1984). With other evidence suggesting continued build-up of pressure in the volcano, this key observation – later found to be erroneous - and the uncertainty of possible transition to a devastating explosive eruption, led the authorities to declare an evacuation of ca. 70,000 people on August 15, which lasted 4-6 months. The evacuation had severe socio-economic consequences, which persisted long after the volcanic unrest had subsided. The costs have been estimated as 60% of the total annual per capita Gross Domestic Product of Guadeloupe in 1976, excluding losses of uninsured personal assets and open-grazing livestock. There were no fatalities, but this eruption stills ranks amongst the most costly of the 20th century (De Vanssay, 1979, Lepointe, 1999).

Figure 1: *Eruptive phenomena and impact of 1975-1977 volcanic unrest at La Soufrière (Guadeloupe). A) South-western flank of La Soufrière volcano showing the new fracture cutting the dome to the right which formed at the onset of eruptive activity of 8 July 1976. This fracture produced copious amounts of volcanic ash and gases that impacted the vegetation downwind (left). B) Volcanic ash covering cars in the village of Saint-Claude, 3 km southwest of the summit, in July to August 1976. C) People evacuating from the Saint-Claude area with belongings on 15 August 1976. D) View looking north from the evacuated town of Basse-Terre, 9 km from the crater, showing an explosion on 4 October 1976 that produced belching clouds of gases and volcanic ash which descended the slopes and dispersed downwind to the west.*

Lessons learned

At La Soufrière, there was a lack of a comprehensive monitoring network prior to the 1976 crisis, limited knowledge of the eruptive history of this particular volcano, and a tendency towards caution exacerbated by the memory of past devastating Caribbean eruptions. These factors all contributed to major scientific uncertainty and a polemical publically-expressed lack of consensus and trust in available expertise (Komorowski et al., 2005, Beauducel, 2006). The combination of markedly escalating and fluctuating activity, and societal pressures - in a small island setting - made analysis, forecasting, and crisis response all highly challenging for scientists and authorities. Prior to the crisis there was no well-founded, and accepted, volcanic emergency response plan, so the authorities were compelled to resort to a “precautionary principle” approach in the face of the uncertain evidence and the absence of scientific consensus on the likely outlook.

Pre-eruption, there was a policy to move the banana export port facilities of Basse Terre to the more sheltered economic capital Pointe-à-Pitre, and the evacuation reinforced this policy. This, in turn, contributed to the ravaging of the economy of the administrative capital, Basse Terre, and to its population's bitterness and feeling of being forsaken. The evacuation is still perceived by some as having been unnecessary and an exaggerated application of the "precautionary principle". Even now, many hold to the view that much of the risk assessment was exaggerated for political reasons.

In its overseas territory context, the volcanic crisis in 1976 became a metaphor for many accumulated socio-cultural frustrations on island, and engendered a distrust of science as a possible contributor to solving such issues. The public debate at the time became polarized on issues of opposing "truths", served up and contrasted by a few strongly opinionated scientific experts, rather than focussing on how science could help constrain epistemic and aleatory uncertainty and foster improved decision-making in the circumstances. Thus this infamous crisis exemplified the need for a structured and transparent approach to evidence-based decision-making in the presence of substantial scientific uncertainty.

A probabilistic approach to quantifying uncertainty

Similarities of volcanic unrest interpretation with uncertainties in medical diagnosis suggest a formal evidence-based approach can be helpful, whereby monitoring data are analysed synoptically to provide probabilistic hazard forecasts. A probabilistic tool to formalise such inferences is the Bayesian Belief Network (BBN) (Bedford and Cooke, 2001). By explicitly representing conditional dependencies (relationships) between the volcanological model and observations, BBNs use probability theory to treat uncertainties in a rational and auditable manner, to the extent warranted by the strength of the scientific evidence. A retrospective analysis is given for the 1976 Guadeloupe crisis by Hincks et al. (2014), using a BBN (Figure 2) to provide a framework for assessing the state of the evolving magmatic system and the probability of a future eruption. Conditional dependencies are characterised quantitatively by structured expert elicitation (Aspinall, 2006, Aspinall and Cooke, 2013).

Analysis of the available monitoring data suggests that at the height of the crisis the probability was high that magmatic intrusion was taking place, according with most scientific thinking at the time. Correspondingly, the probability of magmatic eruption was elevated in July and August 1976, and the signs of precursory activity were justifiably a cause for concern. However, as of 31 August 1976 collective uncertainty about the future course of the crisis was also substantial such that, of all the possible scenarios considered in the BBN, the marginally most likely outcome based on available observations was 'no eruption' (mean probability 0.5); the chance of a magmatic eruption, perhaps associated with a devastating volcanic blast, had an estimated mean probability of ~0.4 (Figure 3). There was, therefore, little or no evidential strength for asserting that one of these scenarios was significantly more likely than the other.

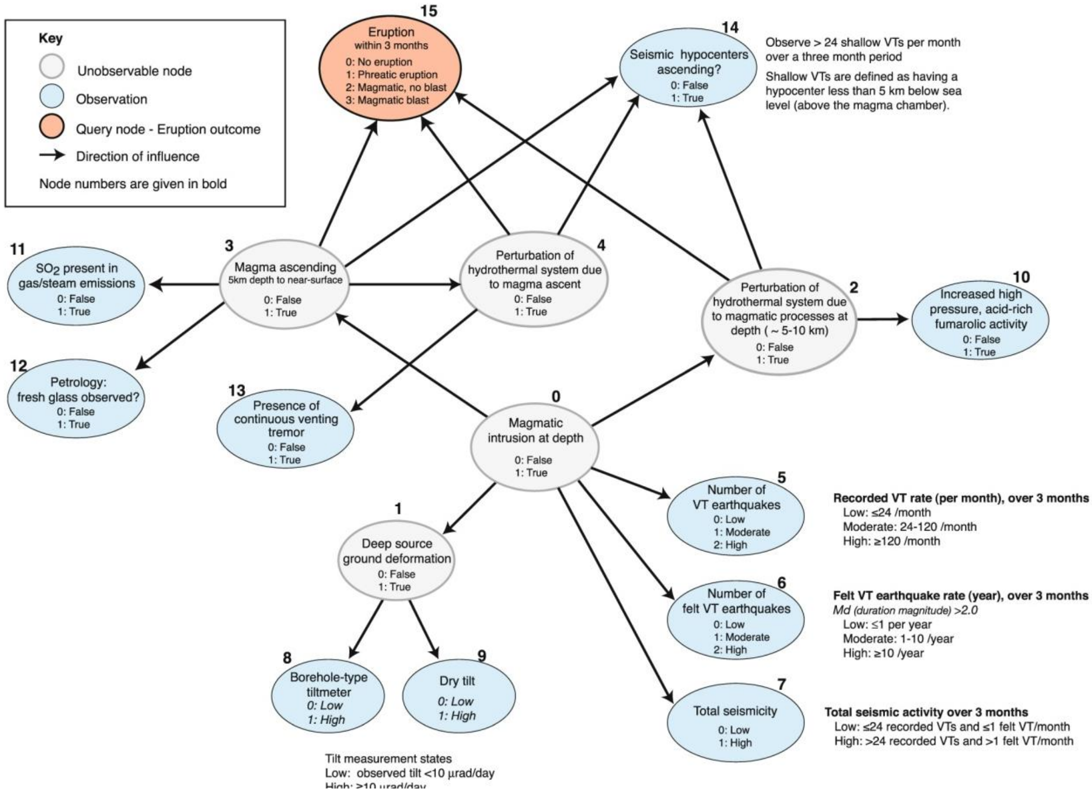

Figure 2: Retrospective Bayesian Belief Network (BBN) for La Soufrière (Hincks et al., 2014) showing the relationship between volcanic processes, states and observations available in 1976; used to make inferences about probabilities of future activity scenarios. Nodes represent both hidden (grey) and observable (blue) states. Arcs between nodes represent conditional dependencies (e.g. direct causal relationships or influence) and are characterised by conditional probability tables (CPTs). Arrows indicate the direction of influence. In this case, all conditional probability distributions (and associated uncertainties) were obtained by expert elicitation, the network structure being agreed by the group prior to elicitation.

A path towards improved decision-making during crises

The analysis by Hincks et al. (2014) provides objective probabilistic expression to the volcanological narrative at the time of the 1976 crisis. Indeed a formal evidential case, such as this, would have supported the authorities' concerns about public safety and their decision to evacuate. Revisiting the episode highlights many challenges for modern, contemporary decision-making under conditions of considerable uncertainty, and suggests that the BBN is a suitable framework for marshalling multiple, uncertain observations, model results and interpretations.

More recently, mild but persistent seismic and fumarolic unrest since 1992 at La Soufrière volcano has prompted renewed interest in geologic studies, monitoring, risk modelling, and crisis response planning. Development of an advanced probabilistic formalism for decision-making could help quantify and constrain scientific uncertainty, and thereby assist public officials in making urgent evacuation decisions and policy choices should the ongoing unrest intensify in a lead-up to renewed eruptive activity.

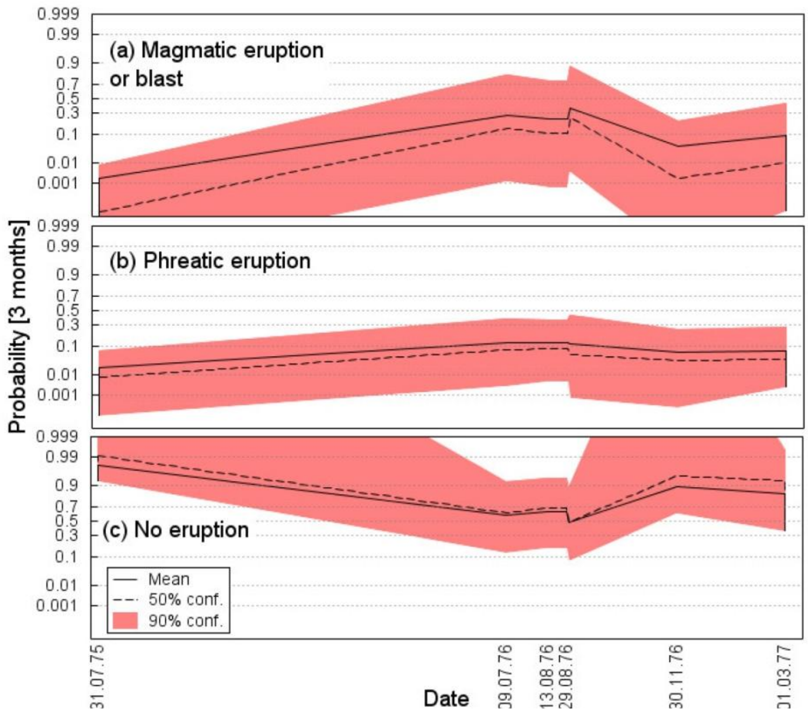

Figure 3: Temporal variations from July 1975 to March 1977 in BBN forecast probabilities for La Soufrière Volcano (Hincks et al., 2014), given observation states shown in the lower part of the figure: (a) a magmatic eruption or magmatic blast; (b) a phreatic eruption, or (c) no eruption. The unbroken black line denotes the expected (mean) probability estimate and the dashed line the median, as determined by Monte Carlo re-sampling of BBN input distributions; the shaded bands show the corresponding 5-95 percentile ranges, indicating the uncertainty in the forecast probability.

The BBN formulation (*Hincks et al. 2014)* can be developed further as a tool for ongoing use in volcano observatories and can be combined with other probabilistic tools (Newhall and Hoblitt, 2002, Marzocchi et al., 2008, Marzocchi and Bebbington, 2012). This approach is complemented by a progressive quantitative hazard and risk assessment approach (CASAVA project: http://sites.google.com/site/casavaanr/home) that considers: (a) interdisciplinary determinations of infrastructural, human, systemic and cultural factors; (b) social vulnerabilities, capacity and resilience, and (c) includes also the influence of risk perception and governance issues on disaster preparedness. This new work has implications for the way monitoring should be organised for Lesser Antilles volcanoes, and for how risk-informed decision-making in crisis response and long-term strategies of volcanic risk mitigation should be formulated.

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CS6. Forecasting the November 2010 eruption of Merapi, Indonesia

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Background

Merapi volcano, Indonesia (7.542°S 110.442°E) is one of the most active and hazardous volcanoes in the world. A large population settled on and around the flanks of the volcano is at risk. Over the past century eruptions were characterised by frequent small to moderate intensity eruptions, with pyroclastic flows produced by lava dome collapse. The most recent eruption in 2010 was of unusually high intensity. In late October and early November 2010, the volcano produced its largest and most explosive eruptions since 1872, displacing about 400,000 people, and claiming nearly 400 lives.

Monitoring

A seismic network has been in place on Merapi since 1982 to identify different kinds of earthquake that are informative about the potential for eruption. Deformation is measured using Electronic Distance Measurements (EDM) of line lengths from the flanks to reflectors near the summit, and (since 2010) also with Global Positioning Satellite (GPS) receivers. Sulphur dioxide gas (SO_2) is routinely measured at Merapi using ultraviolet absorption spectrometers. SO_2 is commonly chosen as the gas to monitor as the atmosphere normally contains only trace amounts so it is relatively easy to detect. During volcanic quiescence the SO_2 is typically emitted at less than 100 tons per day while the emissions can double or treble during small eruptions.

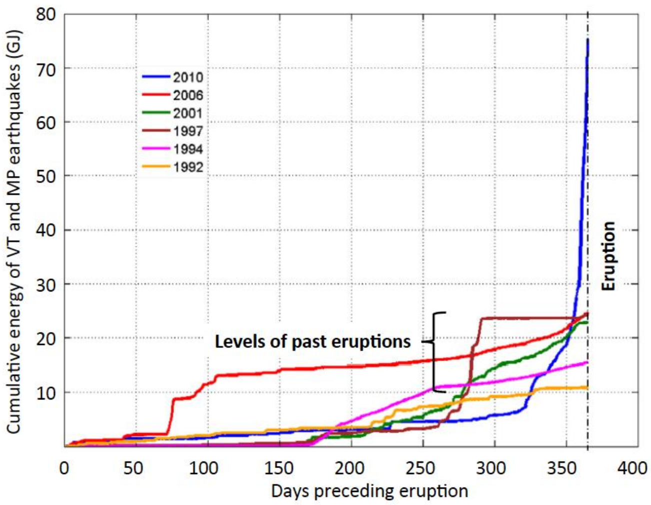

Figure 1. Cumulative seismic energy release of volcano-tectonic (VT) and multiphase (MP) earthquakes for eruptions of Merapi in 1997, 2001, 2006 and 26 October 2010. Modified from Budi-Santoso et al. (2013).

Forecasting the 2010 eruption

Despite the challenges involved in forecasting the 2010 'hundred year eruption', the magnitude of precursory signals (seismicity, ground deformation, gas emissions) was proportional to the large size and intensity of the eruption. Increasing numbers of earthquakes occurred at rates of tens to hundreds of events per day in the weeks before the October 2010 eruption. While increasing seismicity is not a definitive sign of impending eruption it provides an alert of increasing potential. As is common in many volcanoes the earthquakes were located at depths between a few kilometres and the surface. In late September, high levels of CO_2 in summit fumaroles provided early warning of magmatic replenishment. In late October 2010 a series of small phreatomagmatic eruptions took place, with associated SO_2 emissions of tens of thousands of tons per day and peaks in earthquake energy. The observations of exceptionally high gas emissions and high rates of summit deformation as determined with EDM data raised concerns further. In addition and for the first time, near-real-time satellite radar imagery played a major role along with the seismic, geodetic, and gas observations in monitoring and forecasting eruptive activity during a major volcanic crisis. The satellite data documented exceptionally rapid extrusion of a voluminous summit lava dome following the initial phreatomagmatic eruptions and before the climactic eruption on 5 November. Rates of extrusion during 1-4 November were an order of magnitude greater than seen at Merapi during past eruptions, and the resulting summit lava dome quickly reached a volume of ~5 million m^3, and was poised "ready to collapse" at the break-in-slope at the edge of the summit by 4 November.

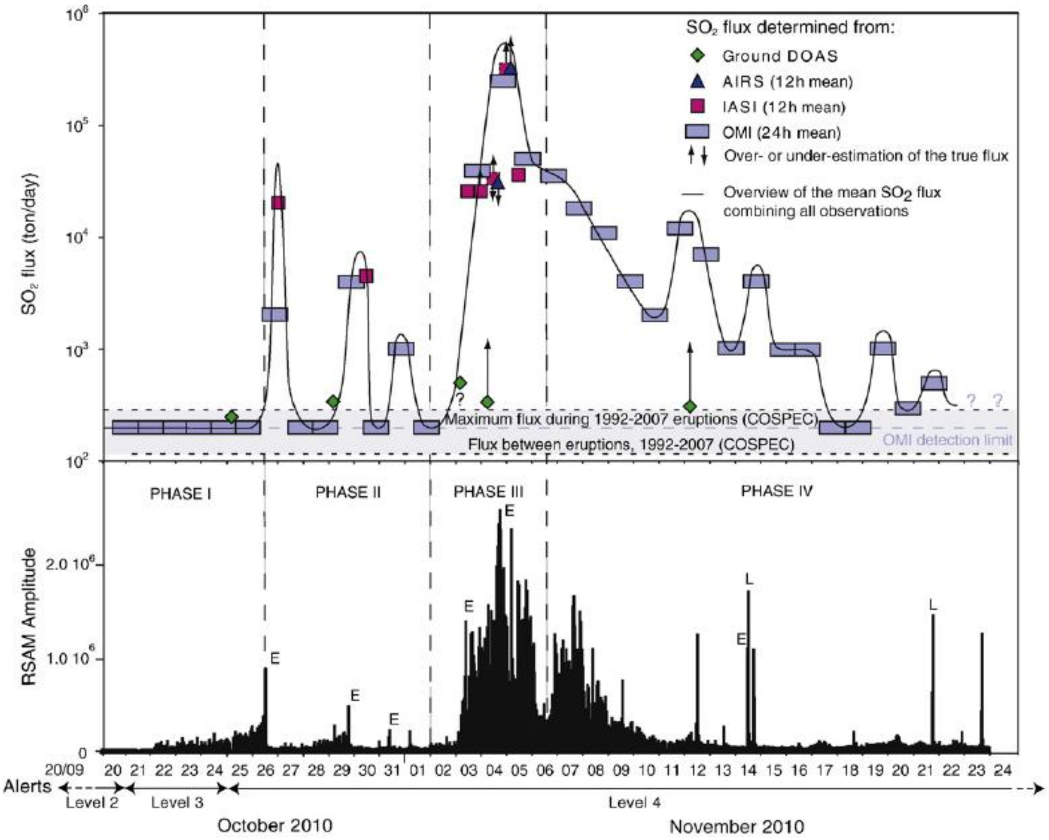

Figure 2. Variations in seismic energy (the RSAM amplitude) and SO_2 emissions in October and November 2010. Phases are phreatomagmatic explosive (I), magmatic (II), climactic (III) and waning (III), E marks eruptions and L marks volcanic mudflows (lahars). RSAM is Real-time Seismic Amplitude

Measurement, DOAS is Differential Optical Absorption Spectroscopy, satellite SO_2 measurements are by AIRS (Atmospheric Infrared Sounder), IASI (Infrared Atmospheric Sounding Interferometer) and OMI (Ozone Monitoring Instrument).

The monitoring data cited above played a key role in anticipating the major eruption of 5 November 2010. Marked escalation in summit deformation, seismic energy, SO_2 and CO_2 emissions, increased temperature of crater fumaroles, and the high extrusion rate of lava observed from satellites led to a major expansion of the evacuated zone [see CS7]. The Indonesian Center of Volcanology and Geological Hazard Mitigation (CVGHM) was able to issue timely warnings of the magnitude of the eruption phases, and evacuations organised by the Indonesian National Board for Disaster Management (BNPB), provincial and local emergency managers saved an estimated 10,000–20,000 lives [CS7].

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CS7. The importance of communication in hazard zone areas: case study during and after 2010 Merapi eruption, Indonesia

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Geological Agency of Indonesia, Indonesia

Merapi is one of the most active volcanoes in Indonesia (2948 metres, summit elevation). Eruptions during the 20th and 21th centuries resulted in: 1369 casualties (1930-1931), 66 casualties (1994) (Thouret et al., 2000), and 386 casualties (2010). The 2010 eruption had impacts that were similar to the unusually large 1872 eruption, which had widespread impacts and resulted in approximately 200 casualties (Hartmann, 1934). These casualties are considered to be a large number given the relatively sparse population in the late 19th century by comparison with the population density today.

The 5 November 2010 Merapi eruption affected 2 provinces and 4 regencies, including Magelang (west-southwest flank), Sleman (south flank), Klaten (southeast-east flank, and Boyolali (northern flank). The eruption led to the evacuation of 399,000 people and resulted in a total loss of US $3.12 billion (National Planning Agency, 2011-2013).

The large number of evacuees of Merapi in 2010 was due to warnings of an unusually large eruption – a warning that was based on precursors during the months to days preceding the eruption. These precursors included large increases in seismicity and deformation of the volcano's summit, high rates of dome extrusion, increased temperature of crater fumaroles (reaching 460°C by 20 October), and an abrupt increase in CO_2 at a summit fumaroles. During the time of crisis, there was rapid escalation in rates of seismicity, deformation and rates of initial lava extrusion. All the monitoring parameters exceeded levels and rates of change observed during previous eruptions of the late 20th century. Consequently, a Level IV warning was issued and evacuations were carried out and then extended progressively to greater distances as the activity escalated. The exclusion zone was extended from 10 to 15 and then to 20 km from Merapi's summit.

Indonesia applies 4 levels of warnings for volcano activity. From the lowest to highest: at Level I (Normal), the volcano shows a normal (background) state of activity, at Level II (Advisory) visual and seismic data show significant activity that is above normal levels, at Level III (Watch) the volcano shows a trend of increasing activity that is likely to lead to eruption, and at Level IV (Warning) there are obvious changes that indicate an imminent and hazardous eruption, or a small eruption has already started and may lead to a larger and more hazardous eruption. At Level III people must be prepared for evacuation and at Level IV evacuations are required. Figure 1 presents the chronology of warnings and radius of evacuations during the 2010 Merapi eruption (time increases from the bottom of the diagram upwards).

	ALERT LEVEL	DATES	RADIUS	ERUPTION
DECREASING	NORMAL	15-9-2011		
	ADVISORY	30-12--2010		
	WATCH	3-12-2010		
		4-11-2010	20 KM (11:00 UTC)	4 Nov. 17:05 UTC (16,5 km)
INCREASING		3-11-2010	15 KM (08:05 UTC)	3Nov. 08:30 UTC (9 km)
	WARNING	25-10-2010,	10 KM (11:00 UTC)	26-10-2010, (10:02 UTC)
	WATCH	21-10-2010		
	ADVISORY	20-9-2010		
	NORMAL	17 -9-2010		

Figure 1. Chronology of warnings and radius of evacuations during the 2010 Merapi eruption (time increases from the bottom of the diagram upwards). Distances given in the eruption column show extent of pyroclastic flows.

Following the first explosive eruption on 26 October 2010 and before the climactic eruption on 5 November, a lava dome was extruded rapidly (at rates of ≥25m^3/s, Pallister et al. (2013)). Explosive eruptions took also took place and were accompanied by pyroclastic flows. The lengths of pyroclastic flows increased from 8 km (26 October 2010) to 12km (3 November) and then to 16.5 km during the climactic eruption on 5 November.

The 2010 Merapi eruption offers an excellent lesson in dealing with eruption uncertainties, crisis management and public communication. Good decision making depends not only on good leadership, but also on the capabilities of scientists, good communication and coordination amongst stakeholders, public communication and on the capacity of the community to respond. All of these factors were in place before the 2010 eruption and contributed to the saving of many thousands of lives.

After the 2010 Merapi eruption with its large impact, revision of the hazard map was carried out to take into account the greater extent of eruption deposits and impacts compared to previous events in the 20th century. This map is the basis for the implementation of land-use planning and it is represented by the "Map of Impacted Area by Eruption and Lahar" (Peta Terdampak Erupsi dan Lahar), shown in Figure 2. The map delineates three hazard zones: Hazard Zone III (directly affected area (ATL)), which includes Forest Conservation/National Park Development areas with 'closed society settlement' (living in harmony with disaster/zero growth) and National Park and Protected Forest; Hazard Zone III indirectly affected area (ATTL), which includes National Park and Protected Forest; Hazard Zone II (not affected and intended for settlement but according to the land-use plan, highly controlled); and Hazard Zone I (area impacted by lahar). The width of restricted development in river overbank areas is decided by the Governor, and integrated into the Regency/City land-use plan.

Figure 2. Map of Impacted Area by Eruption and Lahar (Peta Terdampak Erupsi dan Lahar) (Source: Map by Center for Volcanology and Geological Hazard Mitigation, CVGHM, Aster Landsat, courtesy Franck Lavigne).

The hazard map was approved by the Ministry of Energy and Mineral Resources, Ministry of Public Work, Ministry of Forestry, National Plan Agency, Head of National Disaster Agency, Governor of Yogyakarta and the Governor of Central Java. The map of impacted area by eruption and lahar is the basis for Merapi land-use plan and the rehabilitation and reconstruction plan. The process has been supported by Ministry Decree of the Republic Indonesia No 16, 2011 (Ministry Decree of Republic Indonesia No 16, 2011, on Team of Coordination on Rehabilitation and Reconstruction of area post disaster of Merapi Eruption, in Yogyakarta Special Province and Central Java Province).

An action plan policy for rehabilitation and reconstruction includes the land-use plan as the basis for determination of secure locations for settlementas well as the design for relocated houses, which are constructed with a risk reduction approach. The map below (Figure 3) shows the location of temporary and permanent settlement in Sleman, Yogyakarta and the photos (Figure 4) show examples of permanent and temporary housing.

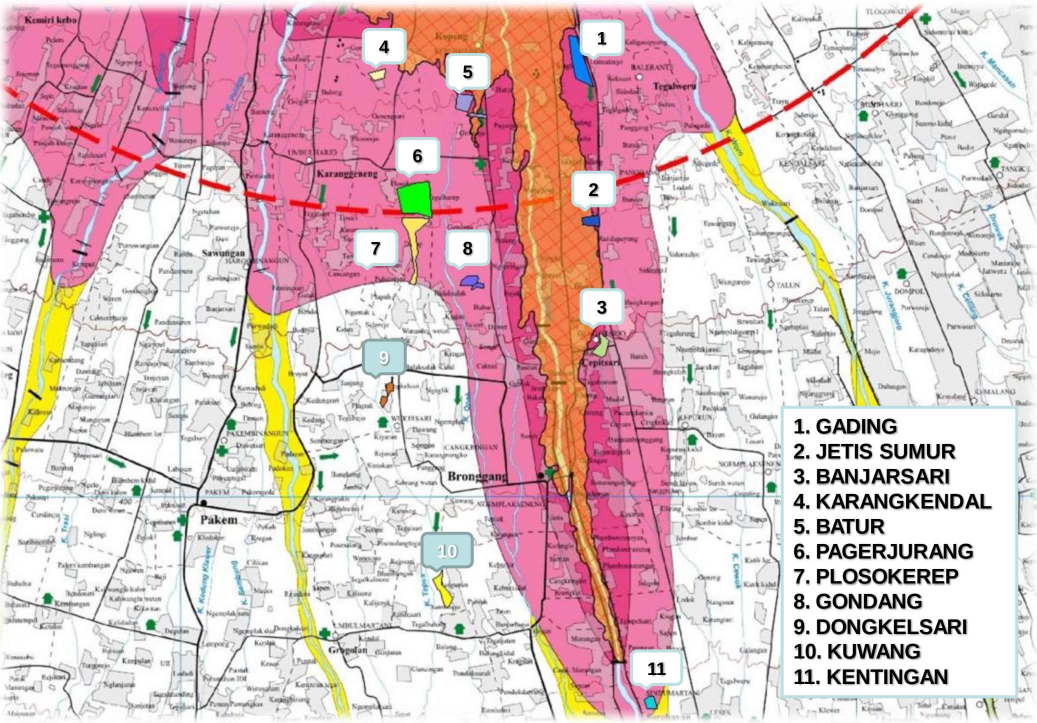

Figure 3. Map of Temporary and Permanent Settlement in Sleman, Yogyakarta (Source: Center for Volcanology and Geological Hazard Mitigation, CVGHM, 2011)

Figure 4. Air photo of temporary and permanent settlements of Dongkelsari, Plosokerep,Jetis-sumur, Gondang 2-3 (see map in Figure 3) (Source: Center for Volcanology and Geological Hazard Mitigation, CVGHM, 2012)

Impacts of Merapi eruptions on the human and cultural environment, livelihood and properties provide a lesson that in densely-populated areas around a volcano there is a need for regular review of hazard mitigation strategies, including spatial planning, mandatory disaster training, contingency planning and for regular evacuation drills. Merapi is well known for a capacity building program named wajib latih (mandatory training) required for people living near the volcano. The aim of this activity is to improve hazard knowledge, awareness and skills to protect self, family and community. In addition to the wajib latih, people also learn from direct experience with volcano hazards, which at Merapi occur frequently. However, the 2010 Merapi eruption showed that well trained and experienced people must also be supported by good management, and that training and mitigation programs must consider not only "normal" but also unusually large eruptions (Mei et al., 2013).

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CS8. Nyiragongo (Democratic Republic of Congo), January 2002: a major eruption in the midst of a complex humanitarian emergency

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Lava flows in town: the 17 January 2002 Nyiragongo eruption

Nyiragongo is a 3470 m high volcano located in the western branch of the East African Rift in the Democratic Republic of Congo (DRC), close to the border with Rwanda. It has a 1.3 km wide summit crater that has been filled with an active lava lake since 1894. The area is affected by frequent damaging tectonic earthquakes and by permanent passive degassing of carbon dioxide (CO_2). Fatal concentrations of CO_2 can accumulate in low-lying areas, threatening the permanent population and internally displaced persons (IDPs) in refugee evacuation centres.

On January 17 2002 fractures opened on Nyiragongo's upper southern flanks triggering a catastrophic drainage of the lava lake (Figure 1). An estimated 25 million cubic metres of lava erupted from many vents along the fractures, which rapidly propagated South towards and into the city of Goma located 17 km away on the shores of Lake Kivu. A small volume of lava entered the lake, which contains deep CO_2 and CH_4 (methane) gas-charged waters. This raised concerns of a potential overturn of the lake, generating lethal gas flows, but the lake was not disturbed. Nyiragongo volcano is responsible for 92% of global lava-flow related fatalities (ca. 824) since 1900. The eruption was accompanied by an unprecedented level of felt earthquakes (Allard et al., 2002, Komorowski et al., 2002/2003, Tedesco et al., 2007b).

Two main lava flows entered the city producing major devastation, and forcing the rapid exodus of most of Goma's 300,000 – 400,000 inhabitants across the border into neighbouring Rwanda. There were international concerns about the evacuation causing an additional humanitarian catastrophe exacerbating the ongoing regional ethnic and military conflict. Lava flows destroyed about 13 % of Goma, 21% of the electricity network, 80 % of its economic assets, 1/3 of the international airport runway and the housing of 120,000 people. The eruption caused about 470 injuries and about 140-160 deaths mostly from CO_2 asphyxiation and from the explosion of a petrol station near the active hot lava flow (Komorowski et al., 2002/2003, Baxter et al., 2003).

This was the first time in history that a city of such a size had been so severely impacted by lava flows. The eruption of Nyiragongo in 1977 produced extremely fluid, fast-moving (up to 60 km/h) lava flows (Figure 1) that entirely covered several villages at night thus killing an estimated 600 persons, but the lava did not reach Goma.

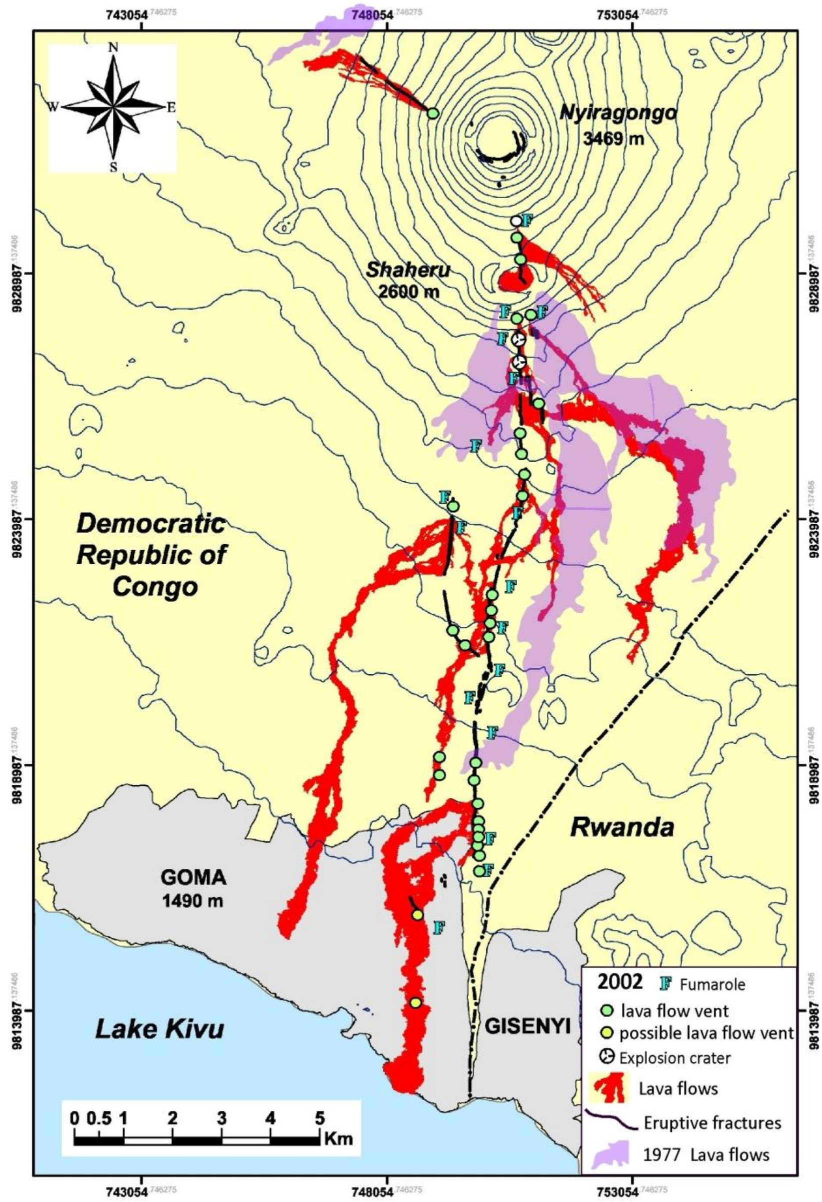

__Figure 1:__ Map of the eruptive fractures, lava vents, and lava flows emplaced during the 17 January 2002 and 1977 eruptions of Nyiragongo volcano, Democratic Republic of Congo (modified from Komorowski et al. (2002/2003)).

