Chapter 2

Global volcanic hazard and risk

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Contents

2.1 Introduction

An estimated 800 million people live within 100 km of an active volcano in 86 countries and additional overseas territories worldwide [see Chapter 4 and Appendix B][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

[1] Chapters 4 to 26 provide additional detail and case studies about subjects covered in this chapter. An electronic supplementary report (Appendix B, www.cambridge.org/volcano) is provided comprising country and regional profiles of volcanism.

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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, Auker et al. (2013)) 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 lahars (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 (Voight, 1990). 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 (Surono et al., 2012) and an estimated loss of US$ 300 million (IDR 3.56 trillion) (BNPB., 2011). 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 (Ragona et al., 2011). 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 (Self & Blake, 2008).

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 (Sparks, 2003, Segall, 2013). Volcanic 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 (Barberi et al., 1984, Potter et al., 2012). 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

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and distribution of these hazards, with wind, for example, determining the direction and extent of hazardous volcanic ash fall, and rain potentially causing volcanic mudflows and landslides. Volcanic eruptions can last minutes to decades (Siebert et al., 2010). 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.

The aim of this book is provide a broad synopsis of global volcanic hazards and risk with a focus on the impact of eruptions on society and to provide the first comprehensive global assessment of volcanic hazard and risk. This work was originally undertaken by the Global Volcano Model (GVM, http://globalvolcanomodel.org/) in collaboration with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI, http://www.iavcei.org/) as a contribution to the Global Assessment Report on Disaster Risk Reduction, 2015 (GAR15), produced by the United Nations Office for Disaster Risk Reduction (UN ISDR).

This chapter complements Chapter 1, which provided a non-technical summary of the topics covered through the rest of the book. This chapter presents a more technical synopsis of volcanism from a hazard and risk perspective, with selected references and links to online resources that will enable a reader to learn about particular topics in more detail. Although more technical from this point, this work does not assume a readership specialising in geosciences.

Chapter 2 comprises eight sections as follows:

- Section 1: Introductory section
- Section 2: Background on volcanoes, the cause of eruptions and the processes driving them
- Section 3:Volcanic eruptions in space and time
- Section 4:Volcanic hazards and their impacts
- Section 5: Monitoring and forecasting of volcanic eruptions
- Section 6: Methods of assessing volcanic hazards and risk
- Section 7: Management of volcanic emergencies and disaster risk reduction
- Section 8: Prognosis on the ways to improve knowledge, emergency management and risk reduction

Here, the readers are frequently pointed towards Chapters 3 through 26. These chapters are designed to illustrate key concepts, methodologies and approaches to the assessment and management of volcanic hazards and risk. These chapters, along with published literature, provide the evidence base for this work.

A complementary report, Appendix B, is provided online in support of this book, in which a country-by-country analysis of volcanoes, hazards, vulnerabilities and technical coping capacity is provided to give a snapshot of the current state of volcanic risk across the world.

2.2 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 (Blong, 1984, Schmincke, 2004, Decker & Decker, 2006, Lockwood & Hazlett, 2013, Papale, 2014), review papers (Sparks, 2003, Newhall, 2007, Cashman et al., 2013, Sparks & Aspinall, 2013) and the Encyclopedia of Volcanoes (Sigurdsson et al., 2015) are recommended starting points. The US Geological Survey website http://volcanoes.usgs.gov/hazards/index 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 (http://www.volcano.si.edu/). The Smithsonian Volcanoes of the World database is the source for much of the basic information used in this book (Siebert et al., 2010, Cottrell, 2014). Version 4 of the database (VOTW4) is online (Smithsonian, 2013). The figures cited throughout this book are from VOTW4.22.

2.2.1 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 2.1). At depths of a few tens of kilometres the solid Earth is very hot (1200ºC 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*).

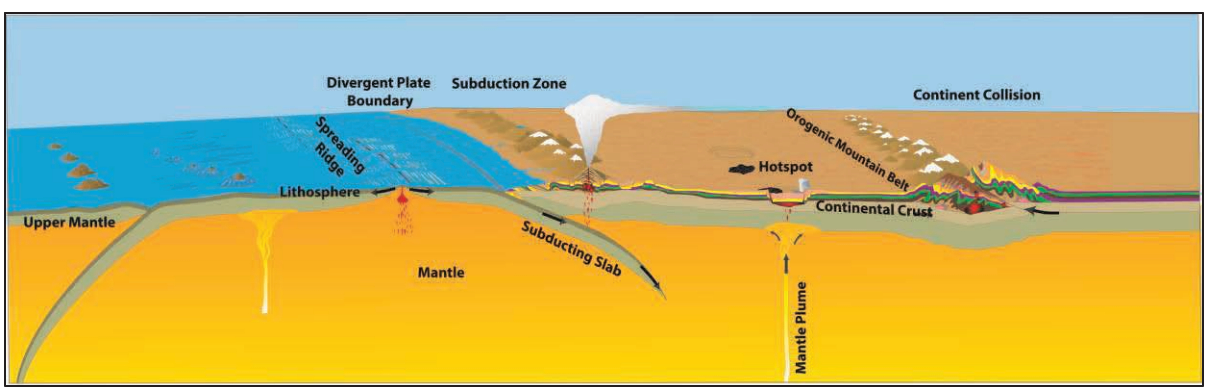

Figure 2.1 A cross-section through the Earth's upper mantle and crust illustrating the plate tectonics and magma generation which gives rise to Earth's volcanoes at subduction zones, spreading ridges and hotspots. (Image courtesy of the Global Volcanism Program, Smithsonian Institution.)

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

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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.

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.