Multiple geohazards and a complex humanitarian emergency

With its rapidly expanding demographics and a large numbers of internally displaced persons (IDPs), the city of Goma (ca. 1 million people in 2014) is one of the highest volcanic risk areas in the world. Indeed, this area is not only threatened by future lava flows from lava-lake draining eruptions of Nyiragongo, but also lava flows from Nyamuragira volcano. Long lava flows from this neighbouring volcano, which erupts on average every two years, threaten the northern shores of Lake Kivu and the town of Sake, where large numbers of IDPs shelter (Favalli et al., 2006, 2009, Chirico et al., 2009, Smets et al., 2014). Ash falls, sulphuric acid, chlorine, and fluorine-rich gases affect public health (Sawyer et al., 2008), the water supply and crops. Other hazards include major earthquakes and potentially catastrophic outbursts of CO_2 and methane gas from Lake Kivu (Schmid et al., 2005, Tassi et al., 2009) and landslides (Figure 3). These acute geohazards can develop in a cascading sequence and are superimposed on a decade of devastating insecurity and military conflicts in the densely populated Kivu region, that have caused a complex emergency requiring a major humanitarian effort and the largest ongoing UN peace-keeping mission (Komorowski et al., 2002/2003).

***Figure 2: Top** and **middle**: Lava flows invading the city of Goma on 17 January 2002 (photo K. Mahinda, GVO, 2002); **Bottom**: Fractures propagating through the village of Monigi 14 km away from Nyiragongo near the city of Goma as magma migrated from the central conduit South towards lake Kivu (see **Figure** 4) (photo J-C Komorowski, January 23 2002)*

The eruption caused a major humanitarian emergency that further weakened the already fragile lifelines of the population in an area subjected to many years of regional instability and military conflicts. The medical and humanitarian community feared a renewal of cholera epidemics that caused a high mortality in refugee evacuations centres after the 1994 genocide. However, rapid and efficient response by relief workers from UN agencies, numerous non-governmental organisations (NGOs), and local utility agencies prevented major epidemics. Epidemiological surveillance found no major increases in infectious diseases (Baxter and Ancia, 2002, Baxter et al., 2003).

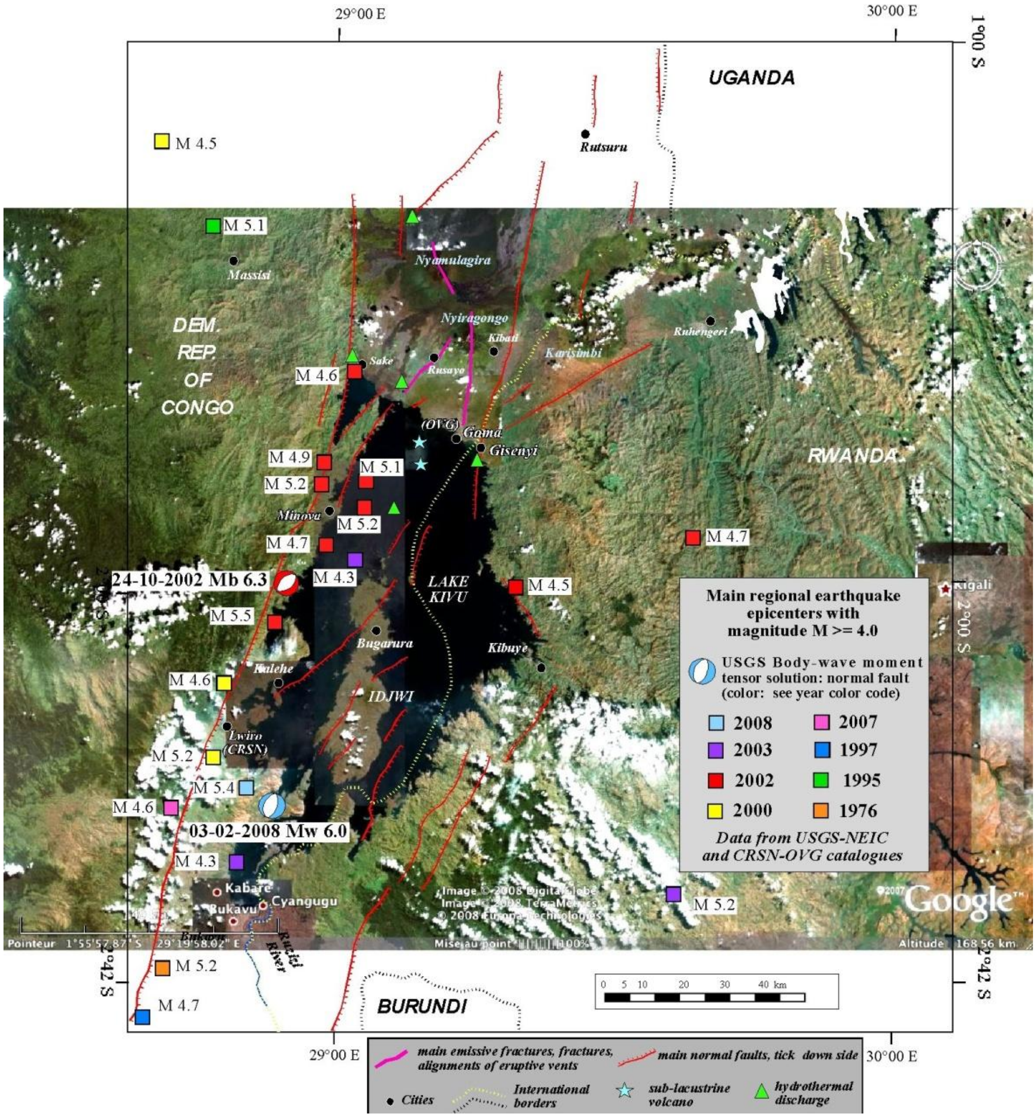

Figure 3: Volcanic and seismo-tectonic general setting of the lake Kivu and Virunga Volcanic Zone (Democratic Republic of Congo, Rwanda, Burundi, Uganda) in the western branch of the East African Rift System. Main normal rift faults and lake Kivu data taken from Pouclet (1977), Villeneuve, (1980), Bellon & Pouclet (1980), Ebinger (1989a, 1989b) and Kasahara et al. (1992, Degens et al.,(1973), Wong & Von Herzen (1974). Main earthquake epicenters with magnitude ≥ 4 since 1973 taken from the USGS National Earthquake Information Center (NEIC) and data from the CRSN and the OVG (Goma, RDC), satellite image background from Google Earth (modified from Komorowski et al., 2004 and references therein).

Lessons learned

Despite being in the midst of a civil war, a lack of funding, institutional support and adequate monitoring equipment, the Goma Volcano Observatory (GVO) scientists successfully made some exceptionally valuable observations about increasing fumarolic and seismic activity. Data from two distant seismic stations were interpreted, as other equipment had been vandalised during the years of military conflict. Those signs were correctly interpreted by GVO as potentially indicating that an eruption could occur, although the precise scenario of a far-reaching flank fissure eruption could not be forecast without an adequate monitoring network. Nevertheless, the GVO played a key role in the recognition of the unrest 1 year prior to the eruption and in providing expert advice to the UN authorities once the eruption began. Memory of the 1977 devastating lava flows triggered life-saving actions by villagers, including panic-less self-evacuation. This, in combination with the presence of a large humanitarian community in Goma and the advice provided by the GVO undoubtedly contributed to the low number of fatalities given the scale of the eruption (Komorowski et al., 2002/2003, Ruch and Tedesco, 2003).

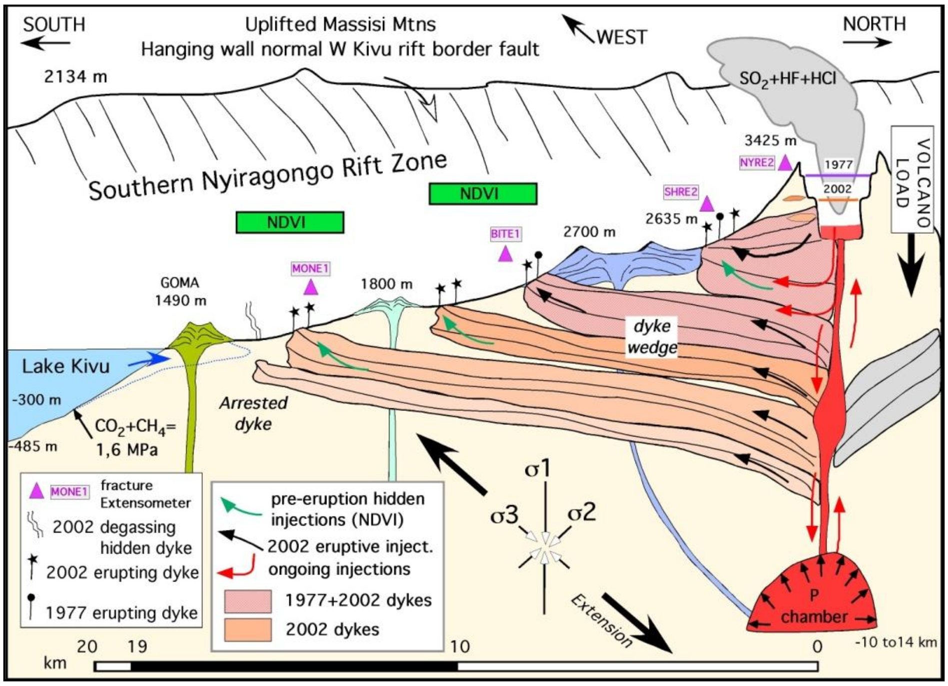

Figure 4: Conceptual model of the southern Nyiragongo rift zone and its volcanic activity in the context of the North Kivu tectonic rift area and gas-charged Lake Kivu (Komorowski et al., 2006, Houlie et al., 2006).

For Nyiragongo, the IDNDR Decade program had not achieved its goals as clearly stated in the 1994 Goma Declaration (Casadevall and Lockwood, 1995). The response to the 2002 Nyiragongo eruption was remarkable, with significant support provided rapidly by the international humanitarian and scientific community under the coordination and with funding from UN agencies. This support came from international and regional NGOs, government agencies, donor countries and academic research programs (Tedesco et al., 2007a). Had the DRR goals for Nyiragongo, laid out as part of the International Decade for Natural Disaster Reduction (IDNDR) and stated in the 1994 Goma Declaration (Casadevall and Lockwood, 1995) been achieved prior to this eruption, such a complex response may have been unnecessary. Therefore one of the first tasks of the post-crisis response to the 2002 eruption was to establish a modern operational volcano monitoring network and team. Thus, the Goma Volcano Observatory was significantly strengthened and a new multi-parameter modern monitoring system was installed gradually along with capacity-building programs. All these efforts have significantly improved the technical and analytical capabilities of the GVO in monitoring the activity of the Virunga volcanoes (including Nyiragongo and Nyamuragira).

The way forward: the Goma Volcano Observatory

Since 2002, a new large lava lake has formed within the 1000 m deep crater and is associated with a significant sulfur, chlorine, and fluorine-rich gas plume, one of the largest in the world. The level of lava has risen slowly but continuously by at least 500 m since October 2002, resting about 400 m below the rim, and only 130 m below the level at the time of the 2002 drainage. There is considerable scientific uncertainty regarding future scenarios (Komorowski et al., 2002/2003):

1) What is the threshold level of the lava lake required to trigger another release of lava through its flanks towards the south like in 1977 and 2002?;

2) How likely is it that magma will be channelled away from the summit crater through the highly fractured southern flanks of Nyiragongo?

3) In a future lateral eruption, will magma propagate faster and further towards the water-saturated ground near lake Kivu, thus increasing the likelihood of explosive eruptions within the city of Goma?;

4) In the worst-case scenario, could magma propagate below the deep gas-charged basin of lake Kivu to trigger subaqueous volcanic eruptions and potential catastrophic lake-overturn events releasing large volumes of CO_2 and methane into the environment?

Successful volcanic risk mitigation depends on a series of integrated timely actions. These include: a permanent secured multi-parameter real-time monitoring network; quantitative hazard and risk assessment that quantifies uncertainty and fills knowledge gaps; early-warning systems; emergency and long-term planning; and awareness programs for crisis managers, decision-makers and the public. Given the high volcanic risk in the Goma area, all these efforts must be further strengthened to support decision-making by the authorities.

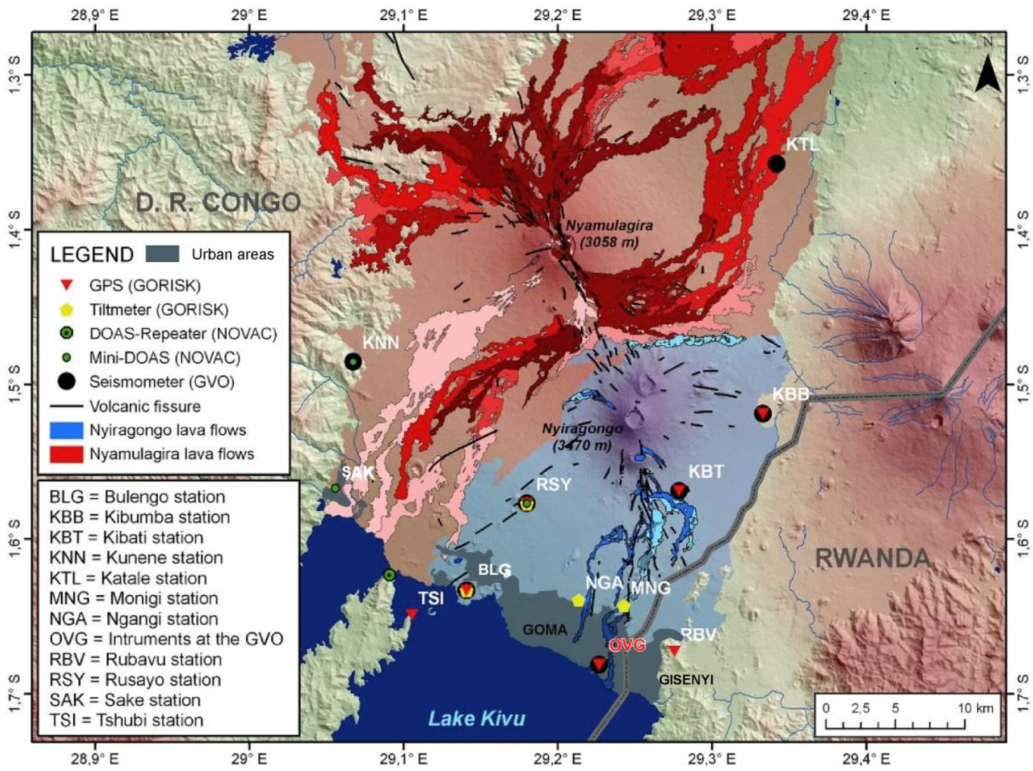

Figure 5: The current multi-parameter monitoring system of the Goma Volcanological Observatory (see legend for the techniques). In cooperation with foreign institutions or universities, GVO is involved in: geochemistry surveys, investigation of Mazuku (pockets of CO_2) CO_2 ground degassing, Lake Kivu chemical and physical surveys, satellite imagery and DEM mapping, geological and structural mapping, lake Kivu stability modelling, lava flow paths modelling, hazard and risk maps, ground deformation benchmarks, continuous temperature measurements and monitoring of the width of eruptive fractures. Some stations are no longer working due to equipment vandalism (GVO; WOVO).

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CS9. Volcanic ash fall impacts

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Overview

All explosive eruptions produce volcanic ash (fragments of volcanic rock < 2mm), which is then dispersed by prevailing winds and deposited as ash falls hundreds or even thousands of kilometres away. Volcanic ash suspended in the atmosphere is well known as a hazard for aviation, as was demonstrated during the 2010 eruption of Eyjafjallajökull, Iceland, which led to substantial disruption to flights in Europe and an estimated US$5 billion loss as global businesses and supply chains were affected (Ragona et al., 2011). Volcanic ash fall can also create considerable impacts on the ground. As a general rule, impacts will be more severe with increasing thickness of ash fall. Relatively thin falls (< 10 mm) may have adverse health effects for vulnerable individuals and can disrupt critical infrastructure services, aviation, agriculture and other socio-economic activities over potentially very large areas. Thick ash falls (>100 mm) may damage crops, vegetation and infrastructure, cause structural damage to buildings and create major clean-up requirements. However, they are typically confined to within tens of kilometres of the vent and, as they occur with large eruptions, are relatively rare.

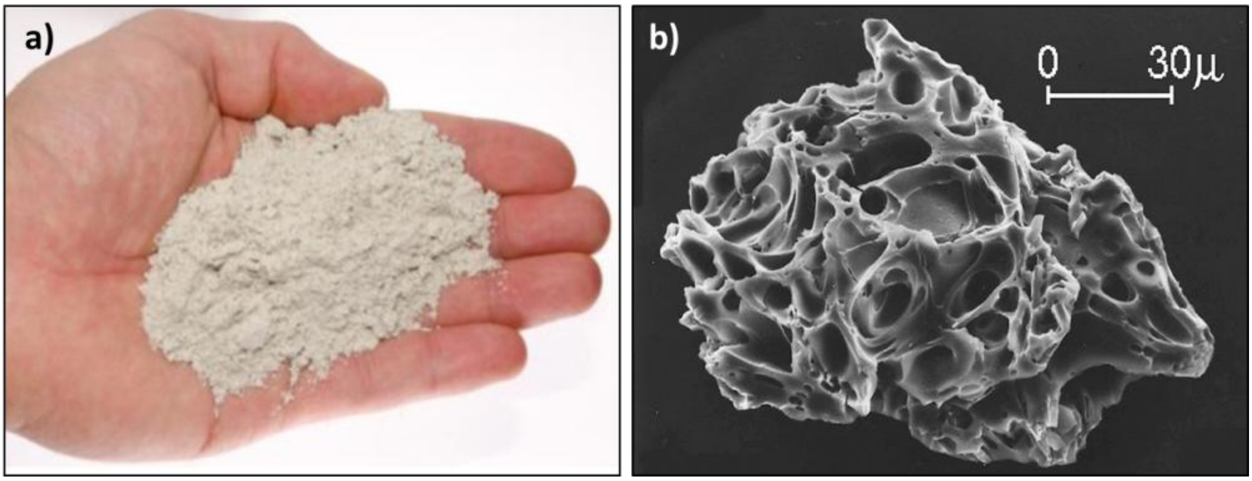

Figure 1 a) Rhyolitic ash produced by the eruption of Chaitén volcano, Chile, in 2008 (median grainsize: 0.02 mm). Photo: G. Wilson; b) Scanning electron microscope image of an ash particle from the eruption of Mount St Helens, USA, in 1980. Vesicles, formed as gas expanded within solidifying magma, are clearly visible. Ash is often highly abrasive because of its irregular shape and hardness. Photo: A.M. Sarna-Wojcicki, USGS.

The quantity of ash (thickness or loading) is not the only mechanism by which ash can cause damage or disruption; the surface chemistry of ash, abrasiveness, friability, ash grain size and density can all influence, or even control, how some systems or components may respond to an ash fall. The physical and chemical properties of fallen ash are largely controlled by eruptive dynamics and magma composition, although dispersal conditions, e.g. wind and rain, also play a role. Ash properties can therefore vary among different eruptions and even during the same eruption.

Environmental factors such as wind and rain may lead to ash remobilisation, which may extend and/or intensify the level of impact.

Impacts

Impacts depend upon the amount of volcanic 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 ash fall impacts (vulnerability). Three main zones of ash fall impact may be broadly expected, each requiring a different approach to impact management and planning: 1) Destructive and immediately life-threatening (Zone I); 2) Potentially harmful to health, damaging and/or disruptive (Zone II); and 3) Mildly harmful to health, disruptive and/or a nuisance (Zone III). These zones are summarised in the schematic Figure 2 where physical ash impacts to selected societal assets are depicted against ash deposit thickness – which generally decreases with distance from the volcano source. The more severe impacts depicted in Zones I and II may not occur in smaller magnitude eruptions because there is insufficient ash fall. A further impact zone (Zone IV) could be applied to areas that extend beyond those receiving ash fall, as aviation disruption from airborne ash can occur in areas where no ash falls on the ground. Below, we elaborate on the impacts shown in Figure 2. See the GAR-15 background paper on 'Volcanic ash fall hazard and risk' and references therein for more detailed information on each point:

Impacts to People: Exposure to volcanic ash fall rarely endangers human life directly, except where very thick falls cause structural damage (e.g. roof collapse) or indirect casualties such as those sustained during ash clean-up operations or in traffic accidents. Short-term effects commonly include irritation of the eyes and upper airways and exacerbation of pre-existing asthma; serious health problems are rare (Horwell and Baxter (2006); see CS10 and www.ivhhn.org). Affected communities can also experience considerable direct and indirect social impacts, for example, impaired psychological functioning due to factors such as disruption of livelihoods and consequent anxiety.

Impacts to Critical Infrastructure: Damage and disruption of critical infrastructure services from ash fall impacts can substantially affect socio-economic activities. 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, typology, ash fall volume and characteristics, and the effectiveness of any applied mitigation strategies (Wilson et al., 2012).

Impacts to Agriculture: Fertile volcanic soils commonly host farming operations; ash falls can be beneficial or detrimental to soil depending on the characteristics of the ash (particularly with respect to its surface composition and the soil (Cronin et al., 1998). The time of year in the agricultural production cycle strongly determines the level of impact (Cook et al., 1981). For example, ripe crops close to harvest are particularly vulnerable to contamination, pollination disruption and damage.

Under very thin ash falls (< 1 mm) crops and pastures can suffer from acid damage or reduced UV light and, with increasing thicknesses, plants may be broken or buried and soil potentially smothered. Thick ash falls (>100 mm) typically require soil rehabilitation, e.g. thorough mixing or removal, to restore agricultural production (Wilson et al., 2011). For livestock, ash falls may cause starvation (damaged or smothered feed), dehydration (water sources clogged with ash), tooth wear, deaths from ingesting ash along with feed, and (more rarely) acute or chronic fluorosis if ash contains moderate to high levels of bioaccessible fluoride.

Impacts to Buildings: The load associated with an ash fall can cause the collapse of roofing material (e.g. sheet roofs), the supporting structure (e.g. rafters or walls) or both and, under sufficiently great 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. Under thinner ash falls (< 100 mm), structural damage is unlikely although non-structural elements such as gutters and overhangs may suffer damage. Ash falls with increased moisture content, as a result of rain for example, will impart a greater load so that resulting damage is more likely. Building components and contents may also be damaged from ash falls due to ash infiltration into interiors, with associated abrasion and corrosion.

Impacts to the Economy (including clean-up): Economic losses may arise from damage to physical assets, e.g. buildings, or reductions in production, e.g. agricultural or industrial output (Munich-Re, 2007). Most economic activities will be impacted, even indirectly, under relatively thin (< 10 mm) ash falls, for example through disruptions to critical infrastructure. Losses may even result from precautionary risk management activities, e.g. covering water supplies, business closure or evacuations. During or after an ash fall, clean-up from roads, properties, and airports is often necessary to restore functionality, but the large volumes make it time-consuming, costly and resource-intensive.

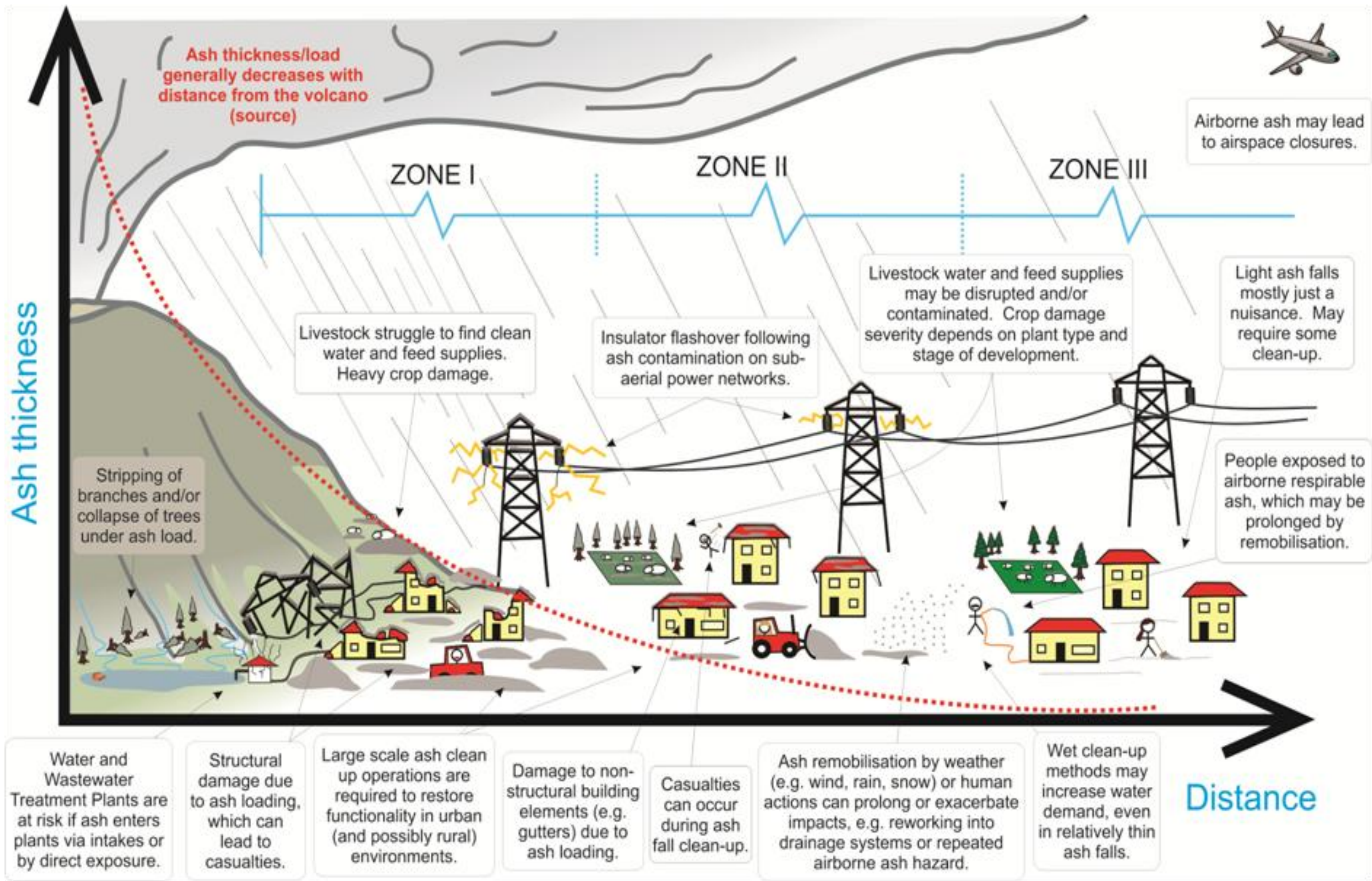

Figure 2: Schematic of some ash fall impacts with distance from a volcano. This assumes a large explosive eruption with significant ash fall thicknesses in the proximal zone and is intended to be illustrative rather than prescriptive. Three main zones of ash fall impact are defined: 1) Destructive and immediately life-threatening (Zone I); 2) Potentially harmful to health, damaging and/or disruptive (Zone II); 3) Mildly harmful to health, disruptive and/or a nuisance (Zone III).

Hazard and risk ranking

The wide geographic reach of volcanic ash falls, and their relatively high frequency, makes them the volcanic hazard most likely to affect the greatest number of people. However, forecasting how much volcanic ash will fall, where it will fall, when it will fall, and with what characteristics is a major challenge. Probabilistic volcanic ash hazard maps [see CS3], developed using ash dispersal models and statistical analyses of likely eruption styles, frequencies, magnitudes and wind conditions, take a step towards robustly quantifying ash fall hazard. Most importantly, the probabilistic nature of such hazard maps means that some of the epistemic uncertainties associated with forecasting how much ash will be erupted, to what height and into what wind conditions are accounted for by simulating many thousands of possible ash fall footprints. By aggregating these difference scenarios, areas of relatively high and low hazard can be identified. A probabilistic ash hazard model was developed for 190 active volcanoes in the Asia-Pacific region, home to 25% of the world's volcanoes and over two billion inhabitants, and the average frequency of ash falls that exceed critical impact thicknesses estimated on a location-by-location, rather than volcano-by-volcano basis (see Jenkins et al. (2012)). By multiplying these hazard estimates with freely available exposure data (in this case LandScan population density) and a proxy for human vulnerability (the UN Human Development Index), a crude 'risk' score could then be established (Figure 3). This offers an insight into the relative risk across the region, building on the probabilistic ash hazard maps. By disaggregating the score, the key risk driver can be identified, which may suggest how risk can best be reduced. For example, Tokyo's risk is dominated by the high cumulative hazard (54 active volcanoes lie within 1000 km), Jakarta's risk is dominated by population exposure and Port Moresby's risk by the vulnerability. While this approach is useful at large regional to global scales, it should never replace a local risk assessment, which should use more detailed knowledge of the volcano and local analyses of societal assets and vulnerability to produce a robust assessment.

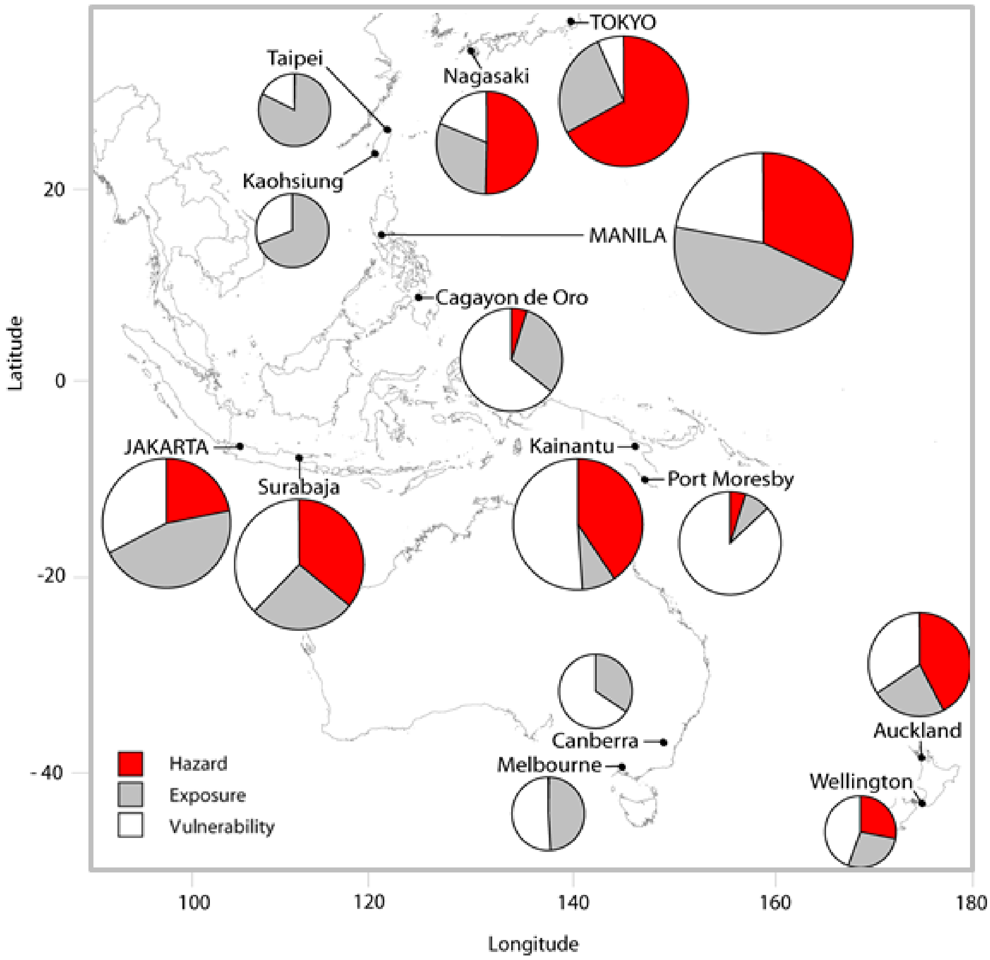

Figure 3: Relative risk scores (shown by circle size) and the contributions of the three factors towards the overall risk (a product of hazard, exposure and vulnerability) for cities in the Asia-Pacific region. Hazard is taken as the estimated frequency of thin (≥ 1mm) ash falls; Exposure: the population density; and Vulnerability: a composite of education, life expectancy and standard of living (the UN Human Development Index).

Mitigation strategies

Greater knowledge of the hazard and associated impact can support mitigation actions, such as crisis planning and emergency management activities. Poor preparedness for ash fall impacts can be costly, delaying an effective response.

A major concern to both the affected populace and authorities before, during and after ash falls are the potential health impacts. Key elements of an effective public health response to volcanic ash fall include: surveillance of health outcomes to inform public health advice and/or provide reassurance to the public; obtaining timely data on air quality from existing monitoring networks to assess population exposure to airborne respirable ash; and characterising ash samples with respect to their mineralogical and toxicological properties, including soluble element content [see CS10]. As a relatively rare public and agricultural health hazard, it can be difficult for agencies to effectively communicate the extent of the risk and to know which ash collection and analysis methods are appropriate. The International Volcanic Health Hazard Network (IVHHN) is invaluable in this role (www.ivhhn.org). Other preparedness activities should include:

- Providing stakeholders with access to specific and relevant preparedness and post-event response/recovery information. Communication regarding the hazard and recommended mitigation steps should be transparent, repeated and from multiple trusted and authoritative sources. (e.g. www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/Eruption-What-to-do/Ash-Impact-Posters).
- Effective and timely warnings. Ashfall warnings are now standard procedures in many countries, such as in the United States, Japan and New Zealand.
- Facilitating appropriate protective actions, e.g. sealing buildings, shutting down vulnerable systems, etc.
- Development of clean-up plans that prioritise critical areas or lines of communication and identification of volcanic ash disposal sites and procedures.
- Mutual support or continuity agreements between municipal authorities, critical infrastructure organisations and businesses, which can facilitate greater access to resources to deal with ash fall events.

While volcanic eruptions cannot be prevented, the exposure and vulnerability of the population to their impacts may, in theory, be reduced, through the considerable tasks of hazard and risk assessment, improved land use planning, risk education and communication and increasing economic development.

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CS10. Health impacts of volcanic eruptions

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Overview

Volcanoes emit a variety of products which may be harmful to human and animal health. Some cause traumatic injury or death and others may trigger diseases, particularly in the respiratory and cardiovascular systems, or mental health problems. The impact on health is related to the style of eruption and type of volcano. Effusive eruptions tend to emit gases and aerosols, which may damage the respiratory system, and lava flows which rarely kill but may cause thermal injuries and mental stress due to loss of property. Explosive eruptions kill, injure and potentially trigger disease via a multitude of hazards ranging from proximal impacts related to production of fragmented rock and more distal impacts from ash, gas and secondary effects.

Injury agents

Injury and death are caused by a range of volcanic hazards (e.g. Auker et al. (2013)), which can be summarised by their impact on the body:

1) *Mechanical injury where the body is crushed.* Explosive eruptions may produce large volumes of fragmented rock, which range in size from boulders to fine ash. Mechanical injury/death occurs from a range of volcanic processes relating to the ejection of material and its transport through air or water (lahars, rock avalanches, ballistics). In 1985, the eruption of Nevado del Ruiz volcano, Colombia, led to glacial melt mixing with ash/rock deposits to form a lahar which buried 23,000 people downstream in the town of Armero. Roof collapse is also a common crushing injury, from the weight of ashfall, particularly on flat roofs [see CS9]. Occasionally those proximal to the volcano may be buried by deposits or suffer asphyxiation from inhalation of particles.

2) *Thermal injury (burns) caused by hot volcanic emissions.* These take the form of pyroclastic density currents (PDCs) and surges (composed of searing gas, ash and rocks), lava flows and hydrothermal waters (which are used for recreational bathing). On Montserrat, West Indies, most of those killed during the Soufrière Hills eruption died on 25 June 1997 when PDCs and surges swept into the exclusion zone, where locals had returned to maintain their farms. Even survivors at the margins of the surge zone suffered serious burns from walking across the hot surge deposits to safety (Loughlin et al., 2002). In most PDC-related deaths, severe burns to the skin (cutaneous) and airways (resulting in pulmonary oedema) may cause immediate mortality, or delayed mortality from respiratory complications and infection (Baxter et al., 1982).

3) *Toxicological effects where emissions react with the body.* Gases, ash and aerosols may be inhaled or ingested. A range of potentially-toxic elements may leach from particles. Cases of poisoning have been associated primarily with high levels of bioaccessible fluorine in ash, particularly for livestock which may ingest large quantities of ash during grazing (Cronin et al., 2003). The surfaces of the mineral particles themselves may be reactive in the lung, particularly if the ash is rich in crystalline silica or iron. Potentially-toxic elements, in particular fluorine, may present issues in some eruptions

if ash contaminates water supplies. However, experience has shown that more common problems include ash blocking and restricting access to livestock drinking water, causing drinking water to become unpalatable and causing water shortages during cleanup operations (Stewart et al., 2006, Wilson et al., 2013).

4) *Electrical impact.* Lightning, generated from friction of particles in the ash plume, may strike people directly or trigger fires.

Airborne volcanic emissions

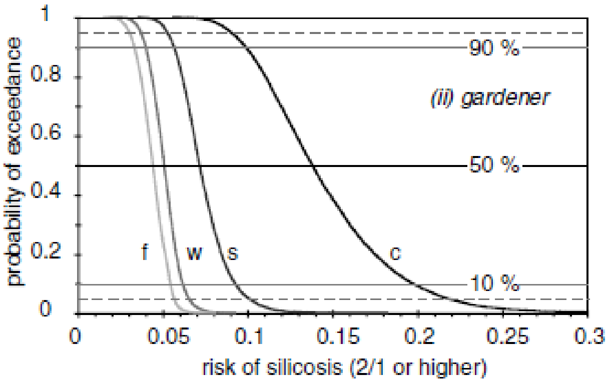
Gases. Volcanoes emit hazardous gases (e.g. CO2, SO2, H2S, HF, HCl & radon). Gas exposures may occur during and following eruptions, and during periods of quiescence, and may be proximal or distal to the vent, depending on the size of eruption. Most gas-related deaths occur due to carbon dioxide or hydrogen sulphide pooling in depressions near the volcano, but large eruptions may generate mega-tonnes of SO2 which can be transported globally and potentially trigger acute respiratory diseases, such as asthma, in exposed populations. Following the Eyjafjallajökull eruption, the potential for a large, effusive Icelandic eruption, such as the Laki eruption of 1783, is considered a major risk to Europe and is ranked as one of the highest priority risks in the UK National Risk Register with concerns that sulphur dioxide, sulphate aerosols and other gases may have substantial health and environmental impacts. Chronic dental fluorosis has been observed in rural residents of Ambrym island, Vanuatu, and linked to volcanic degassing and contamination of rain-fed drinking water supplies by the volcanic plume (Allibone et al., 2012).

Ash. Whilst ash may cause skin and eye irritation, the primary concern for humans is ash inhalation; the style of eruption and composition of the magma govern the size and composition of the particles which, in turn, control the pathogenic potential of those particles when inhaled. The most hazardous eruptions are those generating fine-grained, crystalline silica rich ash, as silica has the propensity to cause chronic lung disease.

Ash mobilization in Yogyakarta following the 2014 Kelud eruption. Photo: Tri Wahyudi.

Explosive eruptions generate inhalable ash through fragmentation of magma; the fine particles travel in a plume and, depending on the size of the eruption, ash may fall over wide areas causing disruption and anxiety to populations [see CS9]. A recent World Health Organization report found that acute and chronic exposures to particles from ambient air pollution, such as $PM_{2.5}$ which can penetrate deep into the lungs, increase both mortality and morbidity (World Health Organisation, 2013). In the volcanic setting, inhalation of fine ash may trigger asthma and other acute respiratory diseases in susceptible people, but chronic effects have not been adequately studied. Active public health precautionary measures will always be needed to protect the population from heavy exposure.

Some volcanoes mass-produce crystalline silica in lava domes – viscous lava piles which grow within volcanic craters - which are prone to collapse, generating clouds of fine-grained silica-rich ash. Strict controls to minimise population exposure may be needed because, in industrial settings, crystalline silica causes silicosis, an irreversible and potentially fatal lung disease, and is also classified as a lung carcinogen. This type of eruption, if long lived, may produce frequent ash falls leaving local populations periodically exposed to potentially hazardous levels of ash which, over time, may place them at higher risk of developing silicosis, although presently no cases have been recorded. At Soufrière Hills, Montserrat, West Indies the eruption, which began in 1995 and has lasted for over 15 years, generated dome-collapse ash composed of up to ~25 wt.% crystalline silica (Baxter et al., 2014, Horwell et al., 2014). Stringent and costly clean-up measures after ash falls were maintained by the UK government to protect the population. The first risk assessment of its kind, by (Hincks et al., 2006), found that those potentially at greatest risk of developing silicosis, if protective measures were not undertaken, were outdoor workers e.g., gardeners, and children.



Probability of exceedance curve for risk of silicosis (classification ≥2/1) for gardeners, calculated from simulated cumulative exposures (see Hincks et al. 2006 for key to curves, which are for specific Montserrat

Secondary effects

Large populations brought together in evacuation camps may contract diseases through poor sanitation. Some evacuees may suffer mental stress and other psychological disorders related to displacement and violence is also common. Widespread ashfall or gas impact (acid rain) may lead to crop failure, loss of livestock and contamination of water supplies which, in turn, may trigger famine and related diseases. Livestock may starve due to smothering of feed and/or if feeding is impaired due to excessive tooth wear as ash is highly abrasive. Ingestion of ash can also cause fatalities due to intestinal blockages (Wilson et al., 2013). Heavy ashfall can cause roof collapse and is also slippery, making clean-up and driving hazardous. Infrastructure may be impacted, affecting primary healthcare responses [see CS9].

Hazard impact and response planning

Planning for ash falls and gas release at volcanoes in states of unrest is an essential part of volcano crisis management. Concerns about the health effects of ash and gases may, in the public perception, exceed even volcanologists' warnings on the risks of death from PDCs. Public health officials must be involved in eruption planning and in the response, and work closely with scientists monitoring the volcanic activity. Planning should include setting up and maintaining airborne particulate (PM_{10} and $PM_{2.5}$) monitoring networks (or gaining permission to utilise existing urban networks) so that timely data can be obtained to assess population exposure to airborne respirable ash. National regulatory or WHO guideline limits for particulate pollution (24 hour) are likely to be exceeded for as long as ash is visibly present in the air or on the ground. During and post-eruption, syndromic surveillance of acute respiratory health symptoms is also helpful for informing public health advice and providing reassurance to the public.

The International Volcanic Health Hazard Network (www.ivhhn.org), the umbrella organisation for volcanic health-related research and dissemination, has produced pamphlets and guidelines on volcanic health issues (such as preparing for ashfall) for the public, scientists, governmental bodies and agencies. IVHHN has also developed protocols for rapid characterisation of ash (such as particle size, crystalline silica content, leachate chemistry and basic toxicology) giving timely information to hazard managers during, or soon after, an eruption, to facilitate informed decision-making on health interventions. These analyses have been carried out following recent crises at Rabaul, Eyjafjallajökull, Grímsvötn, Chaitén and Merapi volcanoes (see e.g., Horwell et al. (2013)). IVHHN is currently researching the effectiveness of various health interventions used during volcanic crises, such as types of respiratory protection.

It is essential to determine levels of crystalline silica as an urgent priority after a heavy ash-fall, by sending ash samples to a laboratory with experience of undertaking the analysis (e.g. through IVHHN). If raised levels are suspected, confirmation will be needed, which is best done by sending split samples for analysis in different laboratories and under strict scientific protocols. Specialist advice on risk assessment may be needed for reassuring the population and providing guidance on measures to reduce exposure to ash to safe limits, particularly for outdoor workers who may be most exposed, as well as children, who may be most susceptible to developing silicosis. Regular measurement of personal exposure to the ash will need to be undertaken for risk assessment purposes by an experienced team of occupational hygienists.

Even without significant concentrations of crystalline silica, there will be many who suffer acute respiratory symptoms on exposure to high levels of ash particles in the inhaled air, if dry ash becomes readily re-suspended by winds and human activity. People with asthma and chronic respiratory conditions are most likely to be adversely affected. The public will need advice on limiting their exposure and officials will need to institute measures to remove ash deposits in public areas. Ash may affect areas hundreds of kilometres away from the volcano, and cross national borders, raising public anxiety over air pollution. Fears may also arise over the presence of fluorine and other toxic elements in erupted ash, and the impacts on the environment and animal health, even with fine or sparse deposits from dispersing plumes. Most laboratories are not used to the analyses required to assess the toxic hazard and the main danger is from alarmist, but erroneous, results being disseminated to the public, politicians and media demanding rapid answers.

Long-lasting versus short-lived eruptions

The most disruptive types of eruption are the continuous, open vent eruptions (e.g., Eyjafjallajökull 2010 which lasted 6 weeks) or the long-lasting dome growth and collapse type (e.g., Montserrat 1995 to present). On Montserrat, most people abandoned the island, with the health risk of the ash playing an important part in their decisions; keeping the accumulating ash deposits clear of populated areas to minimise the risks has been a huge and highly costly undertaking (see Baxter et al. 2014, where most of the evidence-base on the health risks of volcanic ash may be found). These contrast with the major one-off eruptions like Mount St Helens, 1980, and Pinatubo 1991, where visible, re-suspendable ash deposits may persist for many months or even a few years but are not replenished by repeated episodes of emissions or continuous venting of ash and gases with plumes being persistently blown over populated areas by prevailing winds. Another scenario arises where one-off heavy ash falls occur in semi-arid areas, for example, in Patagonia after the large eruptions of Hudson in 1991 and Puyehue Cordón-Caulle in 2011 (Wilson et al., 2013). Abandonment of farm areas and continuing problems with poor air quality in settlements on the steppe occurred due to huge ash deposits downwind of the Andean volcanoes. These deposits continue to be re-suspended by very strong winds, causing economic losses compounded by anxieties over the human health effects of such high, repeated exposures.

An important recent example of the effects of continuous, small scale eruptions in densely populated areas was at the port of Rabaul, Papua New Guinea which, for 2 years (2007-8), was subjected to exposure to gases (mainly SO_2), and freshly erupted fine ash from the Tavurvur cone every day for 6 months until the seasonal prevailing winds moved away from the populated area of 70,000 people. In the second year, a drought lasted for 3 months in the middle of the 6 month eruption period; the disruption nearly closed the main hospital, closed schools and many adults and children experienced asthma symptoms, causing the authorities to consider evacuating Rabaul Town. Fortunately, the eruption subsequently stopped and ordinary life resumed. IVHHN analyses, using the rapid analysis protocol, found the ash to be relatively coarse grained and low in crystalline silica (Le Blond et al., 2010). Rabaul is an active caldera and other populated calderas could experience similar small-scale but high impact eruptions due to their persistence, including disrupting infrastructure and transport, especially in modern cities (a potential example is Naples and the currently quiescent Campi Flegrei; see CS3).

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CS11. Volcanoes and the aviation industry

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There are over 1500 volcanoes around the globe. 247 of these have been active, some with multiple eruptions, since the start of commercial airline travel in the 1950s. Guffanti et al. (2010) provide a document on all the volcanic ash – aviation encounters from 1953 – 2009. They classify the level of encounter by a severity index of 0 – 5, with no encounters at level 5 and only 9 at level 4. Several of the most significant encounters at level 4 occurred in the 1980's. The first two were from the 1982 eruption of Mt. Galunggung volcano, where a B-747 aircraft lost all four engines at an altitude of 11 km above sea level and approx. 150 km from the volcano (Hanstrum and Watson, 1983) and in 1989 from the Redoubt volcanic eruption, Alaska, USA, where another B-747 encountered an ash cloud approx. 150 km from the volcano, at 7.6 km above sea level (Casadevall, 1994).

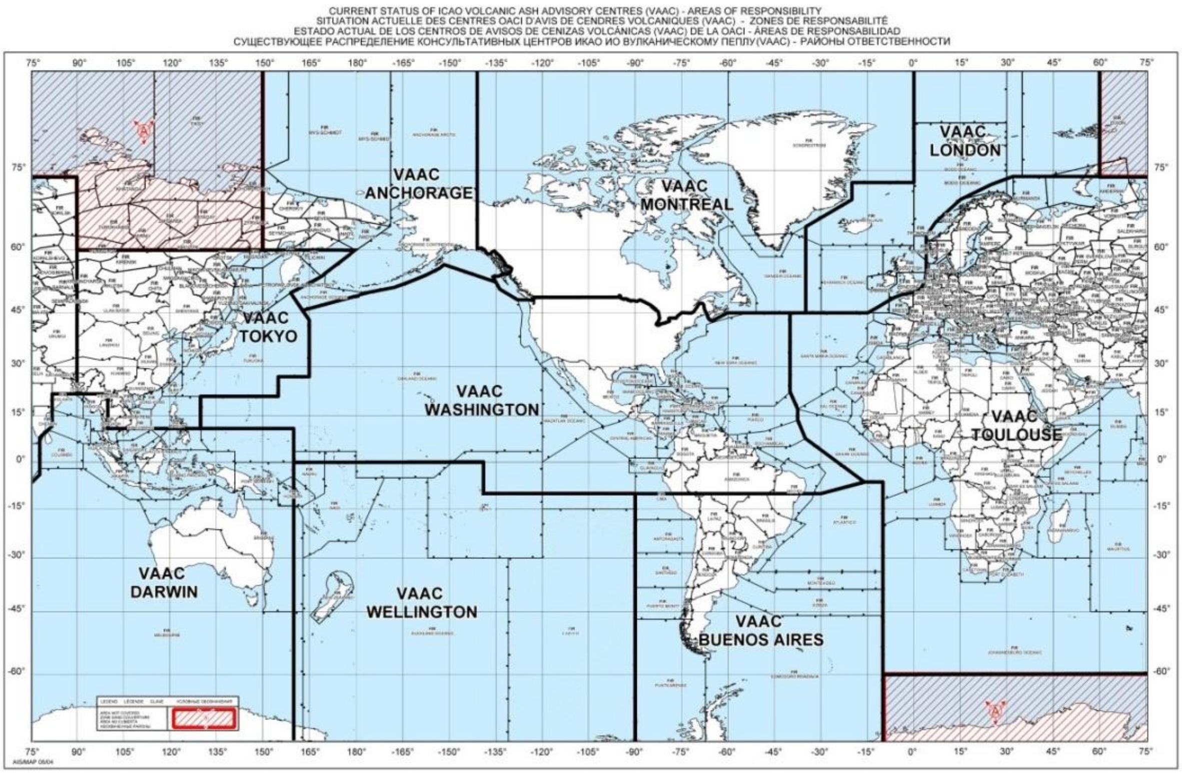
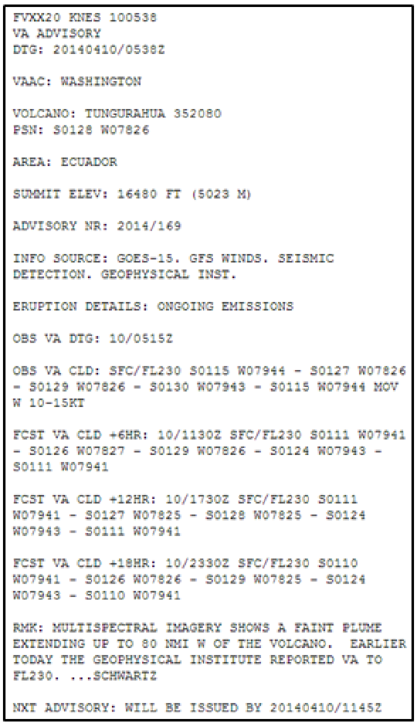


Figure 1. Volcanic Ash Advisory Center (VAAC) area of responsibility map, black lines represent the boundaries of each VAAC. For volcanoes in their area, each VAAC will produce the VAA and VAG for the aviation community.

Along with those from the 1991 eruption of Mount Pinatubo (Casadevall et al., 1996), lead the International Civil Aviation Organization (ICAO) to set up 9 volcanic ash advisory centres or VAAC's (ICAO, 2007). These 9 centres each have own areas of responsibility, see Figure 1 and are maintained by the local weather service. The 9 VAAC's are: Anchorage, Montreal, London, Toulouse, Tokyo, Washington, Darwin, Wellington and Buenos Aires. Each of these produce volcanic ash advisories (VAA) and volcanic ash graphics (VAG) for the aviation community, see example in Figure 2, and link to the aviation industry through local meteorological watch offices, which produce the Significant Meteorological Information (SIGMET) statements for the aviation.



FVXX20 KNES 100538
VA ADVISORY
DTG: 20140410/0538Z

VAAC: WASHINGTON

VOLCANO: TUNGURAHUA 352080
PSN: S0128 W07826

AREA: ECUADOR

SUMMIT ELEV: 16480 FT (5023 M)

ADVISORY NR: 2014/169

INFO SOURCE: GOES-15. GFS WINDS. SEISMIC DETECTION. GEOPHYSICAL INST.

ERUPTION DETAILS: ONGOING EMISSIONS

OBS VA DTG: 10/0515Z

OBS VA CLD: SFC/FL230 S0115 W07944 - S0127 W07826 - S0129 W07826 - S0130 W07943 - S0115 W07944 MOV W 10-15KT

FCST VA CLD +6HR: 10/1130Z SFC/FL230 S0111 W07941 - S0126 W07827 - S0129 W07826 - S0124 W07943 - S0111 W07941

FCST VA CLD +12HR: 10/1730Z SFC/FL230 S0111 W07941 - S0127 W07825 - S0128 W07825 - S0124 W07943 - S0111 W07941

FCST VA CLD +18HR: 10/2330Z SFC/FL230 S0110 W07941 - S0126 W07826 - S0129 W07825 - S0124 W07943 - S0110 W07941

RMK: MULTISPECTRAL IMAGERY SHOWS A FAINT PLUME EXTENDING UP TO 80 NMI W OF THE VOLCANO. EARLIER TODAY THE GEOPHYSICAL INSTITUTE REPORTED VA TO FL230. ...SCHWARTZ

NXT ADVISORY: WILL BE ISSUED BY 20140410/1145Z

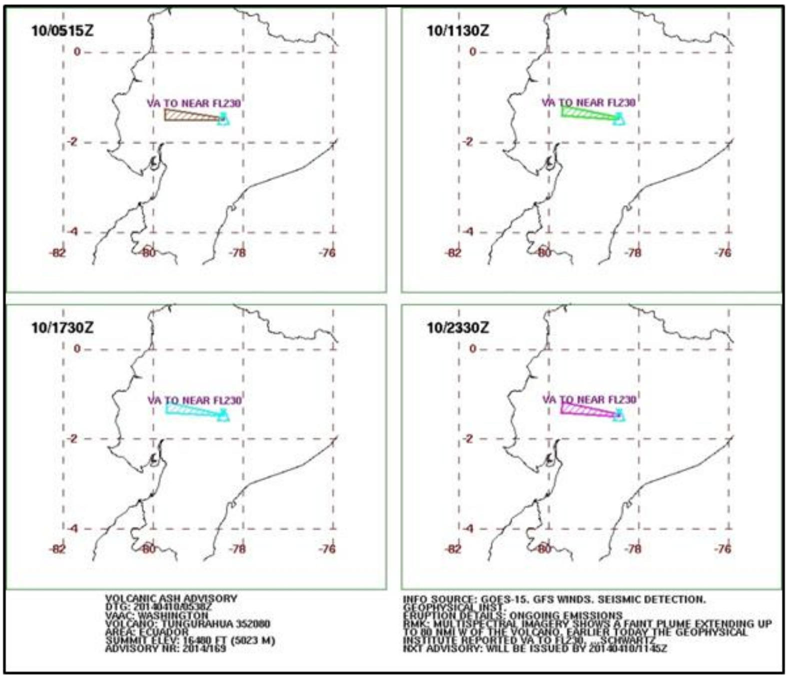


Figure 2. Example Volcanic Ash advisory (VAA) and volcanic ash graphic (VAG) for Tungurahua volcano on April 10, 2014 at 05:38 UTC (Z) as produced at the Washington VAAC.

In addition to the VAAC's, local volcano observatories (VO) have the role, as the state agency, to provide advice on the volcanic activity in their responsible region. VO's provide status updates on the level of activity at their volcanoes, often sending alert notifications and daily updates to the relevant agencies. This information can then be used by the VAAC's to produce their VAA and VAG for the aviation community. There are several different alerting systems used worldwide, each with the aim to update those in local population centres close to the volcano and the aviation community.

One common system used is the United States Geological Survey (USGS) colour code system (Gardner and Guffanti, 2006). This uses a green-yellow-orange-red system for aviation alerts, which with its corresponding text, allows the aviation community to stay informed on the activity levels of the volcano, see Figure 3. The system in Figure 3 is in accordance with recommended ICAO procedures and is currently used by USGS led volcano observatories (USGS, 2014) as well as the Kamchatka Volcanic Eruption Response Team (KVERT, 2014) and GeoNet in New Zealand (Geonet, 2014).

Volcano Alert Levels Used by USGS Volcano Observatories

Alert Levels are intended to inform people on the ground about a volcano's status and are issued in conjunction with the Aviation Color Code. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption and about potential or current hazards and likely outcomes.

Term	Description
NORMAL	Volcano is in typical background, noneruptive state or, *after a change from a higher level*, volcanic activity has ceased and volcano has returned to noneruptive background state.
ADVISORY	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level*, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
WATCH	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway but poses limited hazards.
WARNING	Hazardous eruption is imminent, underway, or suspected.

Aviation Color Code Used by USGS Volcano Observatories

Color codes, which are in accordance with recommended International Civil Aviation Organization (ICAO) procedures, are intended to inform the aviation sector about a volcano's status and are issued in conjunction with an Alert Level. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption, especially in regard to ash-plume information and likely outcomes.

Color	Description
GREEN	Volcano is in typical background, noneruptive state or, *after a change from a higher level*, volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level*, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely **OR** eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Figure 3. USGS volcanic activity alert-level notification system, with volcano alert levels from normal, through advisory and watch to warning and aviation colour code from green to red, adapted from Gardner and Guffanti (2006).

Additionally, to these operational groups, many other organisations have put together global meetings such as the World Meteorological Organization-International Union of Geology and Geophysics (WMO-IUGG) 1st and 2nd workshops on ash dispersal forecast and civil aviation in 2010 and 2013 (WMO, 2013). Also, ICAO has assembled working groups and task forces such as the 2010 – 2012 International Volcanic Ash Task Force (IVATF), (ICAO, 2014b). This task force was brought together as a focal point and coordinating body of all work related to volcanic ash being carried out by ICAO at global and regional levels.

Four meetings were held from 2010 – 2012, where members consisted of the VAAC's, aviation community, representatives for the volcano observatories and regulatory bodies. The IVATF provided a summary of recommendations (IVATF, 2012) centred on science, airworthiness, air traffic management and international airways volcano watch coordination. These recommendations on aviation safety and volcanic watch operations will continue under the ICAO international airways volcano watch operations group (IAVWOPSG), (ICAO, 2014a).

Globally, there can be many volcanoes active and potentially hazardous to the aviation industry. Therefore, the VAAC's and local volcano observatories work closely together to provide the most effective advisory system and ensure the safety of all those on the ground and in the air. Through the release of VAA, VAG and observatory information notices then timely advisories of the ongoing activity is able to reach the relevant organisation and reduce the potential hazard and provide the best tools to mitigate the risk to all.

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CS12. The role of volcano observatories in risk reduction

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Volcanic risk reduction is a partnership between science, responding agencies and the affected communities. A critical organisation in the volcanic risk reduction cycle is a volcano observatory (VO), which is an institute or group of institutes whose role it is to monitor active volcanoes and provide early warnings of future activity to the authorities. For each country, the exact constitution of a VO may differ, dependent on the legislative framework for disaster risk reduction and scientific advice to government. For example, in the USA, the Alaska Volcano Observatory is a joint program of the United States Geological Survey (USGS), the Geophysical Institute of the University of Alaska Fairbanks (UAFGI), and the State of Alaska Division of Geological and Geophysical Surveys (ADGGS), whereas in New Zealand, GNS Science has sole responsibility under the country's Civil Defence Emergency Management Act to provide warnings on volcanic activity and hence provides the function of a volcano observatory.

The responsibilities of a VO also differ from country to country. In some nations, a volcano monitoring organisation may be responsible only for maintaining equipment and ensuring a steady flow of scientific data to an academic or civil protection institution, who then interpret the data or make decisions. In other jurisdictions, the VO may provide interpretations of those data and undertake cutting edge research on volcanic processes. In most cases a VO will provide volcanic hazards information such as setting Volcanic Alert Levels and issuing forecasts of future activity, and in some instances, a VO may even provide advice on when civil actions should take place such as the timing of evacuation. Some of the VOs have responsibility for multiple volcanoes, whereas others may only monitor and provide advice on a single volcano. In some countries an academic institute may fulfil both the monitoring and research function for a volcano.

This wide range of potential roles and responsibilities demonstrates the importance of a VO function, but also shows that there is no single template for the constitution of a VO. However, it is critically important that governments recognise the need for volcano monitoring, provide adequate resourcing and have clear definitions of roles for VOs, academic institutions, civil protection agencies and other key players for the pathway for issuing warnings.

A critical VO role is to provide information to Volcanic Ash Advisory Centres (VAACs). It is stated under regulations of the International Civil Aviation Organisation that states should maintain VOs that monitor pre-eruptive activity and eruptions themselves and provide information on the activity to VAACs, Meteorological Watch Offices and air traffic control authorities.

There are over 100 VOs around the world to monitor ca. 1551 volcanoes considered to be active or potentially active. Many of the VOs are members of the World Organisation of Volcano Observatories (WOVO; www.wovo.org). WOVO is a commission of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) that aims to co-ordinate communication between VOs and to advocate enhancing volcano monitoring around the globe. WOVO is an organisation of and for VOs of the world and has three co-leaders for each of the following regions:

Asia-Pacific, Americas, Europe/Africa. WOVO organises or co-sponsors meetings, workshops and conference sessions that focus on issues of importance for VOs. It also co-ordinates information exchange between the VOs. One of the main recent roles of WOVO has been to enhance communication between VOs and Volcanic Ash Advisory Centres.

To be able to monitor their volcanoes effectively, VOs potentially have a very wide suite of tools available to them. However, the range of the capability and capacity of VOs globally is enormous. Many active volcanoes have no monitoring whatsoever, whereas some VOs in developed countries may have hundreds of sensors on a single volcano [see CS16]. This leads to major gaps in provision of warnings of volcanic activity, particularly in developing countries.

Monitoring programs typically include: tracking the location and type of earthquake activity under a volcano; measuring the deformation of the ground surface as magma intrudes a volcano; sampling and analysing gases and water being emitted from the summit and flanks of a volcano; observing volcanic activity using webcams and thermal imagery; measurements of other geophysical properties such as electrical conductivity, magnetism or gravity. VOs may have ground-based sensors measuring these data in real-time or they may have staff undertaking campaigns to collect data on a regular basis (e.g. weekly, monthly, annually). Some VOs may also the capability to collect and analyse satellite data.

Volcano seismicity is the fundamental backbone for early warnings of eruption. Magma and fluid movement inside volcanoes create a variety of seismic signals. A typical progression of seismicity preceding and eruption starts with rock-breaking earthquakes or volcano-tectonic signals as magma starts to move upwards inside the volcano. As magma, gases or hydrothermal fluids get forced through cracks, the earthquakes change their character reflecting resonance or repetitiveness of the source of the signals. Eruptions and their products (pyroclastic density currents or lahars) also produce diagnostic signals.

There are many different ways of measuring the shape of the earth; traditional surveying methods such as levelling or electronic distance measurement can be used on a campaign basis, although most VOs now use continuous data collection using Global Navigation Satellite Systems or electronic tilt to provide real-time or near real-time sub-millimetre measurements of the location of points around a volcano. Satellite measurements [CS14], particularly Synthetic Aperture Radar, also allow wide spatial coverage of a deforming volcano although this imagery normally has a return period of weeks to months.

Volcanoes emit many different gas species as the magma rises from depth; the magma also interacts with hydrothermal systems, groundwater or surface water and can change the chemistry and physical properties of existing water bodies. Measuring these changes can provide early warning of magma on the move.

The main gas species that are associated with magma are water, sulphur dioxide and carbon dioxide, although many other gases can be measured, especially halogens, and other carbon and sulphur species. Scientists have devised a wide range of techniques to measure these gases, especially sulphur dioxide and carbon dioxide. Water vapour is very difficult to measure as there is already an abundance in the atmosphere. Very few gas monitoring techniques provide real-time data at a comparable rate to measurements of seismicity or ground deformation, although this is a rapidly developing field and over the next 5-10 years, it is likely that such instrumentation will exist.

Changes in water chemistry and properties are relatively simple to measure in real-time, such as the temperature of a crater lake or the pH of a hot spring, although volcanic environments are commonly highly acidic and/or hot and thus it is difficult to maintain sensors for extended periods as they can be destroyed very easily.

Satellite observations can help with both gas emissions and physical properties of water bodies. For example, the Ozone Monitoring Instrument (OMI) onboard the NASA Aura satellite has the ability to monitor large emissions of sulphur dioxide; a variety of satellite platforms provide thermal monitoring with varying degrees of temporal or spatial resolution. However, not all VOs have either the capability or capacity to access or interpret satellite information.

Observations of volcanic activity are critical during eruptive activity to provide information to the VO on how an eruption is progressing. For example, observations of ash cloud heights are vital for VAACs so they can accurately model the dispersion of ash for aviation. Oftentimes, VOs have web cameras at various points around a volcano to provide visual or thermal imagery back to the monitoring scientists. In some cases, ground-based radar can image eruption clouds. Remote imagery is especially important if the VO is located at some distance from a volcano.

Definition of what constitutes an appropriate level of monitoring has received some attention over the last few years (Ewert et al., 2005, Miller and Jolly, 2014). One approach that has been used is to assess broadly the risk associated with each volcano [see CS20], and allocate more resources to those volcanoes that pose a higher risk. This approach has been extended in this submission to GAR15. In some countries, it may be difficult to provide monitoring for all the volcanoes in its jurisdiction, however, consideration should be made of maintaining at least some minimal monitoring for the high risk volcanoes through all periods of quiescence. Volcanoes exhibit fluctuations in their background levels of activity and it is difficult to recognise what constitutes unrest that may lead to an eruption if the VO does not understand the long term behaviour of the volcano fully.

One aspect of VOs that is often underestimated is ensuring that a VO has sufficient human resource to develop and maintain monitoring expertise. Oftentimes, VOs have the ability to purchase capital items, or equipment is provided in an emergency situation through aid donors, but if there is insufficient staffing and/or an ongoing operational budget, the monitoring can quickly fall into disrepair in the recovery period after an eruption. It is important that VOs are resourced sustainably, so that they can maintain at least a minimum level of monitoring through periods with little or no activity, and that they have the ability to call on additional support during crises to bolster a long term core capability. This can be achieved by partnerships with other organisations either in-country, for example, academic institutions that may be able to provide students for routine monitoring tasks such as collecting ash, or overseas, for example, GNS Science has a long term partnership with Vanuatu Meteorology and Geohazards Department. In both cases, there has to be clear understanding of the responsibilities of the VO and any other organisations assisting the VO or undertaking research on the volcano (Newhall et al., 1999).

The process for mitigating risk differs from country to country, but in essence, communities need to understand their risk and take action to mitigate risk (by avoiding, minimising or accepting the risks). This is commonly illustrated through a series of steps in a risk management cycle, such as risk reduction (e.g. using planning legislation to prevent people from living in high risk areas), readiness (e.g. having contingency plans in place so that different parts of the community know what they should do in a crisis), response (e.g. reacting to increased activity by evacuating areas), and recovery (e.g. cleaning up after ashfall). VOs play a role in all aspects of risk management.

VOs are often involved in outreach activities in times of volcanic quiet so that the authorities and the communities can better understand the potential risk from their volcano(es); this may also involve regular exercising with civil protection agencies to test planning for eruption responses.

During the lead up to an eruption, VOs may provide regular updates on activity which inform decisions on evacuations or mitigation actions to reduce risk to people or to critical infrastructure. For example, power transmission companies may choose to shut off high voltage lines if there is a high probability of ashfall. They may also assist organisations in developing contingency plans by providing possible eruption scenarios.

During an eruption, VOs will then provide up-to-date information about the progression of activity. For an explosive eruption, information might include the duration, the height that ash reaches in the atmosphere and areas being impacted on the ground. This can inform decisions such as search and rescue attempts or provide input to ash dispersion forecasts for aviation.

After an eruption has ceased, VOs can aid recovery through advice about ongoing hazards such as remobilisation of ash deposits during heavy rainfall. They can also assist or undertake valuable research on the eruption through collection of time-perishable data. This can lead to better understanding of the volcano so that future responses can be fine-tuned.

The role of VOs is critical in reducing risk from volcanoes, both on the ground and in the air. Volcanic risk reduction can only improve if VOs are adequately resourced by national government. If adequate volcano monitoring is established ahead of a volcanic crisis, the VO can provide a wide range of information to responding agencies and to the potentially affected communities, both in quiescence and during response; ultimately, this results in better preparedness and enhanced safety of people and infrastructure.

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CS13. Developing effective communication tools for volcanic hazards in New Zealand, using social science

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Social science plays an increasing and valuable role in volcanic Disaster Risk Management (DRM); social science research methods are now used globally to investigate and improve the links amongst volcanology, emergency mangement and community resilience to volcanic hazards. The biennial IAVCEI Cities on Volcanoes Conferences, each hosted by an international city at risk from volcanic hazards, holds its eighth meeting in Yogyakarta (Indonesia) in September 2014. These meetings attract large attendances of social and physical scientists as well as emergency managers and DRM practitioners. By incorporating social science methodologies, information derived from volcano monitoring and data interpretation can be used in the most effective way possible to reduce the risk of volcanic hazards to society.

A range of New Zealand researchers at universities, and the government earth science research institute GNS Science, have been conducting applied social research focussed around natural hazards for nearly 20 years, spearheaded by studies of the impacts of the 1995/96 eruptions of Ruapehu volcano. In 2006 the national Joint Centre for Disaster Research was established, a joint venture between Massey University School of Psychology and GNS Science. It includes researchers from other universities and agencies and undertakes multi-disciplinary applied teaching and research aimed at gaining a better understanding of the impacts of disasters on communities, improving the way society manages risk, and enhancing community preparedness, response and recovery from the consequences of hazard events. Researchers also focus on the effective communication of likelihoods for volcanic eruption forecasts (Doyle et al., 2014). Three projects are highlighted here as examples of volcanic hazard focussed research within this collaborative national social science framework.

Development of a revised Volcanic Alert Level system

The communication of scientific information to stakeholders is a critical component of an effective Volcano Early Warning System. Volcanic Alert Level (VAL) systems are used in many countries as a tool to communicate complex volcanic information in a simple form, from which response decisions can be made. Communication tools such as these are required to meet the needs of a wide range of stakeholders, including central government, emergency managers, the aviation industry, media, and the public. They are also required to be usable by the scientists who determine the levels based on volcano observations and interpretation of complex monitoring data.

A recent research project by Potter et al. (2014) involved the exploration of New Zealand's 20-year old VAL system. For the first time globally, a new VAL system was developed based on a robust qualitative ethnographic methodology, which is commonly used in social science research (e.g. Patton (2002)). The research involved interviews of scientists and stakeholders, document analysis, and observations of scientists over three years at GNS Science as they set the VAL during multiple unrest and eruption crises. The data resulting from the interviews underwent thematic analysis, which involves grouping comments made by participants into themes. The findings were triangulated against the document analysis and observation data to produce a draft new VAL system. The draft system then went through multiple iterations with stakeholders and scientists, until a final version acceptable to all interested parties was formed.

The new VAL system, which is presented in Figure 1, was integrated into the Ministry of Civil Defence and Emergency Management's Guide to the National Civil Defence and Emergency Management plan in 2014. For more information on New Zealand's VAL system, visit www.geonet.org.nz/volcano. The methodology utilised in this trans-disciplinary research is applicable worldwide, and potentially could be used to develop warning systems for other hazards.

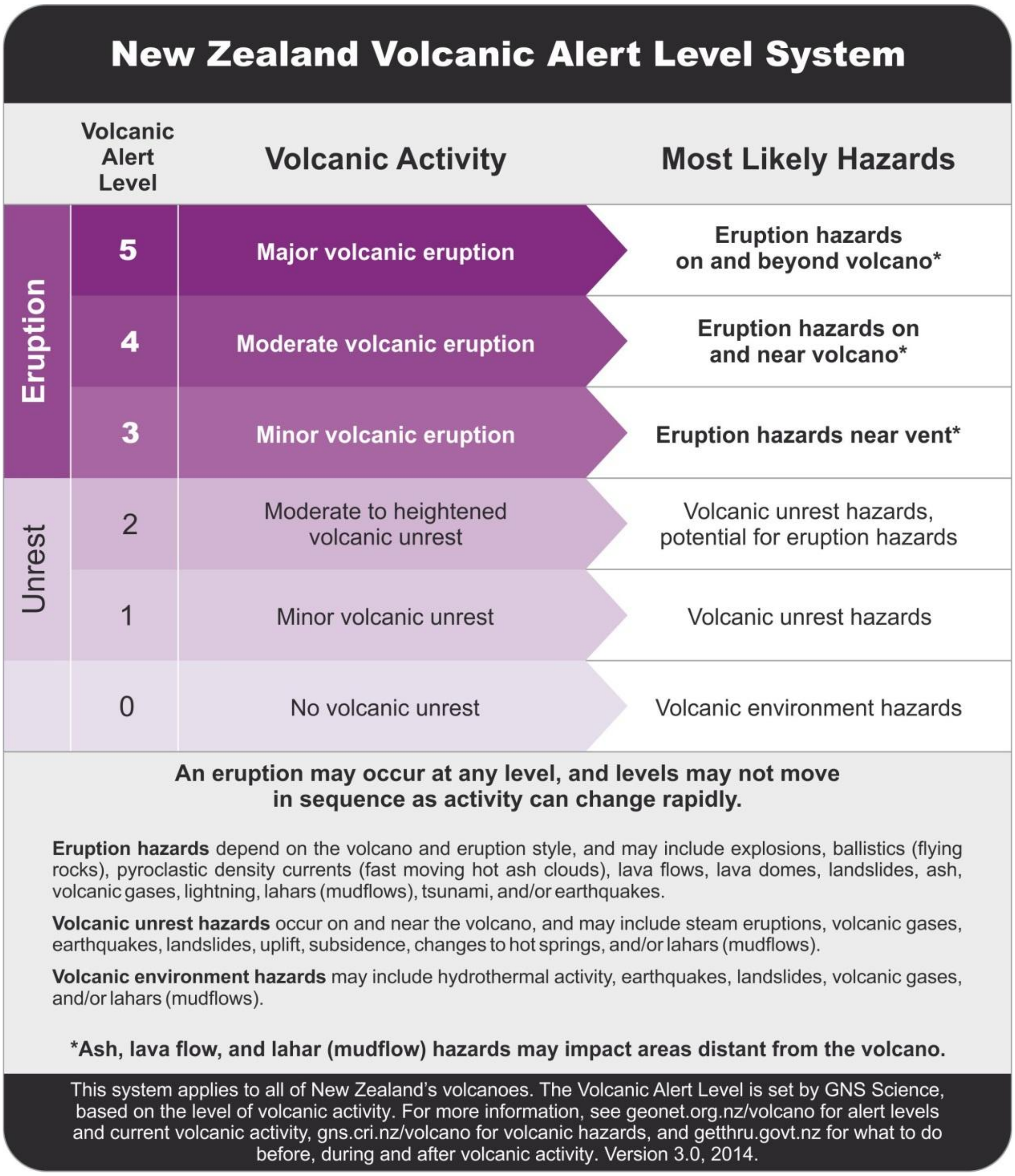

Figure 1. New Zealand's new Volcanic Alert Level system. The most up-to-date system is always accessible via www.geonet.cri.nz/volcano.

Lahar hazard mitigation at Mt Ruapehu

Research into public awareness of, and response to, lahar warnings at one of New Zealand's major ski areas situated on the active Ruapehu volcano has been conducted annually for over a decade. Lahars have travelled through the ski area in multiple eruptions in the last 50 years (e.g., Figure 2 image). Visitors are required to evacuate from lahar-prone valleys immediatly following a siren and voice announcement automatically triggered by eruption sensors. They have as little as two minutes to move to safety and individual and group behaviour amongst visitors and ski area staff must be immediate, decisive and correct. Social research includes:

(a) annual assessment of public and staff responses to simulated events, including truly 'blind' exercises where both staff and the public are un-aware that the warning is an exercise. This has full support from the tourism company operating the ski area, and the Department of Conservation with primary risk management responsibility for the world heritage status national park within which Ruapehu sits.
(b) Awareness surveys of volcanic hazards, recall of education material and messages, and correct actions to take in a warning.
(c) Organisational psychology research into staff behaviour and training needs analysis for specific roles.
(d) Analysis of potential education media and contact points to improve public response to warnings.
(e) Surveys of the demographics of the public who continue to not respond to warnings during exercises, to further direct educational resources.

All of this has indicated potential actions that could be taken to improve future responses, such as increasing ski area staff training (Christianson, 2006) and improving hazard signage (Leonard et al., 2008). It has also lead to technical improvements in hardware performance, audibility and messaging.

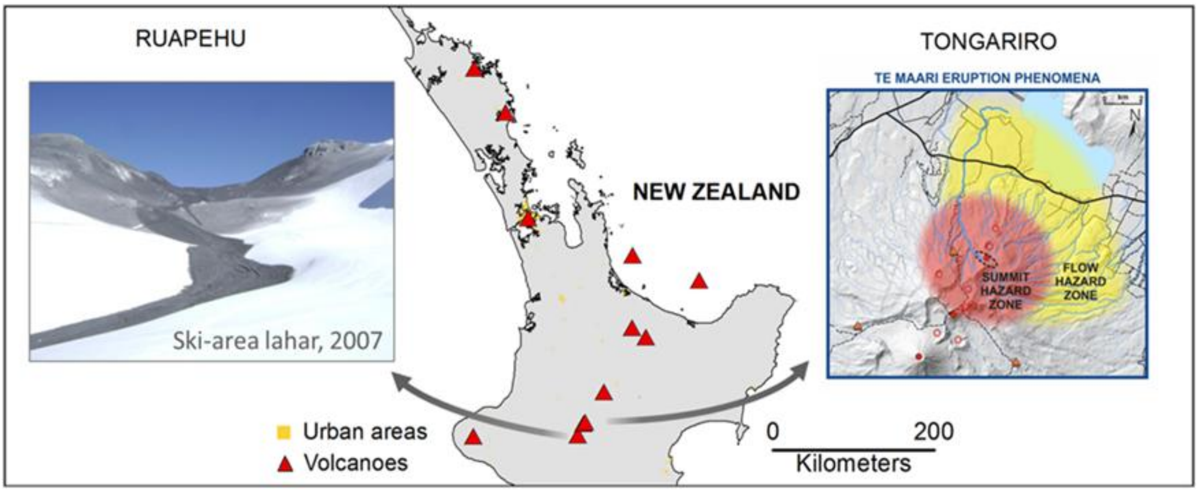

Figure 2. Volcanoes in New Zealand, including a photo of a ski-area lahar at Ruapehu, and the hazard map for Tongariro. The comprehensive Tongariro hazard map can be found at http://gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/Eruption-What-to-do/Hazard-maps

By repeating this research annually and tracking perceptions of visitors through time in response to real events, the communication tools continue to be improved. Surveys demonstrate that tourists appreciate that the hazard is monitored, warned for and that education materials are visible –

leading to strong industry support. A design and communications research project is currently underway to direct new education initiatives to the specific demographics of people seen not responding to warnings.

Tongariro hazard maps

Social research into the perceptions of volcanic hazards and education materials supported the creation of a new volcanic crisis hazard map for eruptions at Mt. Tongariro in 2012 (Figure 2; Leonard et al. (2014)). The area impacted by the eruptions included a section of the popular Tongariro Alpine Crossing walking track, which has nearly 100,000 people passing annually within less than 3 km of the 2012 vent. Requirements of tourists, concessionaires, and local residents were considered alongside scientific modelling and geological information, as well as core messages from emergency management agencies, to produce an effective collaborative communication product.

The crisis map had to accommodate several complex issues:

(1) background hazard maps are used across the many potentially-active vents during non-eruptive periods, but these may not match crisis hazard maps and scenarios with very elevated probability compared to the background;

(2) the scientists' need for conservatism while constraining hazards that were initially in conflict with more probable short term hazards in time-sensitive situations;

(3) hazards tend to grade away spatially and should ideally be shown in a gradual probabilistically-defined way, but maps need to be simple;

(4) messaging covers several severe hazards and actions, needing to be a balance between simplicity to achieve high awareness and not clutter the map, but enough detail to be meaningful; and

(5) the visual representation of elements (1) through (4) on a single piece of paper that can be quickly and correctly comprehended.

Ongoing social research results from Tongariro (Coomer and Leonard, 2005) and Ruapehu were applied to help guide an optimum solution in the face of these issues. International research, especially around the effective presentation of hazard maps (Haynes et al., 2007), and the development of trust amongst scientists, emergency managers and the public (e.g. Barclay et al. (2008), Johnston et al. (1999), Paton et al. (2008)) was also applied.

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Tongariro background and crisis hazard map latest versions can be found in full at: http://gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/Eruption-What-to-do/Hazard-maps

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CS14. Volcano monitoring from space

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2009 eruption of Sarychev Peak, Kuril Islands, seen from the International Space Station (courtesy NASA)

Defining the problem

Unlike many natural hazards, volcanoes usually give warnings of impending eruptions that can be detected from hours to years prior to any hazardous activity (Sparks et al., 2012). The Eyjafjallajökull eruption, for example, was preceded by several discrete episodes of subsurface magma accumulation that highlighted the potential for future eruption (Gudmundsson et al., 2010). Once it begins, an eruption can last for decades, during which time the changing conditions of associated hazards—like ash plumes and lava flows—must be continuously assessed. Unfortunately, the resources and infrastructure needed to conduct ground-based monitoring of a volcano—especially those located in remote areas of Earth that might still have the potential to impact air traffic, like in the north Pacific (Figure 1)—are extreme, and less than 10% of the world's volcanoes are monitored in any systematic way (Bally, 2012). Space-based methods offer a means of bridging this monitoring gap.

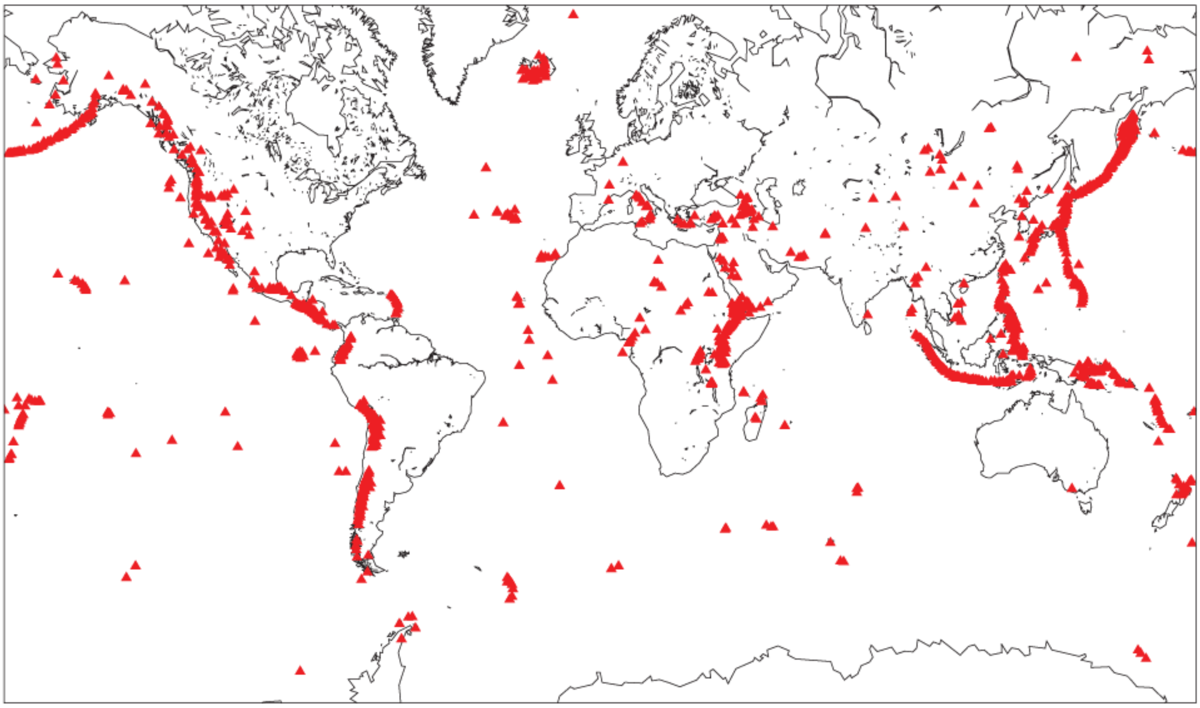

Figure 1. Global map of volcanoes that have erupted within the past 10,000 years (Siebert et al., 2010).

Early warnings

Prior to eruption, most volcanoes provide an indication that magma is ascending towards the surface—most notably through seismicity, ground deformation, thermal anomalies, and elevated gas emissions (Sparks et al., 2012). While earthquake monitoring remains rooted to the terrestrial domain, other expressions of rising magma can be detected from space. Ground deformation, for example, can be mapped by synthetic aperture radar interferometry and sometimes occurs even before earthquake swarms, providing warning of restless volcanoes that might erupt within months to years (Dzurisin, 2003). Unlike ground-based monitoring networks, satellites acquire data over broad swaths, enabling regional surveillance of volcanoes. Observations of entire volcanic arcs—for example, the Andes of South America (Pritchard and Simons, 2004)—have identified numerous volcanoes that are deforming but not erupting (Figure 2). Remote sensing therefore provides leverage for more time- and cost-effective deployment of ground-based resources to the volcanoes that are most likely to erupt and expose population and infrastructure to hazards.

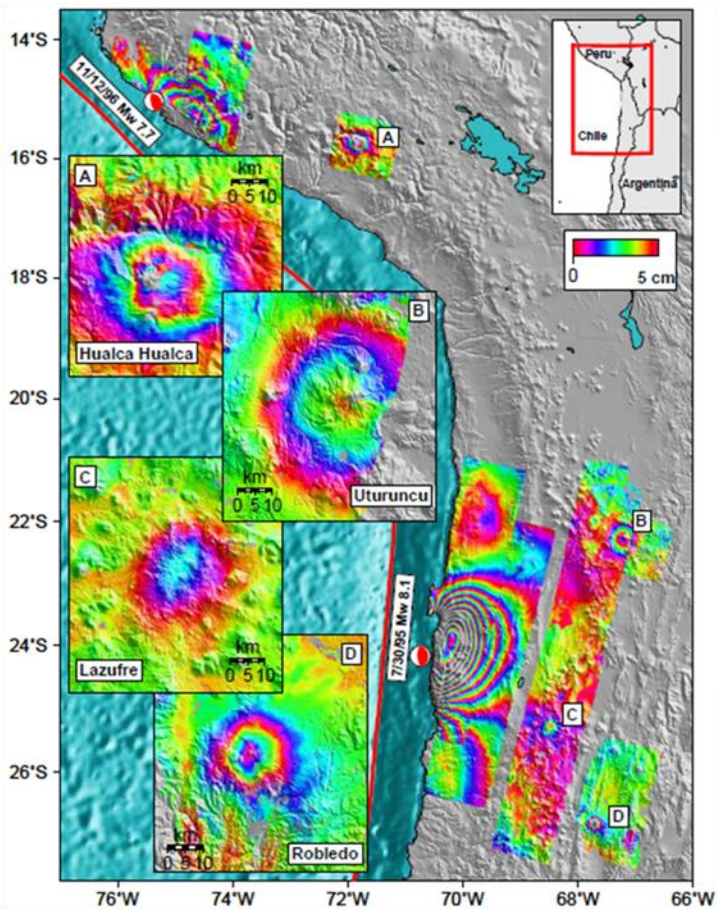

Figure 2. Colour contours of ground deformation draped over shaded relief from three subduction zone earthquakes along the coast and four volcanic centres in Peru, Bolivia, Argentina, and Chile. Each contour corresponds to 5 cm of deformation in the radar line-of-sight direction. Inset maps show higher-resolution interferograms at the four centres of active deformation. Reference map in upper right corner places study area in regional context. Modified from Pritchard and Simons [2004].

Remote-sensing data, primarily from meteorological satellites, also often provide the first indication of unrest or eruptive activity at a volcano. Thermal emissions are tracked by a number of satellite systems, many of which acquire images multiple times per day of the same area on the ground. Near-real-time automated analysis of thermal data is an important alerting tool for eruption onsets and is currently being applied at volcanoes around the world, especially in remote areas (Dehn et al., 2000, Wright et al., 2004). The Alaska Volcano Observatory relies on meteorological sensors for detecting thermal anomalies that can represent precursory heating or lava extrusion, ash clouds, and gas emissions across the 52 historically active volcanoes of the several-thousand-kilometre-long

Aleutian volcanic arc, which, although sparsely populated, is heavily traversed by passenger and cargo aircraft (Schneider et al., 2000). Similarly, daily remote sensing of Kamchatkan and Kurile volcanoes by Russian volcanological authorities is in many cases the sole means of surveillance of dozens of volcanoes that can threaten trans-Pacific aircraft (Neal et al., 2009). At volcanoes that are not monitored by ground-based instruments, satellite data provide the best indication of eruptions that may pose hazards to air travel.

Tracking volcanic hazards

Once an eruption is in progress, timely and repeated satellite data are critical for tracking the evolution of volcanic hazards. Synthetic Aperture Radar (SAR), with meter-scale resolution and ability to "see" though clouds and ash, can detect changes on the surface that might be obscured from thermal/optical satellite data and ground observers. Near-real-time analysis of SAR imagery aided the decision to maintain evacuation zones around Merapi, Indonesia, in 2010—a decision that likely saved several thousand lives when that volcano experienced a large eruption (Pallister et al., 2013). Tracking ash clouds is best accomplished using space-based observations (Pavolonis et al., 2013) and can be used with forecast models to warn downwind communities of impending ash fall and alert air traffic of ash location (Figure 3). Worldwide, Meteorological Watch Offices and Volcano Ash Advisory Centres rely on satellite data for issuing SIGMETs and Volcanic Ash Advisories, which report and forecast ash distribution. The evolution of thermal anomalies in satellite data can track lava and pyroclastic flows, and volcanic gas emissions—an under-appreciated hazard to downwind communities—can be imaged from orbit with better spatial resolution and at lower cost than from the ground (http://so2.gsfc.nasa.gov/), allowing for automated alerts of volcanic plumes.

Figure 3: False-colour visible-infrared image acquired by the Aster satellite over Chaiten volcano, Chile, on 19 January 2009. Vegetation is red, bare or ash-covered ground is grey/brown, ash is light brown, and water is blue. Image shows a thick plume of ash and gas extending to the NNE of the volcano. Image courtesy of NASA (http://earthobservatory.nasa.gov/IOTD/view.php?id=36725).

Bridging the gap

A variety of satellite sensors have repeatedly demonstrated their ability to monitor volcanic unrest, detect eruption onsets, and track eruptive hazards; nevertheless, remote sensing is not yet a globally operational tool for volcano monitoring—some data are costly and not available in near-real time, and resources needed utilise satellite imagery are lacking in many countries. In addition, volcano-monitoring operations are rarely 24/7, so real-time alerting systems, in addition to data management and visualisation software, are required to exploit the volume of potentially available data. To bridge this monitoring, low- or no-cost data are needed with low temporal latency and adequate spatial resolution. In addition, data management systems and capacity-building must be developed to ensure broad use of those data for volcano hazard mitigation and good collaboration across international boundaries where hazards pose more than a local risk. The implementation of this vision, shared throughout the geohazards community, is underway through a number of multi-national projects dedicated to use of remote sensing data for natural hazards risk reduction, including:

- The 2012 "International Forum on Satellite EO and Geohazards," which articulated the vision for volcano monitoring from space (http://www.int-eo-geo-hazard-forum-esa.org/)
- The Geohazard Supersites and Natural Laboratories initiative, which aims to reduce loss of life from geological disasters through research using improved access to multidisciplinary Earth science data (http://supersites.earthobservations.org/)
- The European Volcano Observatory Space Services (EVOSS), which has the goal of providing near-real-time access to gas, thermal, and deformation data from satellites at a number of volcanoes around the world (http://www.evoss-project.eu/)
- The Disaster Risk Management volcano pilot project of the Committee on Earth Observation Satellites (CEOS), which is designed to demonstrate how free access to a diversity of remote sensing data over volcanoes can benefit hazards mitigation efforts

Ultimately, realisation of this vision will depend on commitments from national governments and space agencies to make these data available for disaster risk reduction purposes.

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CS15. Volcanic unrest and short-term forecasting capacity

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Background

Most volcanic eruptions are preceded by a period of volcanic unrest that perhaps is best defined as the deviation from the background or baseline behaviour of a volcano towards a behaviour which is a cause for concern in the short-term because it might prelude an eruption (Phillipson et al., 2013).

Although it is important that early on in a developing unrest crisis scientists are able to decipher the nature, timescale and likely outcome of volcano reawakening following long periods of quiescence there are still major challenges when assessing whether unrest will lead to an eruption in the short-term or wane with time.

Analysis of volcanic unrest

An analysis of 228 cases of reported volcanic unrest between 2000 and 2011 (Phillipson et al. (2013); Fig. 1) recognises five primary observational (predominantly geophysical and geochemical) indicators of volcanic unrest:

Ground deformation: Restless volcanoes often undergo periods of ground uplift or subsidence driven for example by pressure changes in their magma reservoir or overlying geothermal reservoir. In some cases pressure increase may break the ground surface. Ground deformation is generally recorded by ground or space-borne techniques (see also CS14).

Degassing: Plumes of gas may be released from craters or other vents (fumaroles) on a volcanic edifice craters. Alternatively the amount of gas released may increase or the chemical composition of gases may change over time. Ground and space-borne techniques are usually applied to monitor degassing behaviour (see also CS14).

Changes at a crater lake: These changes include variations in lake temperature, lake levels, level of water chemistry, lake colour and gas release and are generally recorded using ground-based or air-borne techniques.

Thermal anomaly: Anomalous temperature changes of the ground or of fumarolic gases can be recorded by ground-based, air or space-borne sensors (see also CS14).

Seismicity: The movement of magma, fluids and gas can cause seismic signals at restless volcanoes as does the breaking of rock from stress increases at depth. Particular seismic wave forms are generated from such processes which may provide clues as to what is driving unrest at a particular volcano. Seismic observations are generally made on the ground.

The same study also recognises five idealized classes of volcanic unrest based on the temporal behaviour of these five most-commonly reported unrest indicators which can be depicted in unrest timelines and whether or not eruptive behaviour resulted from the unrest. These classes of unrest include reawakening, prolonged, pulsatory, sporadic and intra-eruptive unrest. An example of pulsatory unrest is shown in Figure 2 for the case of Cotopaxi volcano in Ecuador. This volcano underwent a non-eruptive period of unrest during 2001 and 2003. Pulsatory unrest consists of episodes of unrest activity (lasting for days) separated by intervals of days to weeks without activity. In contrast, prolonged unrest is often expressed by long-term (years to decades) ground deformation, which may only be identifiable at volcanoes with a long-term geodetic monitoring network or satellite remote sensing.

Phillipson et al. (2013) also showed that unrest episodes at different types of volcanoes have different median unrest durations before the start of an eruption. At stratovolcanoes they last for a few weeks while at calderas their median length is two months. Shield volcanoes have the longest median unrest duration at 5 months. However, volcanoes with long periods of quiescence between eruptions do not necessarily undergo long periods of unrest before their next eruption.

To improve the knowledge-base on volcanic unrest, a globally-validated protocol for the reporting of volcanic unrest (Newhall and Dzurisin, 1988) and archiving of unrest data is needed (Venezky and Newhall, 2007). Such data are important for the short-term forecasting of volcanic activity amid technological and scientific uncertainty and the inherent complexity of volcanic systems.

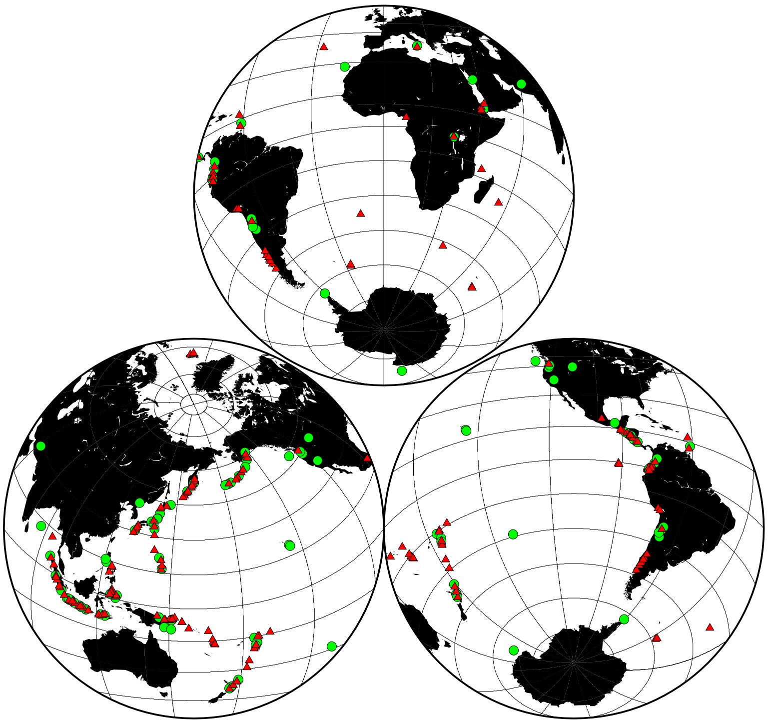

Figure 1: Location maps of 228 volcanoes with reported unrest between January 2000 and July 2011. Green circles show volcanoes with unrest not followed by eruption within reporting period, while red triangles show those with eruption.

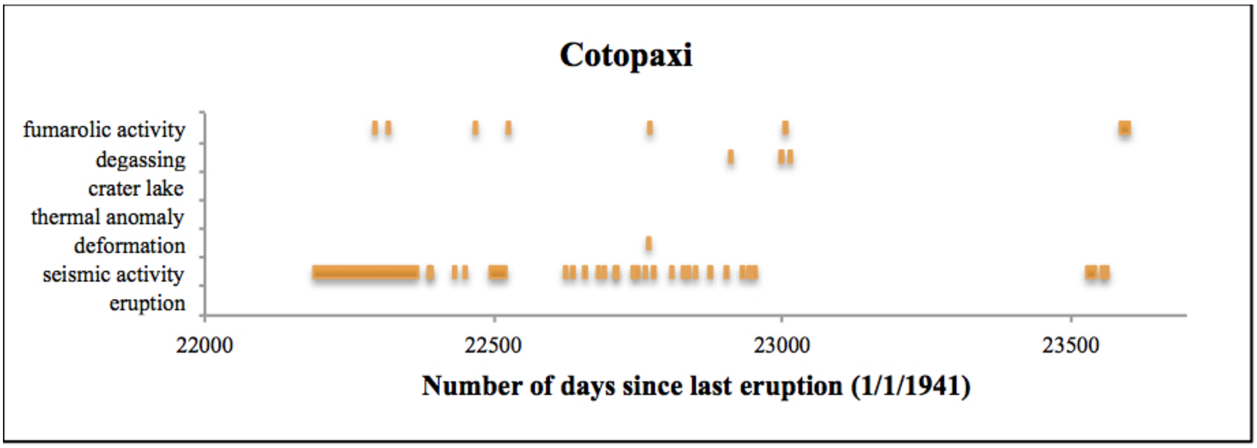

Figure 2: An example of a pulsatory unrest timeline using five key unrest indicators from Cotopaxi volcano in Ecuador from 27/3/2001 to 21/11/2005 (modified from Phillipson et al. (2013)). This episode of intense unrest did not culminate in an eruption.

Short-term forecasting capacity

Forecasting the outcomes of volcanic unrest requires the use of quantitative probabilistic models (Marzocchi et al., 2008, Marzocchi and Bebbington, 2012, Sobradelo et al., 2014) to address adequately intrinsic (epistemic) uncertainty as to how a unrest process may evolve as well as aleatory uncertainty regarding the limited knowledge about the process. Probabilistic forecast models applied in modern volcanology follow event tree structures which allow conditional probabilities to be attributed to different possible future eruptive or non-eruptive scenarios in an evolving unrest crisis.

An example of individual notes of an event tree structure of the HASSET (Sobradelo et al., 2014) probabilistic forecasting tool is shown in Fig. 3. This event tree includes unrest scenarios that culminate in an eruption but also those that do not. For the probabilistic assessment of outcomes of volcanic unrest it is particularly important to assess a number of scenarios regarding the causes of unrest such as magma movement, geothermal excitation, tectonic activity or other processes. It is crucial to discriminate between unrest caused by internal triggers (magma movement) or by external triggers (regional tectonics), which ultimately condition the outcome and further development of unrest.

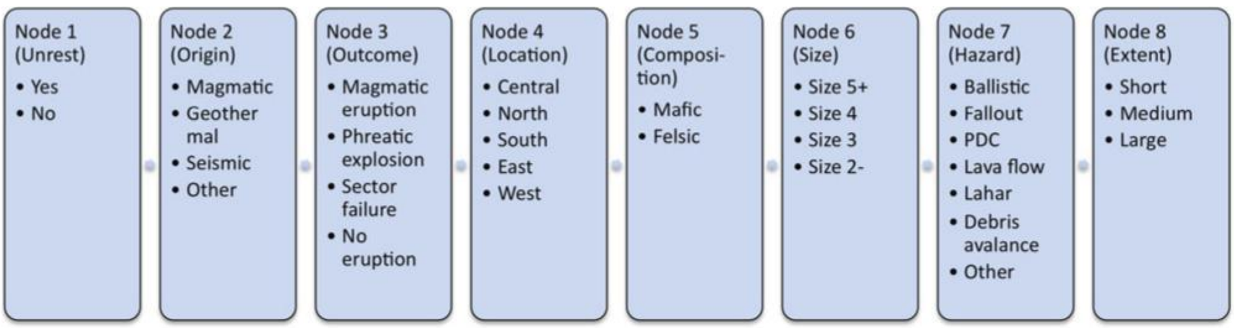

Figure 3. Event tree structure of the HASSET probabilistic forecasting tool (from Sobradelo et al. (2014)) formed by eight individual nodes and corresponding mutually exclusive and exhaustive branches. By the condition of independence of the nodes, the probability of a particular volcanic scenario, as a combination of branches across nodes, is the product of the individual probabilities of occurrence of each branch in that scenario.

Probabilistic forecasts may influence selection of appropriate mitigation actions based on informed societal or political decision-making. Properly addressing uncertainties is particularly critical for managing the evolution of a volcanic unrest episode in high-risk volcanoes, where mitigation actions require advance warning and incur considerable costs (Marzocchi and Woo, 2007). A major evacuation over a period of 4 months in excess of 70,000 individuals on Guadeloupe in the French West Indies in 1976 (see also CS5) was initiated as a result of abnormal levels of volcanic background activity, which culminated in a series of eruptions of hot gas, mud and rock, before waning. Fortunately, no life was claimed by the activity, however, the estimated cost of the unrest was about US$1bn in current currency. 90% of these costs were incurred by the evacuation, rehabilitation and salvage of the French economy. This in turn suggests that had the outcome of the unrest on Guadeloupe been predicted correctly the cost of the unrest would have been almost negligible. At the same time it is now acknowledged that the "proportion of evacuees who would have owed their lives to the evacuation, had there been a major eruption, was substantial" (Woo, 2008).

An improvement of the knowledge base on causes and consequences of volcanic unrest is shared the geohazards community. A number of multi-national projects are dedicated to working towards a better understanding of volcanic unrest including:

- The VUELCO project (http://www.vuelco.net), a European Commission-funded project on volcanic unrest in Europe and Latin America.
- The European Commission-funded MEDSUV (http://med-suv.eu) and FUTUREVOLC (http://futurevolc.hi.is) projects as part of the Geohazard Supersites and Natural Laboratories initiative (http://supersites.earthobservations.org/)
- The WOVOdat database, which enables the comparison of volcanic unrest data using time-series and geo-referenced data from volcano observatories worldwide in common and easily accessible formats (http://www.wovodat.org)

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CS16. Global monitoring capacity: development of the Global Volcano Research and Monitoring Institutions Database and analysis of monitoring in Latin America

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Background

Volcanic eruptions can cause loss of life and livelihoods, damage critical infrastructure, and have long-term impacts, including displaced populations and long-lasting economic implications. Many factors contribute to disasters from natural hazards. One of these is the institutional capacity to enable hazard assessment for pre-emergency planning to protect populations and environments, provide early warning when volcanoes threaten to erupt, to provide forecasts and scientific advice during volcanic emergencies, and to support post-eruption recovery and remediation. Volcano observatories play a critical role in supporting communities to reduce the adverse effects of eruptions (CS12). Their capacity to monitor volcanoes is thus a central component of disaster risk reduction.

The resources are not available for extensive monitoring of all 596 historically active volcanoes. The availability of resources varies on local, national, regional and global scales, resulting in highly variable monitoring levels from volcano to volcano. Some countries have observatories dedicated to volcano monitoring, others monitor from within larger organisations, and still others have no permanent monitoring group. Individual volcanoes may have large comprehensive monitoring networks of multiple monitoring systems whilst a neighbouring volcano is unmonitored.

It is therefore vital to understand the monitoring capacity at local, national, regional and global scales to establish how well volcanoes are monitored, the distribution of monitoring equipment, the human resources, experience and education and the instrumental and laboratory capabilities. To this end a database has been developed: Global Volcano Research and Monitoring Institutions Database (GLOVOREMID).

GLOVOREMID

In 2011 IAVCEI funded the development of VOMODA (Volcano Monitoring Database), whose main purpose was to obtain a realistic diagnosis of volcano monitoring and training of the human resources working on volcanological research and monitoring institutions (VRMI) in Latin America. In 2013, VOMODA was adopted and adapted for worldwide use as GLOVOREMID. The Global Volcano Model (GVM) supports this work. It is currently in both Spanish and English. This database will contribute to improving communication and cooperation between scientists and technicians responsible for volcano monitoring and may help to reduce the effects of volcanic crises. GLOVOREMID can be accessed online via http://132.248.182.158/glovomoda/.

Database development

The structure of GLOVOREMID was designed using a relational model. This consists of a set of tables and links that maintain information related to: volcanoes, VRMI, instrumentation and human resources responsible for volcanic surveillance. The development of the tables and relations in GLOVOREMID was completed under the normalisation method, which is a process of organizing data to minimise redundancy (Kendall and Kendall, 2010).

In order to achieve compatibility of GLOVOREMID with other existing volcanological databases, principally the Volcanoes of the World database of the Smithsonian Institution (VOTW4.0, Siebert et al. (2010)) and the Large Magnitude Explosive Volcanic Eruptions database (LaMEVE, Crosweller et al. (2012)) of the Volcano Global Risk Identification and Analysis Project (VOGRIPA), the same volcano identification codes are used and relevant data were transferred from these databases into GLOVOREMID.

For the development and implementation of GLOVOREMID KumbiaPHP Framework (Comunidad KUMBIAPHP, 2012), PHP language and MYSQL engine were used. Model View Controller (MVC) was used for the architectural pattern giving a natural code organisation (De la Torre, 2010). All views were developed with HTML5 and JAVASCRIPT. The system works as follows: a query comes from browser to controller; the controller interacts with the model that is able to make data transactions directly to the engine database. Finally, the controller sends data in order to visualise it using a view (Figure 1).

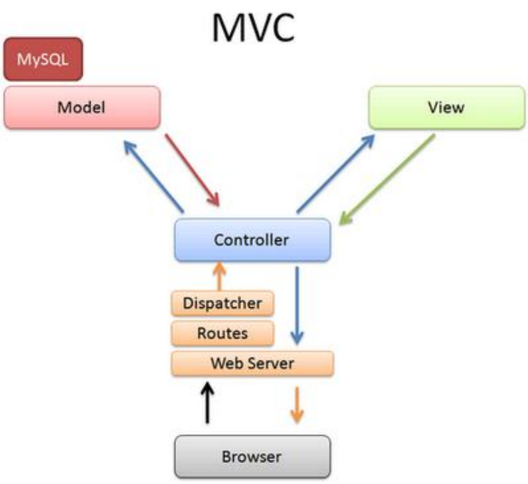

Figure 1: Model view controller pattern in GLOVOREMID.

GLOVOREMID is hosted on a server at the Instituto de Geofísica (UNAM). After development, the VRMI data was collected and entered into the database. Multiple users can be authorised and those working within VRMI are being given access. It is these users who are responsible for data updates. GLOVOREMID is anticipated as a global, sustainable database, accessible to and updated by those involved with volcano research and monitoring, to allow better communication and collaboration between scientists, to highlight knowledge gaps and areas where funding, training and equipment should be prioritised and perhaps even facilitate the sharing of equipment with un- or under-monitored regions as activity develops. GLOVOREMID is in the early stages of population globally, but, as it is expanding from VOMODA, is well populated for Latin America.

Monitoring in Latin America

VOMODA was developed as part of the IAVCEI project “Weaknesses and strengths in Latin America facing volcanic crises: a research for improvement of national capabilities”, and hence focussed on countries of Latin America.

Figure 2: Representation of the Latin American VRMI that populate VOMODA.

Volcanoes with known or suspected Holocene activity, as recorded in VOTW4.0, are included in the database. Additional as yet unidentified volcanoes, or volcanoes with few studies or infrequent activity may also require further research or monitoring. Where volcanoes lie on the border between two countries some may be monitored by one or more VRMI. The VRMI responsible for the volcanoes are identified and were contacted to join the database and provide monitoring information.

There are many methods for monitoring volcanoes, many of which are widespread. On local scales institutions may favour particular monitoring methods or derive their own methods using the resources available to them. The database allows the recording of many types of instrumentations and methods, and can be expanded to include new methods.

To determine the monitoring level for each volcano three main lines of monitoring were chosen: seismology, deformation and gas. Monitoring levels were chosen of 0 – 5 based on the use of these three methods. A volcano with no seismic, deformation or gas monitoring is classed at Level 0. Level 1 is assigned when using only seismic stations. Level 2 is assigned when the volcano is monitored with seismic stations and at least one deformation station, and increasing levels represent increasing deformation and gas stations. A very well monitored volcano is that of Level 5, indicative of seismology, deformation and gas monitoring through multiple stations (Figure 3). For example, Level 5 could represent a volcano with a seismic network, GPS station, EDM line, SO_2 and CO_2 monitoring.

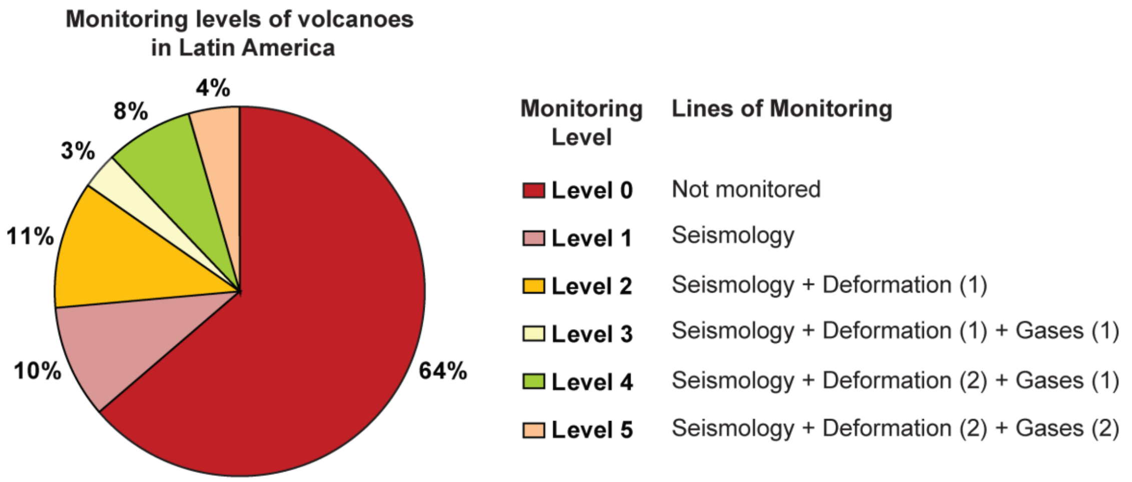

Figure 3: Monitoring levels for 314 Holocene volcanoes in Latin America and assignment of monitoring levels.

There are 314 Holocene volcanoes in Latin America (across the regions of Mexico and Central America and South America). 159 of these volcanoes have confirmed eruptions recorded during the Holocene in VOTW4.0, 113 of which have confirmed historical activity. It is intuitive that a correlation between the age of eruptions and the monitoring level may exist.

Monitoring Level	Number of Latin American volcanoes	% of total Latin American volcanoes	% of monitored Latin American volcanoes
0	202	64%	-
1	30	10%	27%
2	35	11%	31%
3	10	3%	9%
4	24	8%	21%
5	13	4%	12%

Table 1: The number of volcanoes across Latin America that classify with each level of monitoring.

202 Latin American volcanoes classify as Level 0 (i.e. unmonitored). Mexico and Chile have the largest number of unmonitored volcanoes (32 and 50 respectively). These countries host the largest number of volcanoes in Latin America. 64% of Chilean volcanoes and 82% of Mexican volcanoes are unmonitored. Three countries have no *on-site* monitoring at any of their volcanoes: Argentina, Bolivia and Honduras, however, volcanoes on the Chile-Bolivia and Chile-Argentina borders are monitored. Neither Bolivia nor Honduras has recorded Holocene eruptions, with the exception of volcanoes along the Bolivia and Chile border. Four volcanoes in Argentina, excluding those on the border with Chile, have confirmed eruptions as recently as 1988.

86% of unmonitored volcanoes have no recorded historic eruptions. However 30 unmonitored volcanoes have 95 eruptions recorded between 1505 and 2008 AD (Table 2). These eruptions ranged in magnitude from VEI 0 – 5, with four volcanoes producing five large explosive VEI ≥4 eruptions in this time (Cerro Azul in Ecuador, VEI 5 eruption of 1916; Michoacán-Guanajuato in Mexico with two VEI 4 eruptions in 1759 and 1943; Carrán-Los Venados in Chile with the VEI 4 eruption of 1955; Chaitén in Chile with the VEI 4 eruption of 2008). There are populations living within 100 km distance of these 4 volcanoes, with Population Exposure Indices (PEI) of 2 – 7 (see CS1). Over 5.7 million people live within 10 km of Michoacán-Guanajuato volcanic field, ranking this as the most populous volcano (10 km) worldwide, however this is due to the wide distribution of vents in the ~50,000 square kilometre volcanic field. This volcanic field currently has no ground-based monitoring systems specifically designed for volcano monitoring, however regional monitoring networks are available. A further four Latin American volcanoes are Monitoring Level 0 with historical activity and high PEI levels of 5 to 7. Most of the unmonitored historical volcanoes have no hazard classification (see CS19), with just three Hazard Level I and two Hazard Level II volcanoes; risk levels are unclassified for those 25 unmonitored historically active volcanoes with no hazard classification, whilst the majority of classified volcanoes in this group fall in the Risk Level I category (Table 2).

CLASSIFIED	**Hazard III**							
	Hazard II		**Yucamane**				**Atitlán**	Chichinautzin
	Hazard I		**Cerro Azul; Lautaro; Wolf**					
UNCLASSIFIED	**U – HHR**	Robinson Crusoe; Bárcena; Socorro	Huanquihue Group; Putana; Olca-Paruma; Pinta; Viedma; Fueguino; Sumaco; Burney, Monte; Arenales; Darwin; Marchena; Irruputuncu; Tromen; Llullaillaco; Reclus; Santiago	Chaitén; Carrán-Los Venados		Chacana	Acatenango	Almolonga; Michoacán-Guanajuato
	U- HR	Aliso	Aguilera; Antillanca Group; Cayutué-La Viguería; Ecuador; Infiernillo; Longaví, Nevado de; Palei-Aike Volcanic Field; Yanteles	Caburgua-Huelemolle; Huambo; Soche; Sollipulli	Andahua-Orcopampa; Cumbres, Las; Quimsachata; Romeral	Cofre de Perote; Malinche, La; Tecuamburro	Jocotitlán; Naolinco Volcanic Field; Zitácuaro-Valle de Bravo	Nejapa-Miraflores
	U- NHHR	5 volcanoes	80 volcanoes	8 volcanoes	12 volcanoes	14 volcanoes	24 volcanoes	4 volcanoes
		PEI 1	**PEI 2**	**PEI 3**	**PEI 4**	**PEI 5**	**PEI 6**	**PEI 7**

*Table 2: Latin American volcanoes with Monitoring Levels of 0 (unmonitored) shown with their hazard level (see CS19) and PEI (see CS1). The top section shows those volcanoes with a classified hazard level; the historically active volcanoes are shown in **bold** and the warming of the background colours indicates increasing risk levels. Those volcanoes with no hazard classification are shown in the lower section, where historically active volcanoes are shown in section U-HHR; volcanoes with a Holocene record but no historical activity are shown in U-HR; the number of volcanoes with no confirmed Holocene records are shown under U-NHHR*

112 Latin American volcanoes are monitored using seismic, gas or deformation stations. 30 volcanoes (10% of Latin American volcanoes, Table 1) classify as Monitoring Level 1, including 11 with no recorded historical activity (Table 3). About half of these are in well populated regions and 11 classify at Hazard Levels II – III. Of the monitored volcanoes, 35 classify as Monitoring Level 2 making a combination of seismic and deformation monitoring the most popular choice. Further detail is available in the database regarding the type of deformation studies being used (e.g. INSAR, GPS, EDM). 47 volcanoes are classified at Monitoring Levels 3 – 5, indicating that all three monitoring methods are used at 15% of the Latin American volcanoes. Just three countries have monitoring levels of 3 – 5 at over 50% of their *monitored* volcanoes: Mexico (86% of monitored volcanoes here – 6 out of 7), Costa Rica (75% - 6 out of 8) and Colombia (62% - 8 out of 13) indicating that several lines of monitoring are used here and that where monitoring is used in these countries, it is comprehensively undertaken.

Monitoring Level	**Number and % of Latin American volcanoes with historical activity**		**Number and % of Latin American volcanoes with no historical activity**	
	Number	%	Number	%
0	30	27%	172	86%
1	19	17%	11	5%
2	25	22%	10	5%
3	10	9%	0	0%
4	18	16%	6	3%
5	11	10%	2	1%

Table 3: The number of volcanoes with and without historic activity in Latin America. Percentage is percentage of each age group.

Just 13 volcanoes throughout Latin America are at the highest monitoring level (Level 5) with seismic stations and two or more deformation and gas analysis techniques. All but Cuicocha in Ecuador and Cerro Machín in Colombia have recorded historical activity, but both have recent signs of unrest including elevating lake temperatures at Cuicocha (Gunkel et al., 2008) and seismic activity at Cerro Machín. Well monitored Latin American volcanoes (Monitoring Levels (ML) 3 – 5) have low to high PEI levels and hazard and risk levels of I to III, however, most ML5 volcanoes have high levels of hazard and risk, and fatalities in the historic record (Table 4).

The largest numbers of monitored volcanoes are located in Chile, representing just 36% of volcanoes in this country. Countries with high proportions of monitored volcanoes are Colombia (87%), Costa Rica (80%) and Ecuador (53%), with monitoring levels ≥1 (Figure 6). Colombia and Ecuador also have the highest number and highest proportion of volcanoes at Monitoring Level 5, however only about half of the historically active volcanoes of Ecuador are monitored (Figure 7). Four Latin American countries have monitoring at all historically active volcanoes: Colombia, Costa Rica, El Salvador and Nicaragua.

CLASSIFIED	Hazard III			Reventador	Cerro Bravo; Colima; Cotopaxi; Tungurahua	Irazú; Turrialba; Guagua Pichincha; Nevado del Ruiz	Galeras	
	Hazard II		Fernandina; Planchón-Peteroa; Antuco; Chillán, Nevados de; Copahue; Láscar;	Rincón de la Vieja; Ubinas		Santa Ana; Popocatépetl		
	Hazard I		Sierra Negra, San Pedro	Maipo	Arenal; Puracé; El Misti	Poás		
UNCLASSIFIED	U – HHR		Callaqui; Descabezado Grande; Cerro Hudson; Mentolat; Ticsani; Tinguiririca		Chichón, El; Cumbal; Miravalles; Nevado del Huila; San Martín	Ceboruco		
	U- HR		Corcovado; Maca; Melimoyu			Azufral; Machín	Nevado de Toluca; Cuicocha	
	U- NHHR		1 volcano					
		PEI 1	PEI 2	PEI 3	PEI 4	PEI 5	PEI 6	PEI 7

*Table 4: Well monitored Latin American volcanoes (Monitoring Levels 3-5; ML3 in green, ML4 in purple, ML5 in black) shown with their hazard level and PEI. The top section shows those volcanoes with a classified hazard level; the historically active volcanoes are shown in **bold** and the warming of the background colours indicates increasing risk levels. Those volcanoes with no hazard classification are shown in the lower section, where historically active volcanoes are shown in section U-HHR; volcanoes with a Holocene record but no historical activity are shown in U-HR; the number of volcanoes with no confirmed Holocene records are shown under U-NHHR.*

Analysis of the data provided for VOMODA in 2012 shows that with just 13% and 20% respectively of Colombian and Costa Rican volcanoes being unmonitored and 100% of their historically active volcanoes having some monitoring, these countries are proportionally top for having at least minimal monitoring standards at their recognised Holocene volcanoes. Coupled with the monitoring of over 50% of their volcanoes at Levels 3 – 5, these countries show the most comprehensive monitoring regimes. With 200 unmonitored volcanoes throughout Latin America, including 30 unmonitored historically active volcanoes, resources may be required to better equip the region for anticipation and monitoring of volcanic activity.

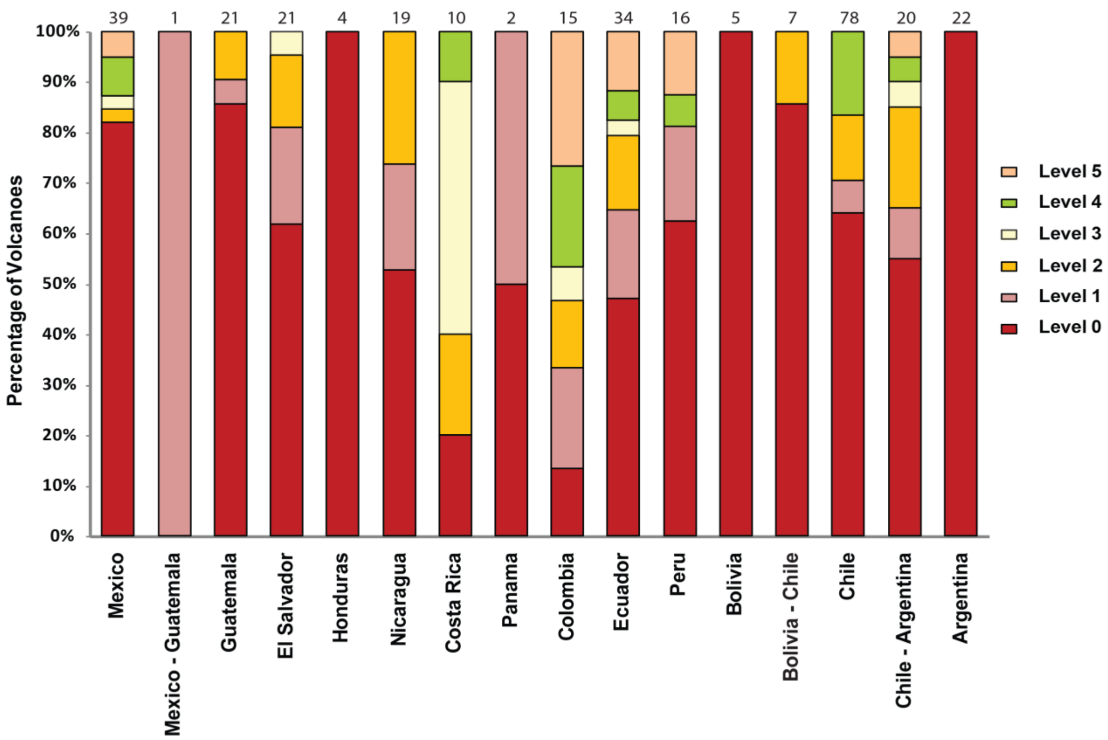

Figure 6: The percentage of all volcanoes in each Latin American country classified at Monitoring Levels 0 - 5. Data provided in 2012.

Conclusions

Efforts are underway to populate GLOVOREMID for a global dataset of VRMI and instrumentation. Further work and international cooperation with the global volcanological community is required to expand this database and the analysis of the data contained within it. Ultimately, an aim is to allow continuous data updates and to embed GLOVOREMID in other global volcanic databases in order to perform ongoing analyses of volcanic activity and monitoring.

GLOVOREMID allows a comparison between the number of active volcanoes and the investment in monitoring resources for each country. In combination with the Hazard Levels and Population Exposure Index it can be used to investigate the monitoring of high risk volcanoes as global data is collated. The database will encourage cooperation between volcano monitoring institutions by facilitating the exchange of expertise in monitoring techniques as well as lessons learned from managing previous volcanic crises.

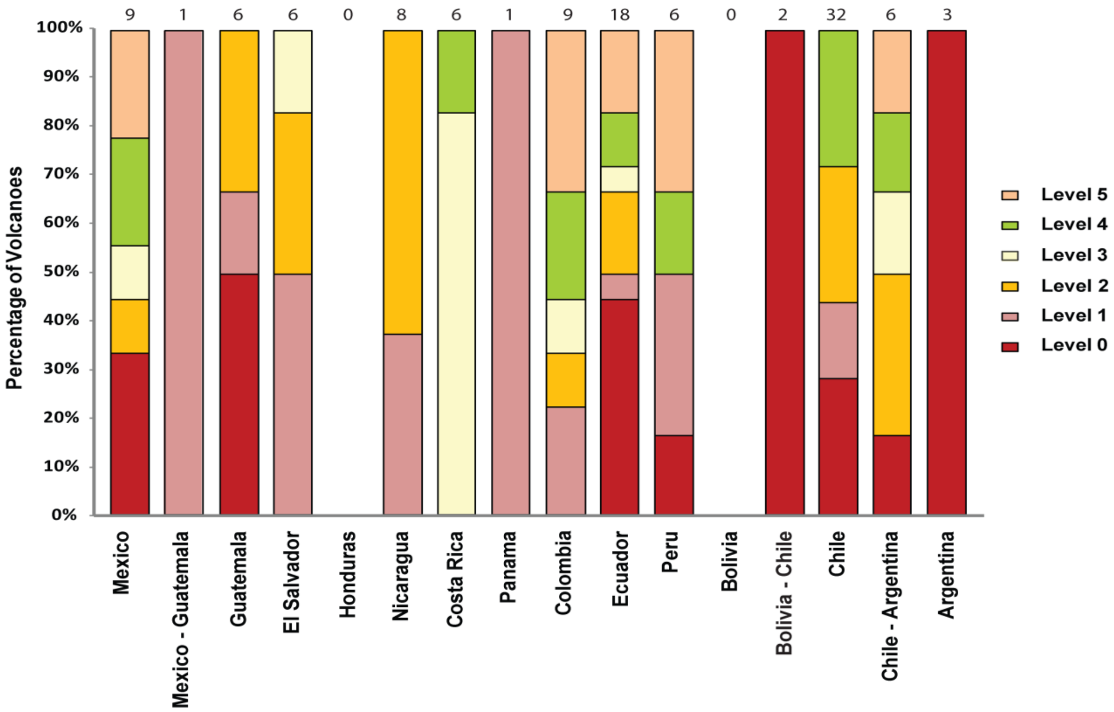

Figure 7: Monitoring levels of historically active volcanoes through Latin America.

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CS17: Volcanic Hazard Maps

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Introduction

Generating hazard maps for active or potentially active volcanoes is recognised as a fundamental step towards the mitigation of risk to vulnerable communities (Tilling, 2005). The responsibility for generating such maps most commonly lies with government institutions but in many cases input from the academic community is also relied on. Volcanic hazard maps communicate information about *a suite* of hazards including tephra (ash) fall, lava flows, pyroclastic density currents, lahars (volcanic mudflows), and debris avalanches (volcanic landslides). The hazard footprint of each of these depends, to a first order, on whether they are erupted into the atmosphere (and therefore dominated by transport in the atmosphere), or whether they form flows which travel along the ground surface away from the volcano. For each hazard type, the magnitude (volume) and intensity (discharge rate) of the event also determines the extent of the footprint. Tephra fall differs from the other hazards in that it can have proximal-to-regional and in extreme cases, global effects. The other hazard types characteristically affect the environs of the volcano, with the most mobile types, lahars and pyroclastic density currents, capable of reaching distal drainages over 100 km from the volcano.

It is of critical importance to understand that a wide variety of methods are currently employed to generate hazard maps, and that the respective philosophies on which they are based are equally diverse, as well as to acknowledge the notion that one model cannot fit all situations. Some hazard maps are based solely on the distribution of prior events as determined by the geology, others take into account estimated recurrence intervals of past events, or use computer simulations of volcanic processes to gauge potential future extents of impact. Increasingly, computational modelling of volcanic processes is combined with geological information and statistical models in order to develop fully probabilistic hazard maps.

Types of Volcanic Hazard Maps Currently in Use

A preliminary review of hazard maps has recently been carried out by the authors. The review was based on 120 hazard maps, which were available either in print form, or electronically from legitimate sources on the internet, such as government institution websites. The hazard maps have been categorised into five main families depending on the type of information incorporated in the map and how it is conveyed (Figure 1):

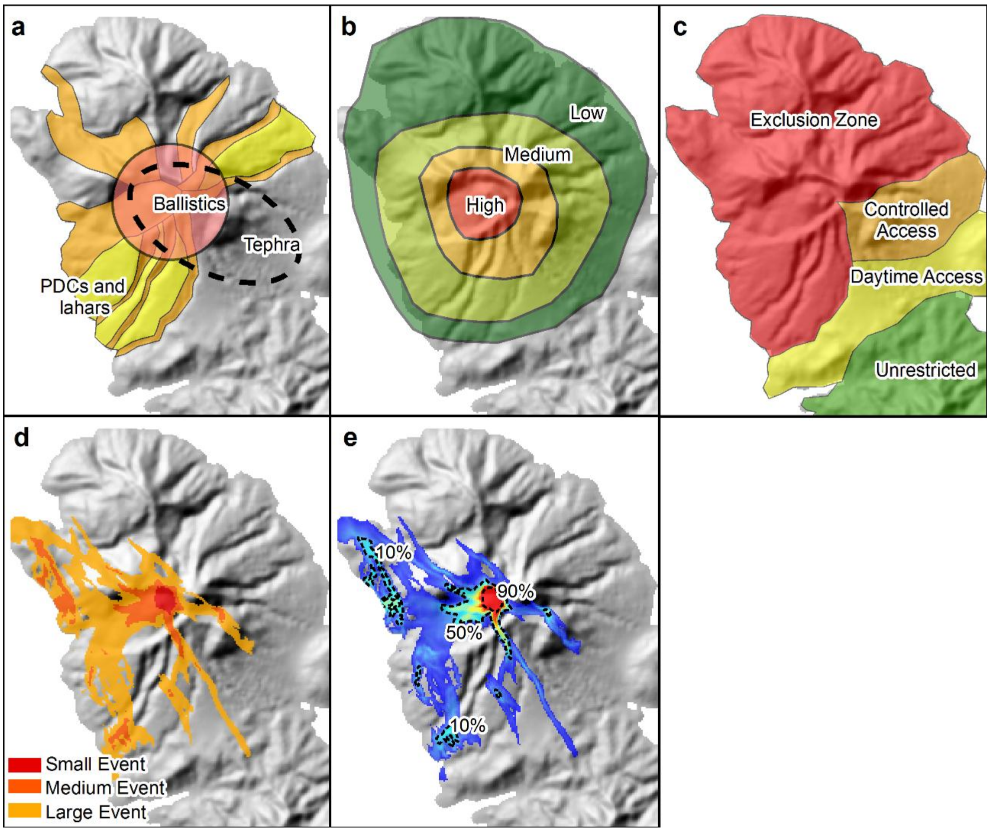

Figure 1: Examples of the five predominant hazard map types found during the review. ***a)*** *Geology-based map,* ***b)*** *Integrated qualitative map,* ***c)*** *Administrative map,* ***d)*** *Modelling-based map and* ***e)*** *Probabilistic map. These examples are not from a real volcano, they are based on a synthetic topography in order to demonstrate the variability in appearance of such maps for the same topography.*

Geology-based maps: Mapped hazard footprints are based directly on the past occurrence of specific types of events. An important limitation of this type of map is that the geological record is an incomplete catalogue of events so that the distribution and extent may reflect previous events, but not all possible future events. Furthermore, the geological record can also be biased by preferentially preserving deposits from larger eruptions and because some deposits of very violent eruptions, such as those formed by volcanic blasts, are easily eroded.

Integrated qualitative maps: All available hazard information is amalgamated, resulting in simple, often concentric-type, hazard zones. The source of the information may be geology and/or modelling. These maps may be more effective for communication because they are simple. Relative hazard is communicated qualitatively (see CS13 Tongariro).

Modelling-based hazard maps: Involve scenario-based application of simulation tools often for a single hazard type.

Probabilistic hazard maps: Maps based usually on the study of a single hazard using stochastic application of computer simulations. The principal limitations are that these maps deal with a single hazard, are sometimes complex to interpret or communicate and include uncertainties associated with the simulation tool or model input parameters (See CS3 Vesuvius).

Administrative maps: These maps are not designed to show hazard distribution, but instead combine hazard levels with administrative needs and are constructed specifically to aid in emergency management. These maps usually inherently contain information about hazard distribution, but the geoscience content may be somewhat opaque.

Based on the review, the hazards of most widespread concern, as indicated by frequency of occurrence on hazards maps are: lahars, pyroclastic density currents (PDCs), tephra fall, ballistics, lava flows, debris avalanches, and monogenetic eruptions (Figure 2a). 75% of maps include lahars and/or PDCs and 63% include tephra. Less than half include lava and/or debris avalanches, while less than 10% include hazards associated with unknown source locations, such as monogenetic eruptions. Those maps based solely on the geologic history of the area are significantly more common (63%) than all other map types (Figure 2b). Integrated qualitative maps make up 17% of hazard maps. Hazard maps indicate likelihood, in some form, to show the relative degree of hazard affecting the map area. The likelihood of impact can be expressed quantitatively or qualitatively, explicitly or generally. It is noteworthy that 83% of all hazard maps use simple qualitative "high-med-low" designations to indicate level of probability of impact. Such designations however, are open to wide interpretations.

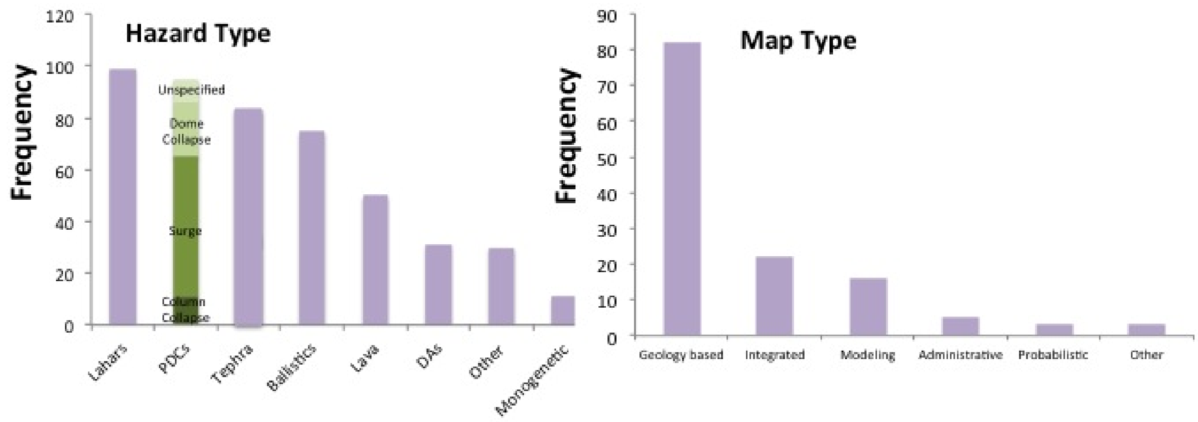

Figure 2a. *Types of hazards in the 120 maps reviewed, including: lahars, PDCs, tephra fall, lava flows, debris avalanches and monogenetic volcanism. PDCs were further distinguished based on specific type (column collapse, surge, dome collapse, or unspecified).* ***b)***. *Hazard maps can be subdivided into categories based on how and what information is conveyed. Those based solely on the geologic history of the area are significantly more common (63%) than all other map types. Map complexity increases to the right as the number of maps in that category decreases.*

Modelling and Uncertainty Quantification in Hazard Maps

The computational models used for hazard mapping comprise two main types (i) complex fluid dynamics and solid mechanics models that attempt to capture as much of the underlying physics of a process as possible; (ii) empirical, or abstracted, models that capture the essence of a complex process. Most commonly it is the latter type of models that are used for hazard mapping (e.g. Iverson et al. (1998), Bonadonna (2005). Simulations are used to indicate the outcome of an eruptive scenario, or set of scenarios (i.e. applied deterministically); or, less frequently, uncertainty is taken into account through probabilistic application of the models (e.g. Bonadonna (2005); Wadge (2009)). Assessing the types of models suitable for use in generating probabilistic hazard maps relies on our understanding of the physical processes involved, but also on our appreciation of aspects of the real phenomena that are not sufficiently captured in models. Models that can be relatively quickly run, in stochastic mode, and are coupled with digital elevation models of volcanic topography or atmospheric wind data, are being increasingly tested and employed in the generation of probabilistic hazard maps during real volcanic crises. Forward modelling applications are still largely at an experimental stage, but ongoing developments of both appropriate models and methodologies pose exciting new opportunities which will likely become more commonplace (e.g. Bayarri et al. (2009)). An increase in the application of computational models to understand potential hazards, and their use in probabilistic hazard mapping, is also intricately bound with discussions on model suitability and inherent uncertainty.

Vision for Future Efforts

The volcanology community currently lacks a coherent approach in dealing with hazard mapping but there is general consensus that improved quantification is desirable. Harmonisation of the terminology is needed to improve communication both within volcanology and with stakeholders. In particular, successful approaches must address and quantify uncertainty related to (i) the incompleteness and bias of the geological record and the extent to which it represents possible future outcomes; (ii) the fact that analyses based on empirical models rely on *a priori* knowledge of the events; and (iii) the ability of complex computational models to adequately represent the full complexity of the natural phenomena. The variation in currently utilised approaches results in part from differences in the extent of understanding and capability of modelling the respective physical processes (for example tephra fall hazards are currently better quantified than other hazards). Probabilistic hazard maps, in particular, are highly variable in terms of what they represent. Yet there is the need for probabilistic approaches to be fully transparent; they are used to communicate and inform stakeholders, for whom an understanding of the significance of the uncertainties involved is also crucial. A recent initiative through the newly-formed **IAVCEI Commission on Volcanic Hazards and Risk**, will focus on hazard mapping. The effort aims to undertake a comprehensive review of current practices with a view toward:

- Constructing a framework for a classification scheme for hazard maps.
- Promoting harmonisation of terminology.
- Defining good practices for hazard maps based on experiences of usage.

Clearly, the needs of today's stakeholders for more quantitative information about hazards and their associated uncertainties also drives the need for further research efforts in priority areas. In particular, sources of scientific advancement that would aid in the production of a new generation of more robust, <u>quantitative</u>, <u>accountable</u> and <u>defendable</u> hazard maps would be:

- Improved methods for probabilistic analysis, especially for lahar and PDC hazards.
- Methods for undertaking hazard assessments for volcanic centres from which we have sparse data.
- Uncertainty quantification.
- Handling 'Big Data' generated by computational modelling.
- Handling uncertainty in digital elevation models and evolving volcanic topography over time.
- Forecasting of extreme events and their consequences.
- Communicating probabilities associated with hazard and risk.
- Approaches for multi-hazard, multi-scenario probabilistic modelling.

These are research problems that require multi-disciplinary expertise to solve. There is consensus that the basic foundation on which any hazard analysis should be undertaken is the establishment of an understanding about a volcano's evolution and previous eruptive behaviour through time, based on combined field geology, dating and geochemical characterization of the products. However, bringing together experts in modelling and statistical analysis with field scientists is then key. Our ability to achieve tangible advances in probabilistic volcanic hazard analysis hinges on the effective use of advanced modelling and statistical methods, and handling of massive and/or complex data. Dealing with such data requires fundamental advances in mathematical, statistical and computational theory and methodology but also requires training a new generation of scientists that are adapted to cross-disciplinary research environments.

Glossary of Hazard Map Types.

Geology-based hazard maps: Indicates hazards based on the distribution of past eruptive products. Can also include information about recurrence rates.

Integrated hazard maps: All available hazard information is amalgamated, resulting in simple, often concentric-type, hazard zones. The information on which these are based can include field distributions as well as modelling. Levels of hazard are usually expressed qualitatively.

Modelling-based hazard maps: Involve scenario-based application of simulation tools often for a single hazard type.

Probabilistic hazard maps: Based on probabilistic application of hazard models (models can be empirical to fully geophysical). Levels of hazard can be expressed quantitatively.

Administrative hazard maps: A type of map used for disaster management that takes into account local infrastructure, land use and populations in addition to information about possible hazard distribution.

Less common, but also in use are the following terms:

Rapid-response hazard maps: Generated by ascertaining the distribution of past eruptive products, rapidly (either remotely or in the field) in response to a period of unrest or impending crisis at a volcano where previously eruptive activity is not established or has not previous been well characterised.

Scenario maps: Provide information about the distribution of eruptive products, based on explicit event scenarios that may be considered likely. If levels of hazard are expressed quantitatively they can be considered conditional.

Nested hazard maps: A type of scenario map indicating the possible distribution of eruptive products of a similar type of event (e.g. lahars), but for scenarios with varying magnitudes or intensities. The distributions are therefore nested within each other.

Hazard-specific maps: Considers only one hazard type in one map.

Multi-hazard maps: Considers multiple hazard types in one map.

Summary

The large majority of hazard maps currently in use by government institutions around the globe are geology-based hazard maps, constructed using the distribution of prior erupted products. Such maps are based on the study of the volcano, and provide a wealth of information about its capabilities. An important limitation though, is that the distribution of previous events (even if known in their entirely), does not represent all possible future events. Increasingly, computer simulations of volcanic processes are used to augment the knowledge gained by geology, to gauge potential areas and extents of impact of future events. The hazards of most widespread concern, as indicated by frequency of occurrence on hazards maps are: lahars, pyroclastic density currents, and tephra fall. Currently, tephra hazards (which can have the most wide-spread effects and far-reaching economical impacts) are the best quantified. Lahars and pyroclastic density currents both have more localised impacts but do account for far greater loss of life, infrastructure and livelihoods. These hazard types present greater challenges for modelling, and as a result quantitative hazard analysis for lahar and pyroclastic density currents lags behind that for tephra fall.

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CS18. Risk assessment case history: the Soufrière Hills Volcano, Montserrat

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Introduction

Volcanic hazard and risk at Soufrière Hills Volcano, Montserrat (SHV) has been assessed in a consistent and quantitative way for over seventeen years (1997 – 2014), during highly variable eruptive activity involving andesitic lava dome growth (Wadge and Aspinall, 2014). This activity has placed serious stresses and constraints on the Montserrat population: about 12,000 people lived on this small Caribbean island prior to the start of the eruption in July 1995 and now (2014) this has stabilised at just over 4,000 souls. Over the years following 1995, a series of five very active dome growth episodes produced many pyroclastic flows, explosions and lahars, whose net effect was to destroy the main town, Plymouth, and most infrastructure, forcing people to leave Montserrat or live only in the northern part of the island. In June 1997, nineteen people were killed when a dome collapse pyroclastic flow caught a number of persons inside the exclusion zone.

The risks faced by the people of Montserrat from volcanic activity are the responsibility of the UK government, and hazard and risk assessment work on Montserrat has been carried out by a Scientific Advisory Committee on Montserrat Volcanic Activity (SAC) (and the predecessor Risk Assessment Panel) appointed by them, working in collaboration with the Montserrat Volcano Observatory (MVO). Whilst the administrative basis of the SAC has changed, the quantitative risk assessment methodology for enumerating risk levels (Aspinall et al., 2002, Aspinall and Sparks, 2002), has been kept the same since 1997 to ensure comparability of findings from one assessment to the next. In a protracted eruption crisis, continuity in scientific inputs to decision-making is essential: any major change in concepts, modelling or assumptions could entail large differences in evaluated risk levels and hence engender doubts for officials and confusion in the minds of the public. This series of multiple, repeated quantitative volcanic hazard and risk assessments must be unique in volcanology.

In the case of Montserrat, by ‘volcanic risk’ we mean the probability that a person will be harmed by some volcanic hazard within some specified timeframe; assessing other risks and losses, such as damage to buildings or infrastructure, have had only a limited consideration in terms of framing scientific advice.

Assessment Methods and their Effectiveness

Comprehensive risk assessments for Montserrat were first undertaken by a Risk Assessment Panel in December 1997, following the fatalities and then a series of violent Vulcanian explosions. Thereafter, whenever activity changed significantly assessments were updated. The SAC came into being in 2003, superseding the risk panel, and further developed risk assessment methods, using the following sources of information in regular meetings, usually every six months:

- MVO data on current activity at the SHV

- Knowledge of other dome volcanoes
- Computer models of hazardous volcanic processes
- Formalised elicitations of probabilities of future hazards scenarios
- Probabilistic event trees
- Bayesian belief networks
- Census data on population numbers and distribution
- Monte Carlo modelling of risk levels faced by individuals and society

Knowledge elicitation about hazard scenarios and analysis of judgements by the Classical Model method (Cooke, 1991) have been used to formulate probabilistic forecasts of future hazardous events, typically over the following 12 months. These scenario forecasts have been used in Monte Carlo simulations to quantify risk exposures of individuals and the population as a whole (Aspinall, 2006).

Hazard scenarios allow volcanologists to visualise - and describe to the authorities and the public – the potential occurrence and dangers of future events. Probabilities of occurrence of hazards, with associated confidence limits, are evaluated by judging factors that make such events likely to happen. This evaluation is done by expert elicitation, informed by experience of previous events at the volcano, its current activity state, by model simulations, and by discussion of precedents elsewhere at similar volcanoes. The elicitation process can be stimulating but also burdensome, so generally only a restricted number of scenarios or outlooks are considered (typically 10-30). The process may thus be limited to major hazards: i.e. explosion; large dome collapse, or lateral blast, and event probabilities are usually evaluated for each, for one year ahead. However, if a significant event occurs then the conditions under which these probabilities were judged will have changed, so a risk assessment is only valid up to the time of the next 'significant event'. Hazard and risk updating is needed at that point.

The accuracy of SAC hazard forecasts has been tested using the Brier Skill Score. Although this metric has some limitations, it is used in weather forecasting and we have adopted the analysis method for volcanic forecasts. We have tested 110 scenario probabilities against actual outcomes: seventy-five of these can be termed life-critical, and for 83% of these a positive Brier Skill Score was achieved. This shows that, in the overwhelming majority of cases, our experts outperformed an 'uninformed' baseline probabilistic forecast, demonstrating the value of the process in supporting the civil authorities and the people of Montserrat to mitigate risk. As yet, no hazard has happened that was a surprise to the scientists, and none has exceeded our scenario envelopes in terms of size or intensity.

In the main, the SAC risk assessment implementation is distinct from day-to-day observatory operations - where the duty is to provide immediate hazard advice - but it is closely linked with and relies on MVO inputs. While this may seem an unusual separation of responsibilities, we believe it has worked well on Montserrat because the SAC brings to bear a separate, independent pool of expertise and long-term experience. This approach offers a deeper analytical perspective on issues of future hazards, complementing the monitoring competencies of MVO. This said, in future it is intended that MVO staff will take on more of the tasks of quantitative risk assessment.

Expressing Risk to the Public

After deriving event scenario probabilities and their uncertainties by elicitation and then quantifying risks and their uncertainties by Monte Carlo modelling, the SAC assessments present the level of risk in several ways:

(i) A Preliminary Statement and the SAC Report generally state whether, overall, risk in the populated part of Montserrat has gone up, down or stayed the same.
(ii) Societal risk is expressed quantitatively as a curve of the probability of exceeding a given total number of fatalities, for different total numbers.
(iii) Individual risk is given as an annualised probability of death (from the volcano) for any person living in a specific area.
(iv) Added occupational risk, due to the volcano, is given for people working under certain conditions in specific areas.

Societal risk is presented as an *F-N* graph (probability of *N* or more potential fatalities in a given time plotted against *N*) and is useful for comparing situations from different periods and for assessing mass casualty scenarios. For instance, in Fig. 1 the *F-N* curve for May 2003 (red), together with a second curve (green), showed how societal risk could be reduced by extending the evacuated area. For natural disaster risk comparison purposes, rudimentary *F-N* curves for hurricane and earthquake risk on Montserrat are also shown.

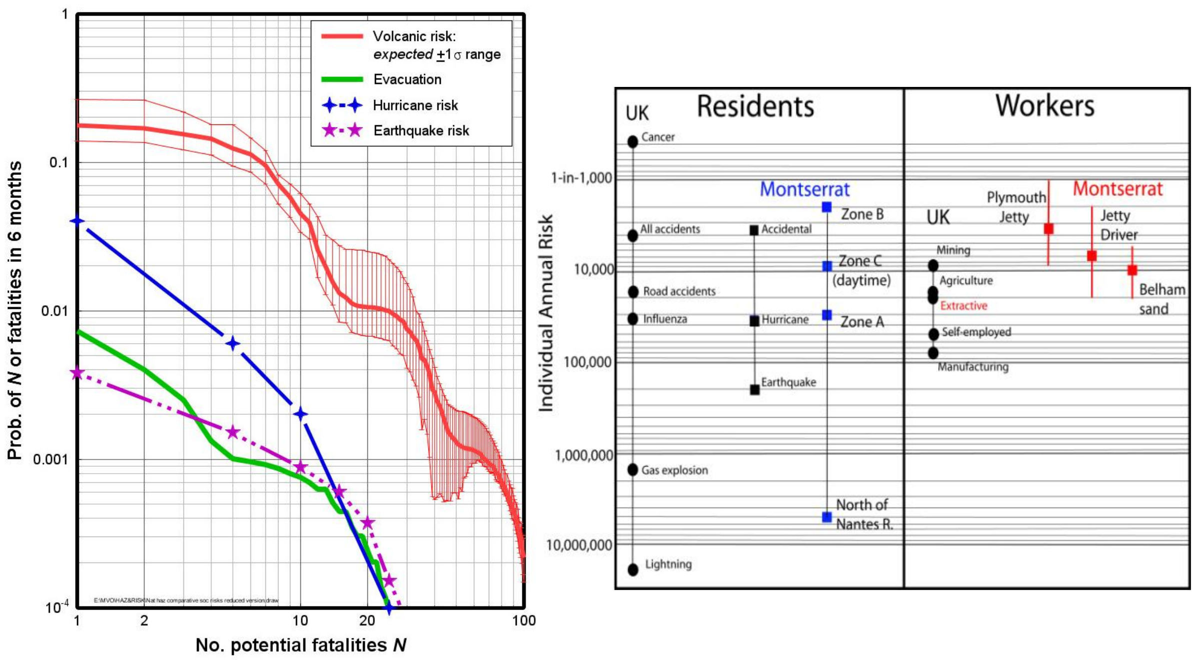

Figure 1: Montserrat quantitative risk assessments: (left) societal risk F-N curve for population exposure (red, with uncertainty estimates), and the risk reduction possible if the evacuation area is extended (green), plus background hurricane (blue) and earthquake risks (mauve); (right) summary plot of annualised individual risk exposures for residents and workers (latter plotted in red, with indicative uncertainties on risk estimates).

Uncertainty analysis of the Monte Carlo societal risk modelling furnishes confidence bounds on these alternative volcanic risk *F-N* curves (Fig. 1), indicating that meaningful risk reductions could be achieved by basic mitigation measures. In contrast with typical linear *F-N* plots for industrial risks, the volcano societal risk curves exhibit marked changes of slope and humps. These arise because an erupting volcano has a variety of ways of doing harm to a population, with differing levels of hazard intensity and spatial extent potentially causing different total magnitudes of casualty numbers, all with different probabilities of occurrence. Such complexity in volcanic *F-N* curve serves to make decision-taking about public safety very much more challenging than in the industrial risks case, especially when the risk findings are convolved with the substantial scientific uncertainties associated with volcano forecasting.

Individual risk can be a more influential measure for expressing exposure in that many people – but not all - base their own responses to threats on their own personal risk level. The SAC has used several measures for individual risk, but mainly we calculate the 'individual risk per annum' (IRPA) metric, expressed in odds form (e.g. a 1-in-1000 chance of being killed in the next year). Graphical comparison of IRPA values on a logarithmic ladder with some relevant published risk levels for everyday hazards and occupations to provide context (Fig. 1) has proved popular with the authorities on Montserrat. The Zones used to calculate individual risk are defined geographically by the Hazard Level System managed by MVO (www.mvo.ms). The positioning of the zone boundaries has implications not just for risk levels but also evacuation actions and emergency management. There is a rudimentary feedback process - from the SAC and MVO through the civil authorities - between the level of hazard estimated and the resultant risks ensuing for a given set of boundaries (Wadge et al., 2008).

Subjectively, the general perception of whether the risk has gone up or down is reflected by changes both in calculated societal risk levels and in individual risk estimates. However, criteria for public safety and tolerable levels of volcanic risks are not established in Montserrat (or elsewhere); this vacuum is exacerbated in a crisis by inevitable tensions between individuals' acceptance of elevated risk and society's wish to avoid casualties.

The SAC risk assessments are made public within a few weeks. There are two reports: a Summary Report of about 4-5 pages and a much longer, Full Report, giving all the technical analysis. They are available at www.mvo.ms.

Government Response to Risk Assessments

How have the authorities used the SAC risk assessments to guide actions in protecting the people of Montserrat? Because volcanic dangers at SHV are dominated by pyroclastic flows and surges, the spatial boundary of the probable extent of any future flow is the overriding concern for risk management. Generally, such actions appear to have been responsive to SAC risk level assessments, but it is difficult to evaluate this in detail (Wadge and Aspinall, 2014). This is partly because the MVO has responsibility for day-to-day guidance and recommends changes in the Hazard Level, the main cue for mitigation measures. Also, there is no formal feedback from the authorities to the SAC in terms of the reasoning about decisions to change zone boundaries. While many such decisions have been taken over the years, few if any can be directly linked to specific SAC advice, but most were consonant with levels of risk assessed by the scientists.

While the aim of the SAC has been to keep the nature and standard of advice consistent from one assessment meeting to the next, changing conditions at the volcano and changing requirements from the authorities inevitably dictated some alteration to the way advice was formulated and presented by the SAC. This said, during recent periods several pyroclastic flows have travelled further towards the populated areas and could have led easily to injuries or deaths had there not been updated official access restrictions in response to the risk assessment advice. Other risk-based decision approaches, such as cost-benefit or probabilistic criteria to inform evacuations have not, thus far, formed part of risk decision-making in Montserrat.

Summary

Since its inception in 2003, the SAC's principal role in efforts to mitigate danger from the Soufrière Hills volcano has been to consider likely future behaviour patterns of the volcano on the basis of observations, data, modelling and expert knowledge and to communicate our collective scientific understanding of processes driving the evolving eruption - and limitations in that understanding. Related advances in probabilistic volcanic hazard and risk assessment methodologies have been achieved, and our appraisals of the volcano's state and the chances of potential impacts on the population by eruptive activity have represented the substantive science input to decision-making by the authorities and the provision of risk information to the public. In the face of scientific uncertainty and other challenges associated with living with an active volcano, risk-informed hazard mitigation measures have ensured there has been no fatality caused by the volcano during all the long years of eruptive activity and dangerous events since the tragic events of June 1997.

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CS19. Development of a new global volcanic hazard index (VHI)

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Background

Globally, more than 800 million people live in areas that have the potential to be affected by volcanic hazards, and this number is growing [CS1]. The need for informed judgements regarding the global extent of potential volcanic hazards and the relative threats is therefore more pressing than ever. There is also an imperative to identify areas of relatively high hazard where studies and risk reduction measures may be best focussed. Various authors have tackled this task at a range of spatial scales, using a variety of techniques. At some well-studied volcanoes, the geological record has been used in combination with numerical modelling to create probabilistic hazard maps of volcanic flows and tephra fall [CS3 and 17]. Such sources of information can be hugely beneficial in land use planning during times of quiescence and in emergency planning during times of unrest. Unfortunately, creating high-resolution probabilistic hazard maps for all volcanoes is not yet feasible. There is therefore a need for a methodology for volcanic hazard assessment that can be applied universally and consistently, which is less data- and computing-intensive. The aim of such an approach is to identify, on some objective overall basis, those volcanoes that pose the greatest danger, in order that more in-depth investigations and disaster risk reduction efforts can then be focused on them.

Previous methods

An index-based approach to volcanic hazard assessment involves assigning scores to a series of indicators, which are then combined to give an overall hazard score. Indicators typically include measures of the frequency of eruptions, the relative occurrence of different kinds of eruptions and their related hazards, the footprints of these hazards, and eruption size. Indices are well suited to the problem of volcanic hazard assessment, as they allow the decomposition of the complex system into a suite of volcanic system controls and simple quantitative variables and factors that jointly characterise threat potential.

Ewert (2007) presented an index-based methodology for assessing volcanic threat (the combination of hazard and exposure) in the USA, to permit prioritisation of research, monitoring and mitigation. The study formed part of the development of the National Volcano Early Warning System (NVEWS). The NVEWS method scores and sums twelve hazard indicators, with the result then assigned to one of five levels. Whilst representing a significant improvement on past indices, the use of a largely binary scoring system obscures much of the complexity of volcanic hazard. For example, the occurrence of Holocene lava flows and Holocene pyroclastic flows are assigned the same weighting, though the latter is far more hazardous, particularly from a loss of life perspective (Auker et al., 2013, Witham, 2005). The inclusion of indicators for historical unrest and unsatisfactory treatment of missing data make application of the NVEWS system problematic in many jurisdictions outside of the USA, where data may be scarce or absent.

Aspinall et al. (2011) developed a method for volcanic hazard assessment for application to the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) priority countries (16 developing countries). The GFDRR method uses eight indicators to assess hazard; uncertainty indicators, used to describe the quality of information, are attached to six of the eight indicators. The summed hazard and uncertainty scores are each assigned to one of three levels.

The time period over which volcanic hazards are being assessed is not explicitly stated in the NVEWS and GDFRR methods. However, hazard assessments are more valuable if the time is specified and indeed the informativeness of the results depends on the time frame. For example, an assessment over ten years will likely yield a very different outcome to an assessment over 10,000 years, in which very large but rare eruptions may be the dominant peril. Both the NVEWS and GFDRR methods are based on the entire Holocene eruption record. The new method developed here gives more weight to recent activity patterns, as these are more likely to indicate the character of future eruptions.

Development of a new methodology

Here, we address limitations in the NVEWS and GFDRR approaches and build on their strong points to develop an improved volcanic hazard assessment approach, which we call the Volcanic Hazard Index (VHI). We aim to assess global volcanic hazard for the next 30-year period using our indicator-based VHI method on a volcano-by-volcano basis.

The main data source is the Volcanoes of the World 4.0 (VOTW4.0) database (Siebert et al., 2010) from which we only consider 'confirmed' eruptions. There is evidence for severe under-recording of events over the entire Holocene period, which diminishes towards the present (Deligne et al., 2010). The fatalities database of Auker et al. (2013) is used in conjunction with VOTW4.0 to provide evidence that justifies indicator choices and their weightings.

Indicator choices

Indicators used in both the NVEWS and GDFRR methods provide a useful starting point for development of an improved methodology. These are:

- Eruption frequency
- Eruption magnitude
- Pyroclastic flow occurrence
- Mudflow (lahars and jökulhlaups) occurrence
- Lava flow occurrence

Eruption magnitude and frequency are intuitive indicators of volcanic hazard. The Volcanic Explosivity Index (VEI) is based on the size of eruptions according to volume of tephra produced; higher VEI eruptions have larger footprints and are thus more hazardous. Modal VEI and largest recorded VEI are used as magnitude indicators, aiming to capture a volcano's 'typical' and 'extreme' eruption size, based on what is known from the record. A future eruption greater than the largest recorded VEI cannot of course be excluded.

With regard to eruption frequency, given identical volcanoes producing eruptions of identical style, magnitudes and intensities, if one erupts twice as often as the other then the former is twice as hazardous as the latter. This notion suggests that eruption frequency should be used multiplicatively rather than additively, as was done in previous methods. Taking AD 1900 as base year, because recording of eruptions is almost complete after this date (Furlan, 2010), four frequency classes are defined: active (one or more eruptions since AD 1900); semi-active (historical (post-AD 1500) eruptions with or without unrest recorded since AD 1900 or Holocene (pre-AD 1500) eruptions and unrest since AD 1900); semi-dormant (Holocene (pre-AD 1500) eruptions with no post-1900 unrest or no Holocene eruptions but recorded unrest); fully-dormant (no Holocene eruptions or unrest recorded since AD 1900). Unrest is identified from Bulletin Reports which accompany VOTW4.0, and is defined subjectively as activity above background levels (for example, the presence of fumaroles does not constitute unrest, however descriptions of periods of intensified emissions does).

The fatalities database of Auker et al. (2013) can be used to infer the relative hazard posed by different eruption phenomena. Pyroclastic flows and mudflows have caused the greatest proportions of fatalities (44% and 22%, respectively), and are therefore deemed very hazardous. Lava flows have caused a relatively small proportion of fatalities (1%) but are recorded in approximately 30% of eruptions. As such, their economic impact could be large and an indicator is used to reflect this. The occurrence of pyroclastic flows, mudflows and lava flows should form part of a volcano's hazard assessment when these are common hazards (rather than rare, extreme events). We define a phenomenon as a significant contributor to overall hazard potential if it has occurred in 10% or more of a volcano's eruptions.

Indicators should capture distinct components of volcanic hazard, and problems known to affect volcanic eruption data, namely under recording, should be compensated for. Testing for the concurrence and under-recording of pyroclastic flows, mudflows, and lava flows was undertaken to identify any potential issues; no corrections were required. Further, the relationship between the occurrence of pyroclastic flows, mudflows and lava flows, and modal and maximum VEI was investigated. However, these aspects are not simply correlated, and thus VEI cannot be used as a catch-all representation of hazard. Separate indicators for pyroclastic flows, mudflows, and lava flows are required. For example, pyroclastic flows due to dome collapse and volcanic blasts can occur in eruptions with quite low VEI, and mudflow occurrence is dependent on external factors such as rainfall and the presence of crater lakes, which are unrelated to VEI.

Time dependence

Exploration of the global under-recording of volcanic eruptions shows two significant improvements in recording completeness, at approximately AD 1500 and AD 1900 (at which point the record becomes largely complete; Furlan (2010)). These findings can inform the length of time over which data are drawn for the hazard assessment, referred to henceforth as the 'counting period', and are useful in characterising each volcano's 'recent' history. The ideal counting period start date would be AD 1900 because of the near completeness of the volcanic eruption record after this date. However, some volcanoes have not erupted frequently enough for this time period to be representative of their recurrence statistics. Consequently we develop a simple approach where the definition of 'recent', and thus the length of the counting period, is specific to each volcano. For active volcanoes (those with at least one year in eruption recorded since AD 1900) a sliding scale is used. The counting period for an individual volcano begins in the year defined by the equation: AD Year =

$1500 + \left[\left(\frac{N}{113}\right) \times 400\right]$, where N is the number of years in which the volcano is recorded as erupting between AD 1900 and AD 2013. AD 2013 is the end year of the counting period for active volcanoes. AD 1500 is used as the base year for active volcanoes' counting periods because of the significant improvement in recording at this time. The entire Holocene is used as the counting period for semi-active, semi-dormant and fully-dormant volcanoes, to maximise the amount of eruption data available for hazard assessment.

The modal VEI and pyroclastic flow, mudflow, and lava flow occurrence indicators are each scored based on eruptions within the counting period only. The maximum recorded VEI is calculated using data for all Holocene eruptions (regardless of the volcano's frequency status), to maximise the likelihood of capturing the volcano's extreme events.

Hazard indicator scores

Modal and maximum recorded VEI are used as a reference in assigning numerical scores to the pyroclastic flow, mudflow, lava flow, and eruption frequency indicators. Comparison of the percentage of fatalities caused by the three phenomena with the percentage of fatalities caused by eruptions of each VEI suggests that pyroclastic flows and eruptions of VEI 4 generate similar impacts; pyroclastic flows have caused 44% of fatalities, whilst VEI 4 eruptions have caused 37%. This comparison leads to assigning a score of 4 to pyroclastic flow occurrence, when 10% or more of eruptions within the counting period have recorded pyroclastic flows. The total number of fatalities caused by mudflows is 50% those caused by pyroclastic flows, and by lava flows 2%. These proportions yield scores of 2 and 0.1 for mudflows and lava flows, respectively, when 10% or more of eruptions within the counting period have these flows recorded. A score of 0 is given for each of the pyroclastic flow, mudflow and lava flow indicators if the relevant phenomenon is recorded in fewer than 10% of eruptions.

Eruption frequency is used multiplicatively rather than additively in our method. As such, scoring of the frequency indicator need not be proportional to the scores of the other indicators; the only requirement is that active volcanoes are scored highest and fully-dormant volcanoes lowest, and that the scores for the four frequency status classes are proportional to each other in terms of their representation of hazard. A score of 1 is used for fully-dormant volcanoes, 1.5 is used for semi-dormant volcanoes, 2 for semi-active volcanoes, and a sliding scale from 2 to 3 is used for active volcanoes, calculated using $2+\left(\frac{N}{113}\right)$, where N is the number of years in which the volcano is recorded as erupting since AD 1900.

Calculating the hazard score

Scores for the indicators are combined to give a volcano-specific hazard score using the following conceptual structure:

[eruption frequency × ('frequent' characteristics of volcano's eruptions)] + extreme characteristics

This can be expressed in terms of the aforementioned indicators as:

[frequency status score × (modal VEI + PF score + mudflow score + lava flow score)]

+ maximum recorded VEI

with indicators for modal VEI, pyroclastic flow occurrence, mudflow occurrence and lava flow occurrence calculated using data for eruptions from the counting period only; maximum recorded VEI is calculated using all available Holocene data.

Maximum VEI is the only indicator score not multiplied by the frequency status score. Testing showed that multiplicative use of the maximum recorded VEI score gave distorted results and very high overall scores for some volcanoes that have particularly large maximum recorded VEIs. Simply adding on the maximum recorded VEI score moderates this propensity, and dilutes the weight associated with infrequent extreme eruptions.

The full method is as follows:

Indicator	Class	Criteria	Scoring
Eruption frequency	Fully dormant	- No time in eruption recorded since AD 1900 and No recorded unrest since AD 1900	1
	Semi-dormant	- No Holocene eruptions but unrest recorded since AD 1900 *Or* - Holocene (pre-AD 1500) eruptions but no recorded unrest since AD 1900	1.5
	Semi-active	- Holocene (pre-AD 1500) eruptions and unrest since 1900 *Or* - Historical (AD 1500-1900) eruptions with or without unrest since AD 1900	2
	Active	- One or more years with eruptions recorded since AD 1900	$2+\left(\frac{N}{113}\right)$ where N is the number of years in which the volcano is recorded as erupting since AD 1900
Pyroclastic flow occurrence	Pyroclastic flows are a significant hazard	Pyroclastic flows are recorded in 10% or more of eruptions occurring partially or fully within the volcano's counting period	4
	Pyroclastic flows are not a significant hazard	Pyroclastic flows are recorded in fewer than 10% of eruptions occurring partially or fully within the volcano's counting period	0
Mudflow occurrence	Mudflows are a significant hazard	Mudflows are recorded in 10% or more of eruptions occurring partially or fully within the volcano's counting period	2
	Mudflows are not a significant hazard	Mudflows are recorded in fewer than 10% of eruptions occurring partially or fully within the volcano's counting period	0
Lava flow occurrence	Lava flows are a significant hazard	Lava flows are recorded in 10% or more of eruptions occurring partially or fully within the volcano's counting period	0.1
	Lava flows are not a significant hazard	Lava flows are recorded in fewer than 10% of eruptions occurring partially or fully within the volcano's counting period	0

Indicator	Class	Criteria	Scoring
Modal VEI	N/A	The modal VEI of eruptions recorded with a known VEI within the volcano's counting period is X. A minimum of 4 such eruptions are required. Where there is no mode, the mean is used	X
Maximum recorded VEI	N/A	The greatest VEI of any eruption recorded within the volcano's Holocene eruptive history is Y	Y

Applicability and data constraints

For many volcanoes in VOTW4.0, data are scarce. The hazard assessment methodology requires enough data for scores to be assigned to all components of the index algorithm. The minimum amount of data required to apply the index is four or more eruptions within the volcano's counting period with a known VEI.

Volcanoes with insufficient data, i.e. those with fewer than four eruptions of known VEI within the counting period are unclassified as a classification would be accompanied by such large uncertainties as to make this irrelevant.

328 volcanoes satisfy this threshold for sufficient data to apply the scoring method fully. Such volcanoes are termed 'classified'. For the 1,223 volcanoes that do not meet these data requirements, termed 'unclassified', an alternative method that includes an assessment of the uncertainty related to lack of data must be used.

The calculation of VHI can be skewed by the inclusion of an unrepresentative modal VEI or prevented by the description of few events due to the persistent nature of activity at some volcanoes. Typically, activity separated by less than three months of apparent repose is considered an ongoing eruption. This persistent activity typically comprises small explosions or continuous effusions with infrequent bursts of larger activity. In VOTW4.22, the VEI for a persistent period of activity is taken as the maximum attained in that time. This can skew the calculation of the modal VEI upwards and result in an anomalously high VHI. These issues are accounted for through the identification of long eruptions, specifically those where the number of years in eruption in the counting period is greater than twice the number of eruptions in that period. Detailed bulletin reports accompanying VOTW4.22 have been studied to better constrain common activity and individual events. This approach will be improved and refined to ensure objectivity.

VHI application for GAR15

VHI scores have been determined for the Holocene volcanoes of VOTW4. The scores for classified volcanoes range from 0 to 30. The volcanoes' hazard scores are divided into the three hazard levels: VHI Level I (Scores 0 to <8; 134 volcanoes), VHI Level II (Scores 8 to <16; 106 volcanoes), and VHI Level III (Scores 16+; 88 volcanoes). These hazard levels are used to reflect the semi-qualitative nature of some of the data used and the approximations employed in creating and applying the method.

Ultimately, the Hazard Levels must be combined with measures of exposure in order to make statements about risk. For example, VHI Level I volcanoes may cause huge impacts if located sufficiently close to vulnerable populations or infrastructures. At this stage both the VHI and PEI are semi-quantitative, being presented as levels based upon numerical values, and risk cannot therefore be calculated as a strict product of hazard and exposure. However, plots of hazard levels against the Population Exposure Index (PEI, see CS1) for each volcano in each country provide a useful visualisation of a risk matrix. This matrix is derived using a qualitative assessment of the product of the VHI and PEI, amended to consider the potential impact of hazardous phenomena within highly populated areas regardless of the hazard level. Risk is defined at three levels, I, II and III with increasing risk, shown by the warming of the colours (Figure 1).

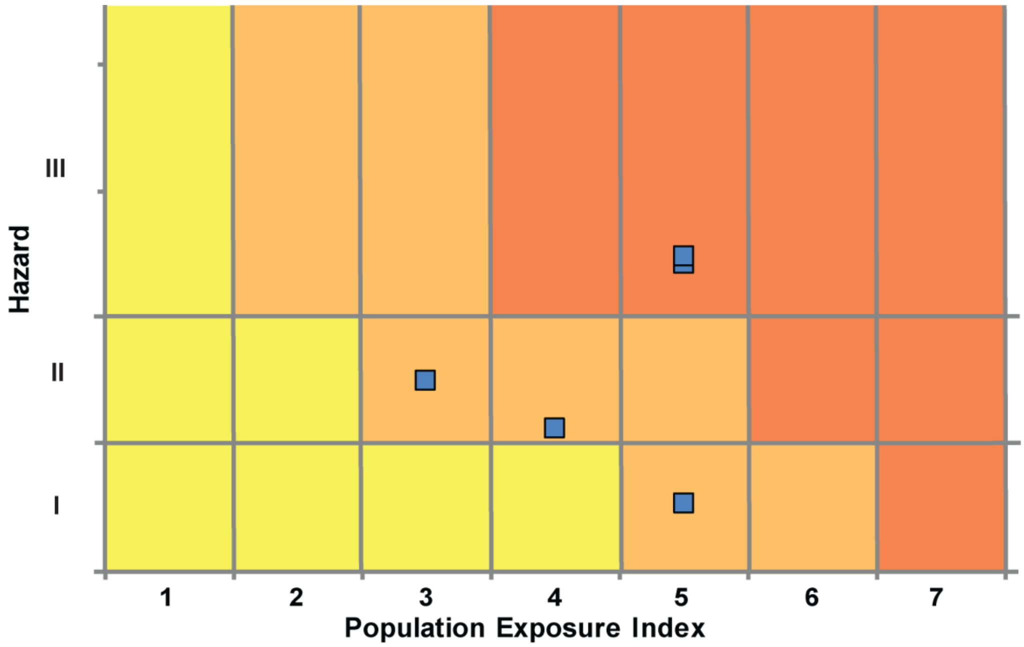

Figure 1: An example matrix combining VHI and PEI levels to indicate level of risk. Each volcano is represented by a point plotted using its hazard score and PEI level. The warming of the colouring of the matrix squares represents increasing risk (Risk Level I is yellow; Risk Level II is orange; Risk Level III is red).

The granularity within the matrix prevents detailed assessment and the matrix is therefore intended as a tool for the relative ranking of volcanoes. It should not be seen as a quantitative tool, as it comprises two ordinal rating scales which could be considered qualitative descriptors. This should not be used to undertake further calculations.

Unclassified volcanoes are presented with the PEI and are grouped according to their eruption record to permit an indication of known activity and for the use of PEI for an approximation for risk.

This globally applied assessment of VHI, PEI and ultimately risk does not substitute for focussed, local assessments. The PEI, for example, considers the population within concentric circles around a volcano, though in reality the exposed population will be governed by a number of factors (e.g. topography, which can shield a population on one side of the volcano and channel hazardous flows towards populations on the other). The impact on the human population is also determined by vulnerability, which is not considered here. The assessment of risk is based on these broad hazard and exposure assessments and therefore does not capture the full complexity of the situation. However, the ranking of volcanoes using this method can help identify volcanoes where monitoring and mitigation resources may need to be focussed and where localised hazard and risk assessments may be a priority.

This information is presented in the Country Profiles report (Brown et al., 2015 Section IV), where the distribution of volcanoes across Hazard Levels, PEI and Risk Levels is briefly discussed for each country. Volcanoes which, at present, lack sufficient data to properly constrain their Hazard Levels should receive attention.

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CS20: Global distribution of volcanic threat

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Within the country profiles (Report IV) individual volcanoes are ranked by risk; however, it would also be beneficial to understand the total volcanic threat borne by each country[1]. We therefore develop two measures of volcanic threat[2] to enable country ranking. The measures variously combine the number of volcanoes in the country, the size of the total population living within 30 km of volcanoes and the mean hazard score, which is calculated for each country from the relevant volcano hazard scores (VHI). We develop and use a 'Pop30' score, which calculates the number of persons, using Landscan 2011 (Bright et al., 2012) data, within a given country living within 30 km of one or more volcanoes with known or suspected Holocene activity. Note that 30 km is chosen as most fatal incidents that are caused directly by volcanic hazards fall within this distance of volcanoes (see CS1). VPI_{30}, supplied by VOTW4.0 (Siebert et al., 2010) based on the analysis of Ewert and Harpel (2004) and Siebert et al. (2008), is specific to a volcano and thus cannot be used in place of Pop30 as this would double count persons living within 30 km of neighbouring volcanoes.

We first develop a simple measure of volcanic threat to life country by country based on the number of active volcanoes, an estimate of exposed population and the mean hazard index of the volcanoes. The sum of this measure (Measure 1) for all countries is itself a simple measure of total threat and so the distribution of threat between countries can be evaluated and they can be placed in rank order using a normalised version of Measure 1. However, this measure of threat distribution can be misleading because an individual country may vary considerably in the proportion of its population that is exposed to the volcanic threat. Volcanic threat is very much higher in relation to its economy and population in a small island nation with an active volcano than in larger countries even if they have many volcanoes. Nation states vary greatly in their populations from, for example, China with 1.3 billion people (<1% exposed) to St. Kitts and Nevis in the Caribbean with only 54,000 people (100% exposed). Thus we need a measure of threat that reflects its importance to each country. Here we develop a measure (Measure 2) that rates the importance of volcanic threat in each country based on the proportion of the population that is exposed: numbers of volcanoes and the total exposed population are not included in the calculation.

There are some caveats and limitations to our measures. Clearly the measures are not a full evaluation of risk and in particular do not take account of vulnerability. In general populations in high income countries are less vulnerable to loss of life than in low-income countries for a wide variety of reasons. Thus a risk measure might usefully include measures of vulnerability to natural hazards, such as GDP, the Human Development Index (HDI) and the World Risk Index (WRI). For volcanoes these general indicators of vulnerability might not be adequate; for example a measure

[1] The phrase "country" is used here to denote both countries and some territories, e.g. overseas territories are classed separately to the nation state.

[2] We use threat rather than risk to describe these measures. Threat is defined here as the combination of hazard and exposure. Risk requires assessment of vulnerability, which has many different influences. Some jurisdictions can have high threat but low risk because steps have been taken to reduce the vulnerability (for example through having a well managed and equipped volcano observatory).

specific to volcanic hazard should include the existence and resourcing of a volcano observatory. There was not time in this study to explore possible ways that our measures might be combined with vulnerability indicators. If the measures of country volcanic threat were to be combined with vulnerability measures there would be an issue of how to weight the vulnerability indices relative to the hazard and exposure data.

This global assessment of volcanic threat must be understood as a tool for relative ranking based on coarse global data. This approach cannot substitute for focussed local assessments of hazard and risk, as vital information such as topography, which exerts strong controls on hazard emplacement and population exposure, cannot be incorporated into our assessments at present.

Data completeness

The assessment of threat per country is partially dependent on the hazard classification for the constituent volcanoes. About 20% of the world's volcanoes have been assigned a hazard score, VHI, on the basis of their eruption records (see CS19 and individual country profiles for results). The use of these classified volcanoes to inform global threat distribution limits the number of countries that can be analysed, with approximately half of the countries having no classified volcanoes.

Hazardous phenomena and eruption size are somewhat associated with volcano morphology, as it is the nature of eruptions which largely determines volcano structure. The volcano type can therefore be used to provide a very approximate indicator of the hazard level at unclassified volcanoes. All volcanoes are grouped into similar types, as indicated by their morphology (the classification of types is adapted from Jenkins et al. (2012), Table 1), and the mean hazard scores of the classified volcanoes of each volcano type can be used as proxies for the unclassified volcanoes.

Volcano type group	**Includes VOTW4.0 volcano types**
Caldera(s)	Caldera, Caldera(s), Pyroclastic shield
Large cone(s)	Complex, Compound, Somma, Stratovolcano, Stratovolcano(es), Volcanic Complex
Shield(s)	Shield, Shield(s)
Lava dome(s)	Lava dome, Lava dome(s)
Small cone(s)	Cinder cone, Cinder cones, Cones, Cone, Crater rows, Explosion craters, Fissure vent(s), Lava cone, Maar, Maar(s), Pyroclastic cone(s), Scoria cones, Tuff cones, Tuff rings, Volcanic field
Hydrothermal field	Hydrothermal field, Hydrothermal field(fumarolic)
Submarine	Submarine
Subglacial	Subglacial

Table 1: Volcano type classification modified after Jenkins et al. (2012).

Substitution of proxy VHI scores at unclassified volcanoes in practice introduces rather limited uncertainty with most of these volcanoes being scored over a narrow range, with the key drivers of threat ranking being the number of volcanoes and the size of the population within 30 km.

The following measures therefore use a combination of data from classified and unclassified volcanoes. The percentage of volcanoes per country which are classified and on which the ranking is partially controlled by is presented to provide a sense of data quality.

Volcanic threat to life by country (Measure 1)

A measure of overall threat in a country is obtained using the following equation:

$$Overall\ threat = mean\ VHI\ x\ number\ of\ volcanoes\ x\ Pop30$$

The sum of the resultant scores for all countries with active volcanoes is an indicator of total global volcanic threat. The countries are normalised by this total and ranked as a percentage of the total global threat:

$$\frac{Overall\ threat\ score}{Total\ global\ threat\ score} x\ 100$$

% classified	Rank	Country	Normalised %	% classified	Rank	Country	Normalised %
40	**1**	Indonesia	66.0	18	**11**	Papua New Guinea	0.4
17	**2**	Philippines	10.6	37	**12**	Nicaragua	0.4
38	**3**	Japan	6.9	33	**13**	Colombia	0.4
10	**4**	Mexico	3.9	0	**14**	Turkey	0.4
2	**5**	Ethiopia	3.9	50	**15**	Costa Rica	0.3
17	**6**	Guatemala	1.5	0	**16**	Taiwan	0.2
31	**7**	Ecuador	1.1	8	**17**	Yemen	0.2
43	**8**	Italy	0.9	14	**18**	Chile	0.2
14	**9**	El Salvador	0.8	29	**19**	New Zealand	0.2
5	**10**	Kenya	0.4	0	**20**	China	0.2

Table 2: The top 20 countries with highest overall volcanic threat to life. The percentage classified is the percentage of volcanoes in the country which have a classified VHI. The normalised percentage represents the country's threat as a percentage of the total global threat.

Indonesia scores the highest level of threat and accounts for about two thirds of the total score (Table 2) as a consequence of the number of volcanoes (142), extent of population exposure (nearly 69 people million live within 30 km of a Holocene volcano) and the number of Hazard Level II and III volcanoes. The Philippines, which has the second highest rank has just 16% of the score of Indonesia. The Philippines has a similar mean VHI to Indonesia, but has about a third of the number of volcanoes (47) and less than half the exposed population (still over 30 million people). Japan ranks third for overall threat to life, with a comparatively small exposed population of about 9 million, reflecting concentration of the population in Japan in coastal cities and communities. All countries ranked in the top ten for overall volcanic threat have exposed populations of over 4 million.

The global distribution of this volcanic threat is illustrated in Figure 1, where the warming of the colours indicates increasing risk rank.

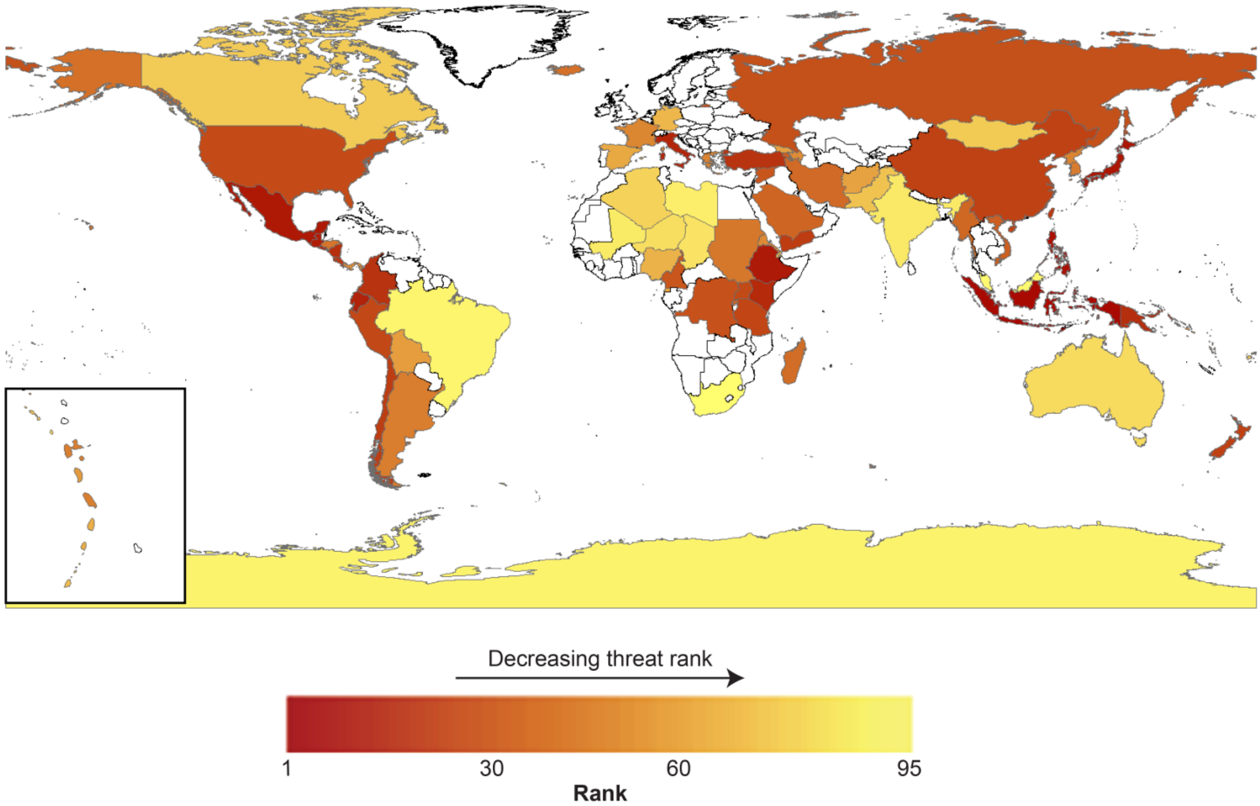

Figure 1: Global distribution of volcanic threat to life. Inset map shows the West Indies.

Distribution of volcanic threat and fatalities

Auker et al. (2013) undertook an analysis of fatality distributions, and found that Indonesia, Melanesia and the Philippines have had the highest number of fatalities (with the largest ten disasters removed). The regions considered in Table 3 are amended from the standard regions of VOTW4.0, to correspond with those used in Auker et al. (2013) incorporating the volcanic threat data for only those countries in which fatalities are recorded. Indonesia's history of fatal incidents corresponds well with the overall volcanic threat, and indeed ten regions only change in rank by a maximum of two positions, indicating a reasonable correlation between the overall threat and occurrence of fatalities.

The correlation between overall threat and regional distribution of fatalities where the largest ten disasters are included is less clear, with just five regions being of similar rank (within 2 positions). These high fatality events can significantly alter the regional ranking, and are shown by Auker et al. (2013) to dominate the fatalities record in several regions, obscuring the record of smaller events.

Overall threat rank	Region* (Country)	Fatalities Rank	% of Fatalities
1	Indonesia (Indonesia)	1 (=)	38
2	Philippines and China (Philippines, SE China)	3 (-1)	10
3	Japan (Japan)	6 (-3)	8
4	Mexico and Central America (Costa Rica, El Salvador, Guatemala, Mexico, Nicaragua)	4 (0)	10
5	Africa and Red Sea (Cameroon, DRC, Ethiopia, Tanzania)	9 (-4)	3
6	South America (Chile, Colombia, Ecuador, Peru)	7 (-1)	5
7	Mediterranean (Italy, Greece, Turkey)	5 (+2)	9
8	Melanesia (Papua New Guinea, Solomon Islands, Vanuatu)	2 (+6)	11
9	New Zealand to Fiji (New Zealand, Tonga)	11 (-2)	0.53
10	North America (Alaska, Canada, USA-contiguous states)	12 (-2)	0.11
11	Atlantic Ocean (Azores, Canary Islands, Cape Verde)	10 (+1)	0.90
12	Kuril Islands and Kamchatka (Russia)	14 (-2)	0.07
13	Indian Ocean (Comoros, French territories)	15 (-2)	0.05
14	Iceland (Iceland)	16 (-2)	0.02
15	West Indies (Martinique and Guadeloupe, Montserrat, St. Vincent and the Grenadines)	8 (+7)	4
16	Hawaii (Hawaii)	13 (+3)	

*Table 3: Regional ranking of volcanic fatalities (from Auker et al. (2013) and the threat measure.*The regions used here comprise only the countries or territories named, allowing for comparison of ranks with the fatality data. The percentage of fatalities per region with the largest ten disasters removed is shown (Auker et al., 2013).*

Proportional threat – Measure 2

The calculation of volcanic threat in Measure 1 considers the total number of people exposed and the number of volcanoes within a country. We have developed a second measure that is independent of country size but indicates how important volcanic risk is to each country. The following measure (Measure 2) is used:

$$Proportional\ threat = \frac{Pop30}{TPop}\ x\ Mean\ VHI$$

The countries in which volcanic threat is highly significant in terms of the proportion of population exposed are small-area nations. The top twenty countries or territories ranked most highly using this measure are dominantly countries of Central and South America and small island nations or territories. All islands of the West Indies, with the exception of the Dutch Antilles, are ranked in the top 20, as most have comparatively high mean hazard scores and significant proportions of their populations living within 30 km of a volcano. The Dutch Antilles ranks at position 24, with several non-volcanic islands located in the southern Caribbean Sea off the coast of Venezuela.

% Classified	Rank	Country	% Classified	Rank	Country
100	1	UK- Montserrat	17	11	Guatemala
100	2	St. Vincent & Grenadines	0	12	Sao Tome & Principe
100	3	France – West Indies	33	13	Canary Islands
0	4	St. Kitts & Nevis	50	14	Grenada
0	5	Dominica	43	15	Vanuatu
29	6	Azores	37	16	Nicaragua
0	7	St. Lucia	0	17	Samoa
0	8	UK – Atlantic	0	18	American Samoa
14	9	El Salvador	0	19	Armenia
50	10	Costa Rica	17	20	Philippines

Table 4: The top 20 countries or territories ranked by an index of proportional threat: the product of the proportion of the population exposed per country and the mean VHI.

There are some strong caveats about the rankings in Table 4 and the information should not be over-interpreted. As emphasised earlier the assessment is quite crude and takes no account of important local factors, including the detailed distribution of populations and, the specifics of the particular volcano in a small island state. Here it is even more important not to conflate the threat measure with risk. Many of the jurisdictions in Table 4 are small territories with only one volcano and so a complete assessment of risk and ranking against other jurisdictions would need to take account of many local factors that affect vulnerability. In some jurisdictions the threat can be ranked high but the risk is in fact low and vice versa; the relationship between threat and risk is now explained.

Montserrat appears at the top of the list but such a ranking would be highly misleading if the measure were used to imply high risk. The Soufriere Hills Volcano, Montserrat, has a well-established volcano observatory and the population has been relocated to the north of the island, which is now at very low risk because of the intervening topography. Thus, even though the population all live within 30 km, vulnerability and hence risk is actually very low. The volcanic threat though on Montserrat remains high, and continues to prevent re-population of areas where most people lived before the eruption, requiring the continued vigilance of a well-founded Observatory.

Indonesia and the Philippines ranked most highly for threat by Measure 1, but these countries drop in rank to 23 and 20 respectively when using Measure 2. Measure 2 cannot be used to infer either how risk is distributed globally or to rank in terms of risk, but highlights small nations with high exposure to volcanic hazards in relation to their size (Figure 2).

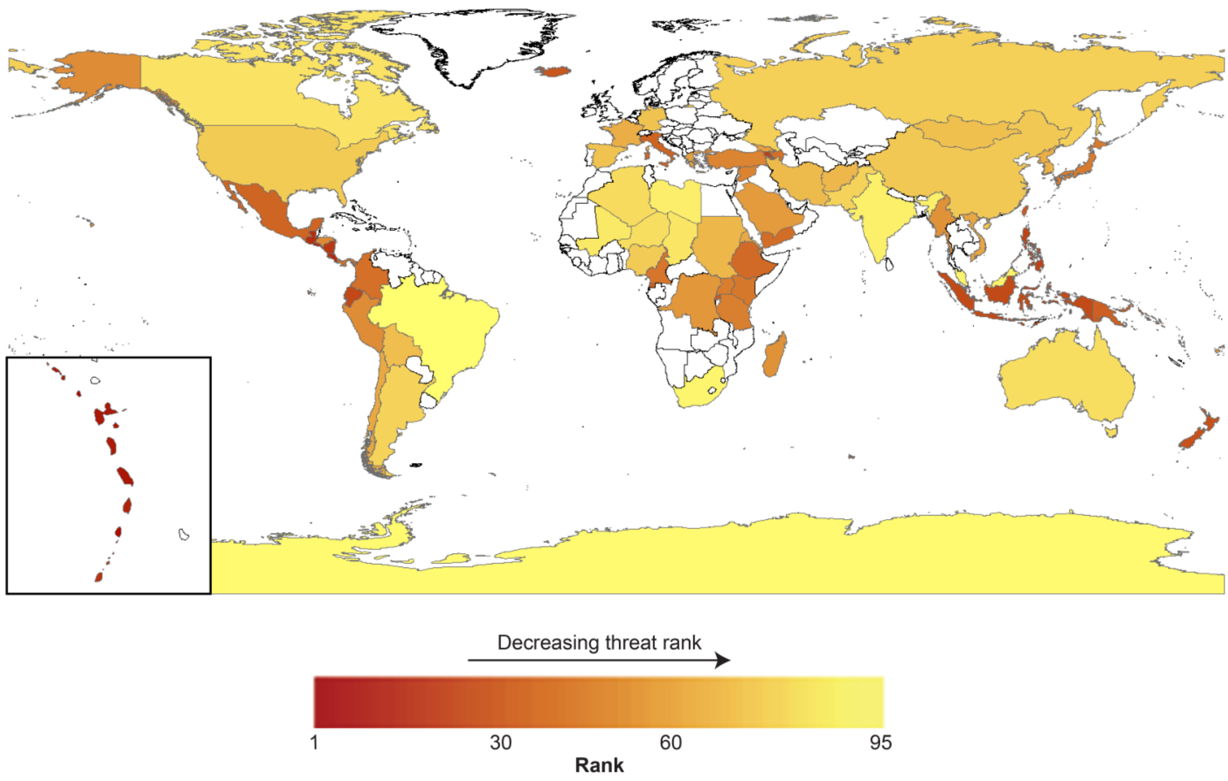

Figure 2: Global distribution of proportional risk. Inset map shows the West Indies.

Regional distribution of proportional threat

Many of the highest ranking regions for proportional threat comprise multiple small island groups: notably the small island nations and territories in the West Indies, the island groups of the Canaries, the Azores and Cape Verde in the Atlantic, and those of Fiji, Samoa and Tonga in New Zealand to Fiji (Table 5). Not all of the highest ranked regions comprise small island groups. Mexico and Central America ranks highly, comprising multiple nations in which high proportions of the population are exposed. Africa and the Red Sea region also ranks highly, comprising countries that range in size from small (e.g. Sao Tome and Principe, 964 km^2 area (United Nations Statistics Division, 2014)) to large (e.g. Algeria, 2,381,741 km^2 (United Nations Statistics Division, 2014)) resulting in a range of exposed populations from less than 1% of the country's total to 97%. It is those small nations which control this region's ranking.

Proportional threat rank	Region	% of Top region
1	West Indies	100
2	Mexico & Central America	35
3	Atlantic Ocean	32
4	Africa & Red Sea	17
5	New Zealand to Fiji	14
6	Melanesia & Australia	9
7	Mediterranean & West Asia	9
8	Middle East & Indian Ocean	8
9	South America	5

Proportional threat rank	Region	% of Top Region
10	Philippines & SE Asia	4
11	Indonesia	3
12	Japan, Taiwan, Marianas	3
13	Iceland & Arctic	2
14	Alaska	<1
15	Hawaii & Pacific	<1
16	Kamchatka & Mainland Asia	<1
17	Canada & Western USA	<1
18	Antarctica	-

Table 5: Proportional threat as ranked by region. Note the Kuril Islands region is not included due to the absence of population data. The percentage shows the percentage risk of the top ranked region: e.g. Indonesia has about 3% of the proportional risk of the West Indies.

Discussion

There are numerous methods available for the classification and determination of global volcanic threat. Here we only consider threat to life. The two ranking systems adopted here are shown in Table 6 in full.

Measure 1 allows the identification of those countries with the highest overall level of threat to life due to a combination of large numbers of people living within 30 km of an active volcano, large numbers of volcanoes and high hazard scores. Indonesia by far has the highest level of volcanic threat worldwide, with about 30% of the population living close to volcanoes. To better understand the importance of volcanic risk to individual countries, the calculation of the proportional threat is independent of the country size and number of volcanoes (Measure 2). This highlights those countries where large portions of their population live within close proximity of volcanoes – chiefly small island nations and territories where the population and volcanoes share small areas.

The differences in threat rank illustrate how whilst many countries could be expected to suffer large losses in absolute terms as shown by a high rank using Measure 1, it is the small island nations where the relative social and economic losses could be much larger (Measure 2).

Country	% of volcanoes in country with classified VHI	Measure 1: Overall threat to life rank	Measure 2: Proportional threat rank
Indonesia	40	1	23
Philippines	17	2	20
Japan	38	3	43
Mexico	10	4	34
Ethiopia	2	5	36

Guatemala	17	6	11
Ecuador	31	7	22
Italy	43	8	33
El Salvador	14	9	9
Kenya	5	10	42
Papua New Guinea	18	11	31
Nicaragua	37	12	16
Colombia	33	13	39
Turkey	0	14	47
Costa Rica	50	15	10
Taiwan	0	16	29
Yemen	8	17	37
Chile	14	18	62
New Zealand	29	19	26
China	0	20	74
Tanzania	10	21	45
Peru	24	22	50
Uganda	0	23	44
USA Contiguous States	19	24	75
Russia	12	25	77
DR Congo	33	26	55
Syria	0	27	46
Cameroon	20	28	41
Spain – Canary Islands	33	29	13
Portugal - Azores	29	30	6
Vietnam	0	31	61
Armenia	0	32	19
Rwanda	0	33	30
Saudi Arabia	0	34	57
Burma (Myanmar)	0	35	53
Iran	0	36	69
Madagascar	0	37	54
France – Indian Ocean	11	38	27
Iceland	50	39	28
USA - Alaska	24	40	51
Vanuatu	43	41	15
Honduras	0	42	49
Sudan	20	43	67
South Korea	0	44	66
Argentina	10	45	78
France – West Indies	100	46	3
Greece	40	47	60
North Korea	0	48	65
France - Mainland	0	49	64
Eritrea	0	50	63
Azerbaijan	0	51	38
Panama	0	52	40
Solomon Islands	25	53	35

Comoros	50	54	21
USA - Hawaii	27	55	52
Cape Verde	33	56	25
Dominica	0	57	5
Bolivia	0	58	70
Afghanistan	0	59	68
Georgia	0	60	58
Equatorial Guinea	0	61	32
Spain - Mainland	0	62	72
Samoa	0	63	17
Saint Vincent & the Grenadines	100	64	2
Saint Lucia	0	65	7
Nigeria	0	66	76
Djibouti	0	67	48
Germany	0	68	73
USA – American Samoa	0	69	18
Grenada	50	70	14
Saint Kitts and Nevis	0	71	4
Sao Tome and Principe	0	72	12
Pakistan	0	73	79
Fiji	33	74	56
Mongolia	0	75	71
Canada	0	76	84
Tonga	33	77	59
Algeria	0	78	81
UK – West Indies	100	79	1
Netherlands	0	80	24
Australia	67	81	82
UK - Atlantic	0	82	8
Niger	0	83	83
Chad	0	84	85
France – Pacific Ocean	13	85	80
India	33	86	89
Mali	0	87	86
Libya	0	88	88
USA – Marianas Islands	14	89	87
Norway	33	90	90
South Africa	0	91	91
Malaysia	0	92	92
Brazil	0	93	93
Antarctica	13	-	-
Kuril Islands	27	-	-

Table 6: All countries or territories ranked in order of overall risk to life (Measure 1). Ranking through Measure 2, proportional threat, is also shown. The percentage of volcanoes per country which are classified is shown.

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CS21. Scientific communication of uncertainty during volcanic emergencies

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Summary

Forecasting potential outcomes of volcanic unrest and activity is usually associated with high levels of scientific uncertainty. Knowing whether particular volcanic unrest will end with an eruption or not implies reliance on scientific knowledge on how the volcano has behaved in the past and on how monitoring signals can be interpreted in terms of magma movement. This may be relatively straightforward in volcanoes that erupt frequently, but may be much more challenging in volcanoes with long eruptive recurrence intervals or even more in those without historical records. The dramatic consequences that wrong interpretation of volcanic unrest signals may have should persuade volcanologists to understand that communication among them during an emergency is crucial. Consensus to quantify scientific uncertainty must be reached, in order to provide the decision maker with a simple and clear forecast of the possible outcome of the volcano reactivation. Unfortunately scientific communication during volcanic emergencies is not an easy task and there is not a general agreement on how such communication should be conducted, not only among scientists, but also between scientists and other stakeholders (e.g. decision makers, media, local population). The critical questions here, as occurs with other natural hazards, are how to quantify the uncertainty that accompanies any scientific forecast and how to communicate this understanding to policy-makers, the media and the public. In addition to scientific advance in eruption forecasting, future actions in volcanology should also address improving management of uncertainty and communication of this uncertainty.

Rational

One of the most challenging aspects in the management of volcanic emergencies is scientific communication. Volcanology is by its nature an inexact science, such that appropriate scientific communication should convey information not only on the volcanic activity itself, but also on the uncertainties that always accompany any estimate or forecast. Deciphering the nature of unrest signals (volcanic reactivation) and determining whether or not an unrest episode may be precursory to a new eruption requires knowledge of the volcano's past and current behaviour to help establish future behaviour. In order to achieve such a complex objective it is necessary to have different groups of individuals involved in information exchange, including those from disciplines such as geology, volcano monitoring, experimentation, modelling and probabilistic forecasting. Communication is required on a level that caters for needs and expectations of all disciplines; i.e. there is a need to share a common technical language. This is particularly relevant when volcano monitoring is carried out on a systematic survey basis without continuous scientific scrutiny of monitoring protocols or interpretation of data. In an emerging unrest situation, difficulties may arise with communication among scientists and between scientists and Civil Protection officers, decision makers, media or the public, due to the different skills and degree of knowledge of volcanic phenomena.

Of particular importance is the communication link between scientists with Civil Protection agents and decision makers during evolving volcanic crises. In this case, it is necessary to translate the scientific understanding of volcanic activity into a series of clearly explained scenarios that are accessible to the decision-making authorities. Also, direct interaction between scientists and the general public is inevitable both during times of quiescence and activity. Information coming directly from the scientific community has a special influence on risk perception and on public confidence in this information. Therefore, effective volcanic emergency management requires identification of feasible actions to improve communication strategies at different levels including: scientists-to-scientists, scientists-to-technicians, scientists-to-Civil Protection, scientists-to-decision makers, and scientists-to-general public.

The main goal of eruption forecasting seeks to respond to how, where, and when an eruption will occur. To answer these questions there is an emerging recognition that probabilities should be used for characterisation of associated uncertainties. However, communicating probabilities and, in particular, uncertainty, is not an easy task, and may require a very different approach depending on who is the receptor of such information. Making forecasts on future volcanic activity follows basically the same approach as in other natural hazards (e.g. storms, landslides, earthquakes, tsunamis). However, this approach does not necessarily require the same level of understanding by the population and decision-makers. Compared to meteorologists who have much more data and observations, volcanologists have to deal with a higher degree of uncertainty, mainly derived from this lack of observational data. It is also important to consider that all volcanoes behave in a different way, so a universal model to understand behaviour of volcanoes does not exist. Each volcano has its own particularities depending on magma composition and physics, rock rheology, stress field, geodynamic environment, local geology, etc., which make them unique, so that what is indicative in one volcano may be not relevant in another. All this makes volcano forecasting very challenging and even more difficult to communicate this high degree of uncertainty to the population and decision makers.

How to communicate volcano forecast?

Significant work has been done during last years to improve communication in natural hazards (Atman et al., 1994, Morgan et al., 2002, Karelitz and Budescu, 2004, Visschers et al., 2009, Stein and Geller, 2012). In a similar way, several studies on communication during volcanic emergencies have been carried out (Newhall et al., 1999, McGuire et al., 2009, Aspinall, 2010, Donovan et al., 2012a, Donovan et al., 2012b, Marzocchi and Bebbington, 2012, Doyle et al., 2014). The common factor in all these studies is the need to communicate the uncertainty that accompanies any forecast on the future behaviour of a natural system. Most of these studies agree that probabilities are the best way to communicate scientific forecasts and, consequently, its associated uncertainties. In this sense the use of probability theory is common in natural hazards (Cooke, 1991, Colyvan, 2008, Stein and Stein, 2013) and also in volcano forecasting (Aspinall and Cooke, 1998, Marzocchi et al., 2004, Aspinall, 2006, Sobradelo and Martí, 2010, Marzocchi and Bebbington, 2012, Donovan et al., 2012c).

Probability can be defined as one measure of uncertainty. The way in which probabilities are understood depends on the degree of numeracy we have. However, during our life we are everyday confronted with situations that require making decisions, and in many cases, even if we are not aware of doing this, we use probabilities (commonly known as "common sense") to evaluate the degree of uncertainty in a decision. A common situation were we to use probabilities, even if they are not expressed mathematically, is when making decisions based on weather forecasts (e.g. do we take an umbrella? Do we go to an outdoor festival? etc) that we see everyday in newspapers or on TV. We do not have problems with understanding and accepting a forecast that says the probability of having rain tomorrow is high. It is not necessary for the meteorologists to indicate this in a more precise way (e.g. the probability of rain for tomorrow is of 80%); although in some countries this is communicated. The accuracy of contemporary weather forecasts is typically quite high for periods of a few days in advance. But still there may be incorrect forecasts that may cause serious trouble, for example when bad weather is predicted people may change their plans and important economic losses may result.

Making predictions on the future behaviour of a volcano basically follows the same reasoning that is behind weather forecasts (analysis of past data, monitoring of the current situation and identification of possible future scenarios). However, typically there is less familiarity about the behaviour of volcanoes than about the weather. Thus volcano forecasts are not so easily understood by the population and decision makers. Although there are some scientists who are highly experienced communicators in well–established volcano observatories and teams, there is still need for taking this practise to a higher extent as meteorologists have done. This is in part due to lack of observational data and, consequently, to the limitations that volcanologists have to obtain precise probability estimates. This makes it difficult to communicate volcano forecasts in a simple language, difficulty that usually increases because population and decision-makers are not as used to listening to volcano forecasts as they are with weather forecasts. Therefore, scientific communication of volcano forecasts needs to reduce the considerable distance that today still separates the proper scientific language from its understanding by a non-scientific audience.

The uncertainty that accompanies the identification and interpretation of eruption precursors, derives from the unpredictably of the volcano as a natural system (aleatory uncertainties) and from our lack of knowledge on the behaviour of the system (epistemic uncertainties). These uncertainties can be redefined as shallow or deep (Cox Jnr, 2012, Stein and Stein, 2013) depending on the eruption frequency of the volcano. Highly active volcanoes with high eruption frequencies can be more easily predicted (i.e. they are reasonably well known) than those characterised by low eruption frequencies, respectively.

There are different ways in which probabilities (and uncertainties) can be described. These include words, numbers, or graphics. The use of words to explain probabilities seeks to offer a language that appeals to people's intuition and emotions (Lipkus, 2007). However, it usually lacks precision as it tends to introduce significant ambiguity by the use of words such as “probable”, “likely”, “doubtful”, etc, which lack precision or clear definitions. Probabilities are defined mathematically, but such descriptions may fail when the audience has a low numeracy. In the last years it has been increasingly common to use graphics to represent probabilities in natural hazards (Kunz et al., 2011, Spiegelhalter et al., 2011, Stein and Geller, 2012). The advantage of communicating uncertainties (or probabilities) visually is that we are everyday better prepared and trained to use and understand infographics. A graphic can be adapted to the aims of the communicator, stressing the importance of the context of the communication exercise and the needs and capabilities of the audience (Spiegelhalter et al., 2011). Volcanologists can adapt these modern methodologies to their needs, in order to make volcano forecasts and their intrinsic uncertainty clear enough to any potential receptor of this information.

In addition to these “formal” or “academic” ways to describe and communicate probabilities (and uncertainties) there are other important aspects (namely odds, regulations and culture) related to each particular society, that volcanologists should take into account for communication purposes. “Odds” is an expression of relative probabilities that is well understood by many communities (e.g. gambling, games of chance) and can also be effective to communicate volcano forecasting if it is correctly adapted to such a goal. Regulations are not a direct communication tool but are frequently used to manage environmental and natural hazards. Some regulations are widely understood or at least accepted by the public even if they don’t understand the science behind them. Regulations are not widely used in volcanic crisis management but can be useful in communication. An example is in Case Study 18 where occupational risk regulations were used to explain risk to workers. Finally, culture is of key importance in communication. The cultural diversity of societies facing volcanic threat determines that some communication approaches may work in one country or culture but not in another. Therefore, it is important to analyse and understand the particular cultural aspects of each society in order to define the best communication procedures and languages in each case.

What should be communicated?

Forecasting the future behaviour of a volcano requires good knowledge of its past behaviour, based on the analysis of the geological record and/or historical eruptive records, and a precise understanding of its current activity through monitoring systems. Will the eruption occur? What style of eruption will it be? When the eruption will occur? Where the eruption will occur? What is the size of the problem?, are the basic questions that the decision makers will surely pose to the scientist once an alert has been declared and the process of managing a volcanic emergency has begun. Usually, scientists can answer these questions with approximations (with probabilities in some cases) based on knowledge of previous cases from the same volcano, or from other volcanoes of similar characteristics, knowledge of the past eruptive history of the volcano, the degree of accuracy in the detection of warning signals (geophysical and geochemical monitoring), and knowledge about the significance of these warning signs. Giving probabilities as outcomes of volcano forecasts may be relatively easy for the scientist depending on the degree of information available, but it may be not fully understood by the decision-maker or any other receptor of such information. It is necessary to find clear and precise ways to transfer this information from scientist to decision-maker, to avoid misunderstandings and misinterpretations that could lead to incorrect management of the volcanic crisis and, consequently, to a disaster.

Volcano forecasts should be focussed on the science, just communicating precise and clear scientific advice on the potential evolution of volcanic phenomena in the most appropriate terms, in order to make it understandable to all potential receptors. Scientists may also recommend safe behaviour directly to the public, providing advice that saves people’s lives (e.g. go up a hill if a lahar threatens). However, this should not imply or be confused with making decisions on how to manage a volcanic emergency (e.g. evacuation), as this belongs strictly to the decision maker.

When volcano forecasts should be communicated?

Scientific communication in active volcanic areas should be always present. This means that there should be a permanent flow of information from scientists to the population and policy-makers on the eruptive characteristics of the volcano, its current state of activity, or its associated hazards, even when volcanoes do not show signs for alarm. This is crucial preparation for when an emergency starts and things need to move much faster. However, in many cases scientific communication in hazard assessment and volcano forecasting is just restricted to volcanic emergencies. This may reduce considerably the understanding of the scientific information and its reliability due to the previous lack of knowledge on these subjects by the population and decision-makers.

When volcanic unrest starts and escalates, the origin of this unrest needs to be investigated to assess the likelihood of evolving into an eruption. As previously mentioned, the calculation of probabilities will be subjected to considerable uncertainties, as most of the data will be obtained from monitoring systems, so they will constitute indirect evidence of what could be happening inside the volcanic system. In volcanoes with a high eruption frequency comparison with previous unrest episodes will assist understanding unrest.

Past experience shows that good detection and interpretation of precursors allows prediction of what will happen with a considerable degree of confidence. This implies that scientific communication during volcanic crises needs to be constant and permanently updated with the arrival of new data. The longer is taken in making a decision the higher could be the costs incurred, as reaction time decreases and vulnerability increases. This constitutes the main worry in managing volcanic crises, WHEN to make a decision, which in most cases could be to order an evacuation. In essence, the relationship between the decrease of uncertainty in the interpretation of the warning signs of pre-eruptive processes to acceptable (reliable) levels, and the time required to make a correct decision, is a function of the degree of scientific knowledge of the volcanic process and the effectiveness of scientific communication. Therefore, scientific communication during volcanic emergencies needs to be effective from the beginning of the process, but would be significantly improved if this communication channel has already been established when the level of activity of the volcano did not represent a cause of concern.

What needs to be done?

In order to improve scientific communication during volcanic crises comparisons between communication protocols and procedures adopted by different volcano observatories and scientific advisory committees is recommended, in order to identify difficulties and best practice at all levels of communication: scientist-scientist, scientist-technician, scientist-Civil Protection, scientist-general public. Experience from the management and communication of other natural hazards should be brought in and common communication protocols should be defined based on clear and effective ways of showing probabilities and associated uncertainties. Although each cultural and socio-economic situation will have different communication requirements, comparison between different experiences will help to improve each particular communication approach, thus reducing uncertainty in communicating eruption forecasts.

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CS22. Volcano Disaster Assistance Program: Preventing volcanic crises from becoming disasters and advancing science diplomacy

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The Volcano Disaster Assistance Program is a cooperative partnership of the USAID Office of U.S. Foreign Disaster Assistance (OFDA) and the U.S. Geological Survey (USGS). Founded in 1986 in the wake of the Nevado del Ruiz catastrophe wherein more than 23,000 people perished needlessly in a volcanic eruption, VDAP works by invitation to reduce volcanic risk, primarily in developing nations with substantial volcano hazards. The majority of emergency responses and capacity building projects occur in, but are not limited to, Pacific Rim nations. The single most successful VDAP operation was its response with the Philippine Institute of Volcanology and Seismology to the reawakening and subsequent eruption of Mount Pinatubo in 1991. This response alone saved 20,000 lives, including U.S. military personnel at Clark Air Base, and a conservative estimate indicates that at least 250 million dollars in tangible assets were removed from harm's way ahead of the eruption (Newhall et al., 1997). More recently, in late 2010 VDAP assisted Indonesia's Center for Volcanology and Geologic Hazard Mitigation respond to the eruption of Merapi volcano, which saved 10,000-20,000 lives.

Figure 1: Map of VDAP deployments 1986 - 2012

Current activities

The VDAP team is on call to respond to volcano emergencies globally with crisis response teams. Since 1986, VDAP has responded to 25 major volcano crises. In addition to this on-call activity, VDAP has conducted capacity-building projects and helped build or strengthen volcano hazards institutions in a dozen Pacific Rim countries. The VDAP approach is to work in the background to support and strengthen our partners' crisis response and hazard mitigation programs.

Chile

Figure 2: Gas, ash, and steam erupt from the growing lava dome in the crater of Chaitén, southern Chile, May 26, 2008. USGS photo

On May 2nd, 2008, Chaitén volcano in southern Chile suddenly re-activated after hundreds of years of dormancy and produced the largest eruption so far in the 21st century. A town of more than 4000 people lying just 10 km from the volcano had to be evacuated within 48 hours of the eruption onset. A VDAP rapid-response team assisted the Chilean Servicio Nacional de Geología y Minería (SERNAGEOMIN) to deploy radio-telemetered monitoring instruments and forecast eruption hazards. Added to the disruption of lives and livelihoods on the ground, the Chaitén eruption severely disrupted air traffic in the region. In addition to the VDAP response, two experts on volcanic ash hazards to aviation from the USGS Volcano Hazards Program traveled to Argentina and Chile to advise civilian and military aviation interests on procedures to ensure safe operations during eruptions in the region. Although not widely known prior to the Iceland eruptions of 2010, volcanic ash clouds threaten aircraft daily on a global basis and planes must be warned away from ash-contaminated airspace. Since the near-crash of several fully loaded 747's in the 1980's, the USGS, FAA and NOAA have been leaders in developing a global ash avoidance program under the auspices of the International Civil Aviation Organization.

Chile has within its borders more than 122 active volcanoes, only a handful of which have any monitoring in place or modern hazard assessments completed. The eruption of Chaitén spurred the Government of Chile to implement a new national plan to address its considerable volcano hazards. The resulting Red Nacional de Vigilancia Volcánica (RNVV) is modeled directly on the USGS National Volcano Early Warning System (NVEWS), an element of the USGS science strategy for natural hazards.

In 2009 and 2011, under a revitalised Memorandum of Understanding between the U.S. and Chile for cooperation in earth science and technology, VDAP teams traveled to Chile to advise and assist with the RNVV plan's implementation. In addition, SERNAGEOMIN and USGS are continuing to work together to assess the volcanological and ecological impacts

Figure 3: Group photo of VDAP team with President Michelle Bachelet, U.S. Ambassador to Chile, Paul Simons (left) and USGS Director's representative Tom Casadevall (right). Photo taken following briefing by the team on the situation at Chaitén volcano and SERNAGEOMIN's new national volcano early warning plan (Red Nacional de Vigilancia Volcánica)

Colombia

VDAP has had an ongoing collegial crisis response and capacity-building relationship with Colombia since the disaster at Nevado del Ruiz in 1985. Over the years, VDAP has worked closely with the Instituto Colombiano de Geología y Minería (INGEOMINAS) on various projects, including direct involvement in establishing the three volcano observatories now functioning in Colombia.

In 2007-2011 VDAP worked closely with the INGEOMINAS Observatory in Popayan to monitor and forecast eruptions at Huila volcano. Like Nevado del Ruiz, Huila is a large snow-and-ice-clad volcano with a history of producing exceedingly dangerous debris flows (lahars). On 20 November 2008, following a period of escalating unrest of several weeks, Huila erupted and generated a huge debris flow. Owing to accurate forecasting and good communications with downstream communities, fewer than 10 casualties occurred in an area where in 1994 an event of similar sized killed more than 1000. Most of the credit for the success of this risk mitigation effort belongs to INGEOMINAS and other involved Colombian institutions, but the effort was, and still is, substantially supported by VDAP.

USGS and INGEOMINAS personnel meet to define alert level system for Huila volcano, Colombia. February 2007. USGS photo

Eruption-generated debris flow overran portions the town of Belalcazar, Colombia approximately 15 miles downstream of Huila volcano on 20 November 2008. Accurate forecasts and warnings triggered evacuation of the 4000 residents, saving lives and property. INGEOMINAS photo

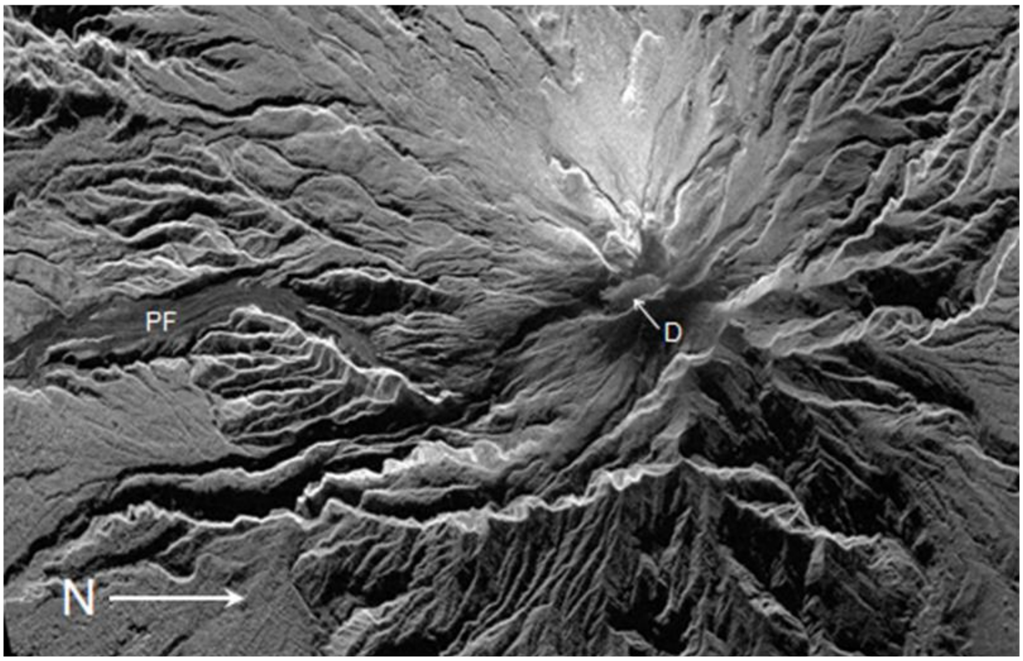
In 2008 a Memorandum of Understanding between the USGS and INGEOMINAS was signed, and subsequently the Director of INGEOMINAS has sought a Project Annex with VDAP to work with them to develop their volcano monitoring and analysis capabilities on all 15 Colombian volcanoes. Within the limitations of its resources, VDAP will continue to work with INGEOMINAS on volcano hazard mitigation in this important South American country.

Indonesia

Indonesia is the world's most volcanically active nation, with numerous eruptions each year and several million people living directly on the flanks of the volcanoes. Currently, VDAP's largest capacity-building project is conducted in partnership with the Indonesian Center for Volcanology and Geologic Hazard Mitigation (CVGHM). USGS collaboration with CVGHM's predecessor, the Volcanology Survey of Indonesia, dates back to the 1980's. At that time USGS helped evaluate hazards and establish monitoring at several of the highest-risk volcanoes, such as Merapi, located in the suburbs of Yogyakarta (metropolitan area population, 1.6 million). Following an absence of 20 years, at the invitation of CVGHM and with support of OFDA, VDAP returned to Indonesia in 2004 to help build a new regional volcano observatory in the North Sulawesi and Sangihe islands region. Over the succeeding five years, CVGHM and VDAP built what is now one of the best monitoring networks in the country, with real-time seismic monitoring of the 10 active volcanoes in place and signals relayed in real-time by satellite and internet to CVGHM offices in Bandung. In 2006, VDAP sent a crisis response team to assist CVGHM during eruptions of Merapi volcano, which directly threatens the lives of several hundred thousand people. VDAP also provided seismic monitoring equipment, eruption forecasts, remote sensing, and a technical advisor to assist the OFDA Disaster Assistance Response Team (DART) during their response to the M 6.3 Yogyakarta earthquake, which took place during the eruption and killed 5,700.

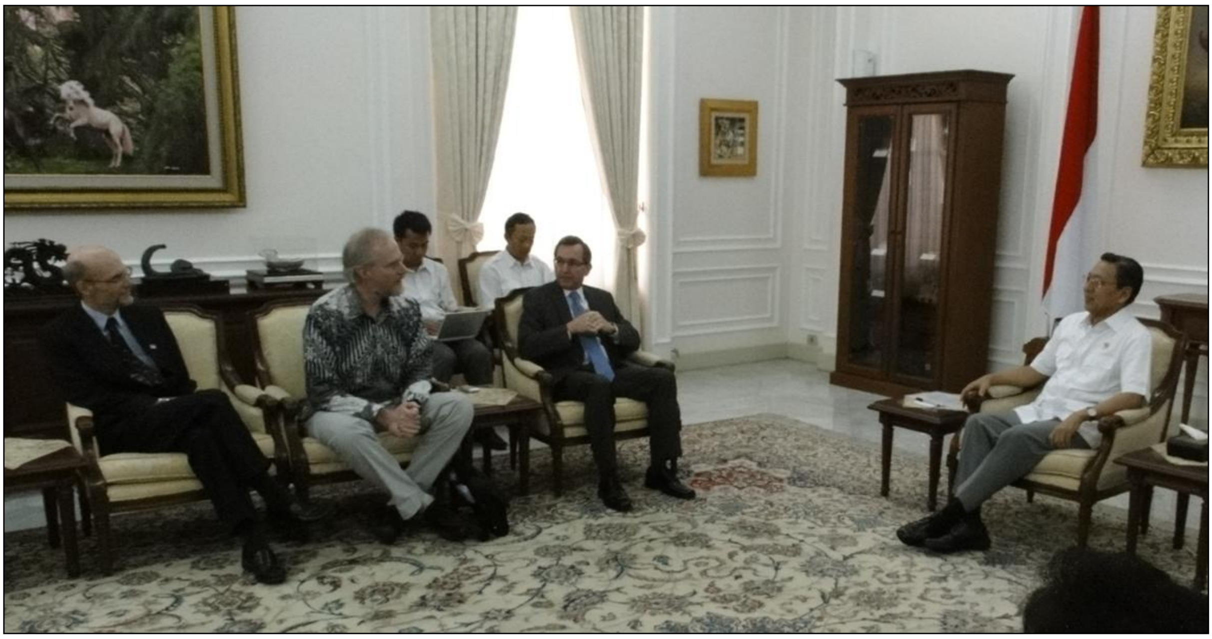
VDAP and CVGHM scientists install a seismic station to monitor volcanic activity in North Sulawesi. USGS photo

In 2010 at the request of the President of Indonesia, a VDAP team was again deployed to assist CVGHM in their response to the largest eruption at Merapi in more than 100 years. VDAP and international partners utilised satellite radar data to "see through" clouds that obscured the volcano and delivered near-real-time analyses of changes directly to the CVGHM response team during the crisis. This information allowed CVGHM to assess the magnitude of the eruption and areas affected, thereby informing their decisions regarding the extent of evacuations needed. In addition, the on-site VDAP team provided technical assistance and monitoring equipment to replace systems destroyed in the early phase of the eruption and to expand the monitoring program. Although ~380 fatalities were recorded, it is estimated that CVGHM warnings and prompt actions by the Government of Indonesia saved 10,000-20,000 lives.



TerraSAR-X Synthetic Aperture Radar image of 4 Nov 2010, showing pyroclastic flow deposits (PF) from the 26 October eruption and a new lava dome that growing at the summit. Very rapid growth of the lava dome was followed by a large eruption during the night of 4-5 November.

U.S. Ambassador Cameron Hume and the Director of the Indonesian Geology Agency, Bambang Dwiyanto, signed Annex IV to the 2006 Memorandum of Understanding between the governments of Indonesia and the U.S. for Cooperation in Science and Technology for Natural Hazards. This Annex calls for continued VDAP assistance to CVGHM. Subsequently, VDAP was singled out among multiple international donors by CVGHM with a request to assist them in modernising volcano monitoring networks and hazard assessments in Java, where more than 100 million people live in the shadows of active volcanoes. This expansion of VDAP work was approved by OFDA and USGS in 2009. In 2010, VDAP and CVGHM completed monitoring installations in North Sulawesi, conducted joint training workshops and began the Java expansion with new installations and hazard assessments at Tangkuban Perahu volcano, the highly populated "city volcano" near Bandung, Java. In subsequent years, VDAP and CVGHM have worked together at Ijen, Raung and Dieng volcanoes in Java and at Agung volcano in Bali.



USAID Mission Director, Walter North (far left), VDAP Chief John Pallister (left centre) and U.S. Ambassador to Indonesia Scot Marciel (centre) brief Indonesian Vice President Boediono on the 2010 eruption of Merapi and the effectiveness of the response by Indonesia's Center for Volcanology and Geologic Hazard Mitigation. USGS photo

VDAP benefits to the USGS Domestic Program

Over the past 25 years, the VDAP program has served as a development and proving ground for much of the volcano monitoring technology and eruption forecasting science that is applied at U.S. volcanoes. International experience in crisis response and risk mitigation has informed, strengthened, and helped guide development of domestic capabilities. The Scientists-in-Charge at the USGS Alaska and Cascades Volcano Observatories and the Director of the USGS Volcano Science Center are alumni of VDAP, and current and former VDAP scientists have helped lead responses to recent eruptions in Washington State, Alaska, and the U.S. Commonwealth of the Northern Mariana Islands. The USGS plan for domestic volcano hazard mitigation (National Volcano Early Warning System (NVEWS)), outlined in the USGS Bureau Science Strategy, draws many key elements from decades of VDAP experience. VDAP serves as an enduring and productive strategic partnership between the U.S. Departments of State and Interior. VDAP seeks to enhance U.S. relationships with other nations through science diplomacy and to build international friendships through work toward a shared goal of saving lives and property.

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CS23. Communities coping with uncertainty and reducing their risk: the collaborative monitoring and management of volcanic activity with the *Vigías* of Tungurahua

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Long-lived episodic volcanic eruptions share the risk characteristics of other forms of extensive hazard (such as flood, drought or landslides). They also have the capacity for escalations to high intensity, high impact events. Volcán Tungurahua in the Ecuadorian Andes has been in eruption since 1999. The management of risk in areas surrounding the volcano has been facilitated by a network of community-based monitoring volunteers that has grown to fulfil multiple risk reduction roles in collaboration with the scientists and authorities.

Inception and Evolution

Renewed activity from Tungurahua (1999) prompted the evacuation, via Presidential Order, of the large tourist town of Baños and surrounding communities. Social unrest associated with the displacement and attendant loss of livelihood culminated in a forcible civil re-occupation of the land, crossing and over-running military checkpoints (Le Pennec et al., 2012). This re-occupation prompted a radical re-think of management strategy around the volcanic hazard, shifting emphasis from enforcement to communication (Mothes et al., 2015). This enabled the community to continue their way of life alongside the volcano when it is relatively quiet and to prepare for and rapidly mobilise themselves during acute activity.

To do this, a network of volunteers, formed from people already living in the communities at risk, was created with two main goals in mind: (i) to facilitate timely evacuations as part of the Civil Defence communication network, including the management of sirens, and (ii) to communicate observations about the volcano to the scientists (Stone et al., 2014). These volunteers are collectively referred to as '*vigías*' and their input provides a pragmatic solution to the need for better monitoring observations and improved early warning systems when communities are living in relative proximity to the hazard. As a part of the solution, the communities feel strong ownership and involvement with the network (Stone et al., 2014). The communication pathways, formal and informal are shown in Figure 1.

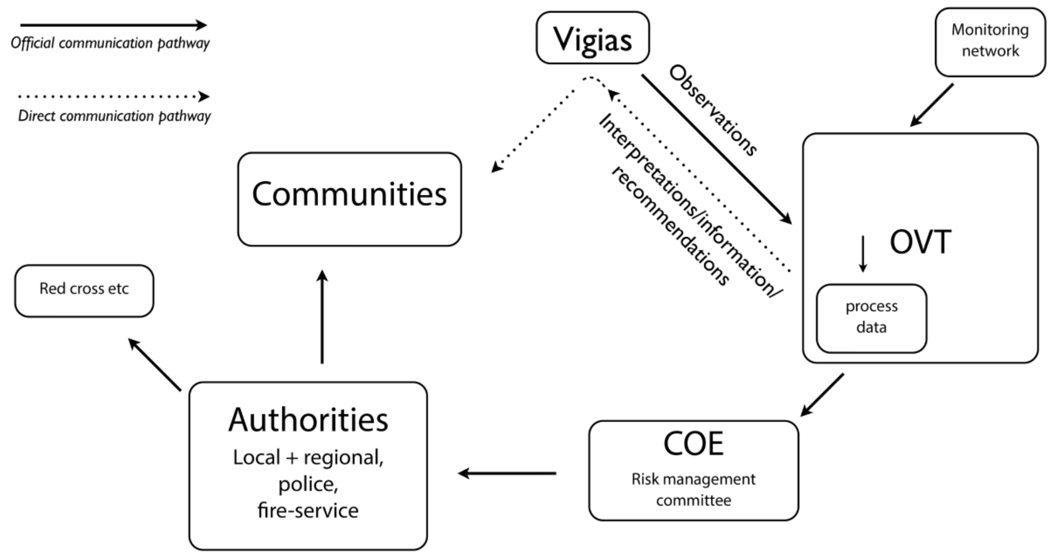

Figure 1: The volcanic risk communication network, with its official pathway and the more direct 'vigia mediated' pathway. Adapted from Stone et al. (2014).

Success and Value of the Network

The current network consists around 25 *vigías* who use radios with which they maintain daily contact with the observatory (see Figure 2). In theory there are up to 43 *vigías,* but not all have radios or actively take part currently. The network has been sustained and has even grown since its inception in 2000. There was a rapid expansion in numbers of *vigias* after the August 2006 eruption. This was a pivotal event, whereby lives saved in the Juive Grande area were attributed to the presence of *vigías* working with the local volcano observatory and lives lost in Palitahua were thought to be in part due to a lack of *vigías* there (Stone et al., 2014). No loss of life has been recorded in recent events in July and October, 2013 and on 01 February, 2014 and this can be attributed to the prompt actions to evacuate and reduce risk via the network. Further, community trust in scientific advice and information has reformed since the events of 1999, with vigías acting as intermediaries. Some of the *vigías* now maintain the scientific monitoring equipment near their houses and make daily observations that add considerably to the sum of knowledge of the range and impact of the volcanic behaviour (Bernard, 2013, Mothes et al., 2015), often assisting with visual confirmation of inferred activity seen on the geophysical monitoring network. Apart from reducing volcanic risk, the network has been able to coordinate the response to fires, road traffic accidents, medical emergencies, thefts, assaults and to plan for future earthquakes and landslides. The economic value of allowing affected communities to remain and adapt their existing livelihoods has not, as yet, been determined, but is considered by those communities to be immeasurable.

So far, the communities have responded dynamically to the risk from the volcano, allowing them to live in close proximity and evacuating rapidly when necessary. Tungurahua is capable of producing far larger eruptions than those seen in the last 14 years (Hall et al., 1999), but the trust developed by the network should engender the capacity for action should such an eruption be forecasted, and crucially allows the people to manage their risk in the mean-time, when long term relocation is simply not an option.

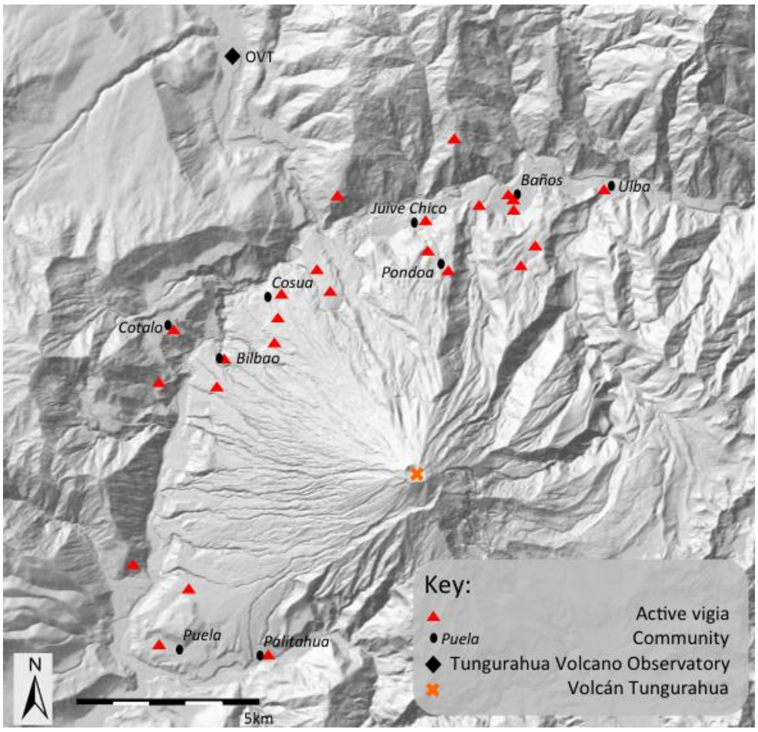

Figure 2: Map showing the locations of vigias relative to the volcano and communities significantly affected by volcanic hazards (adapted from Stone et al. (2014)).

Requirements of the Network

Even now, the network still consists of volunteers; and the main requirement from all stakeholders is just the time needed to maintain shared goals and values. The voluntary aspect of the network is vitally important and the motivations of those involved are to help reduce risk to their communities. Nonetheless, its success is due to the willingness with which time is given by *vigías*, observatory scientists (and those in civil protection during its early years) to listen and to share. While some initial *vigías* were drawn from those already involved with Civil Defence (26%), many were also recruited by scientists due to their location relative to the volcano (21%), for their position in the community (26%) and ultimately through other vigias (5%). The vigías were given basic training from the scientists about what to observe, how to describe phenomena and how to communicate with the local observatory. The largest infrastructural investment was in a VHF radio network, upgraded by another volunteer, and the distribution of handheld radios. Radio communication is a key ingredient in developing relationships and is strictly and professionally observed: every night at 8pm, someone from civil protection calls on the joint (OVT, Civil Defence) radio system and asks the *vigías* to report in. If activity changes then communication frequency increases. Initially, if a *vigía* missed several radio checks they were told to participate properly or not be part of the team. Similarly a sense of shared pride in the role comes from the uniforms provided, initially, by civil defence.

Sustainability of the network

The network is entering into its 15th year; and like conventional geophysical monitoring instruments, relationships continue to function only with regular maintenance; in this instance through contact and discussion. Although the actual financial requirements are small; those that are required (maintenance of the radio network; uniforms) become important symbols to all for the value of the network; long-term neglect of this funding represents a significant threat.

The clear value that the transmission of timely messages to evacuate also reinforces the value of the *vigias and the scientists* to the wider community, providing a strong incentive to volunteers to continue. There is less evidence for whether these motivations would persist in the absence of a volcanic threat but this type of network is exceptionally well suited to extensive hazards and risks.

Risk reduction for more than 14 years

The sustained involvement of *vigias* (community-based monitoring volunteers) has allowed communities surrounding Tungurahua to live with dynamically changing risk. The network of *vigías* have greatly assisted the monitoring efforts of scientists providing visual observations and by maintaining equipment. Frequent interactions with the scientists have fostered strong trust-based relationships, allowing the *vigias* to act as intermediaries between scientists and the communities during risk communication. These activities have undoubtedly saved lives and helped to preserve livelihoods in the area. The nature of long-lived episodic volcanic eruptions, and thus their similarity to other extensive hazards, means that this type of approach could reduce risk in the case of flooding, landslides and droughts.

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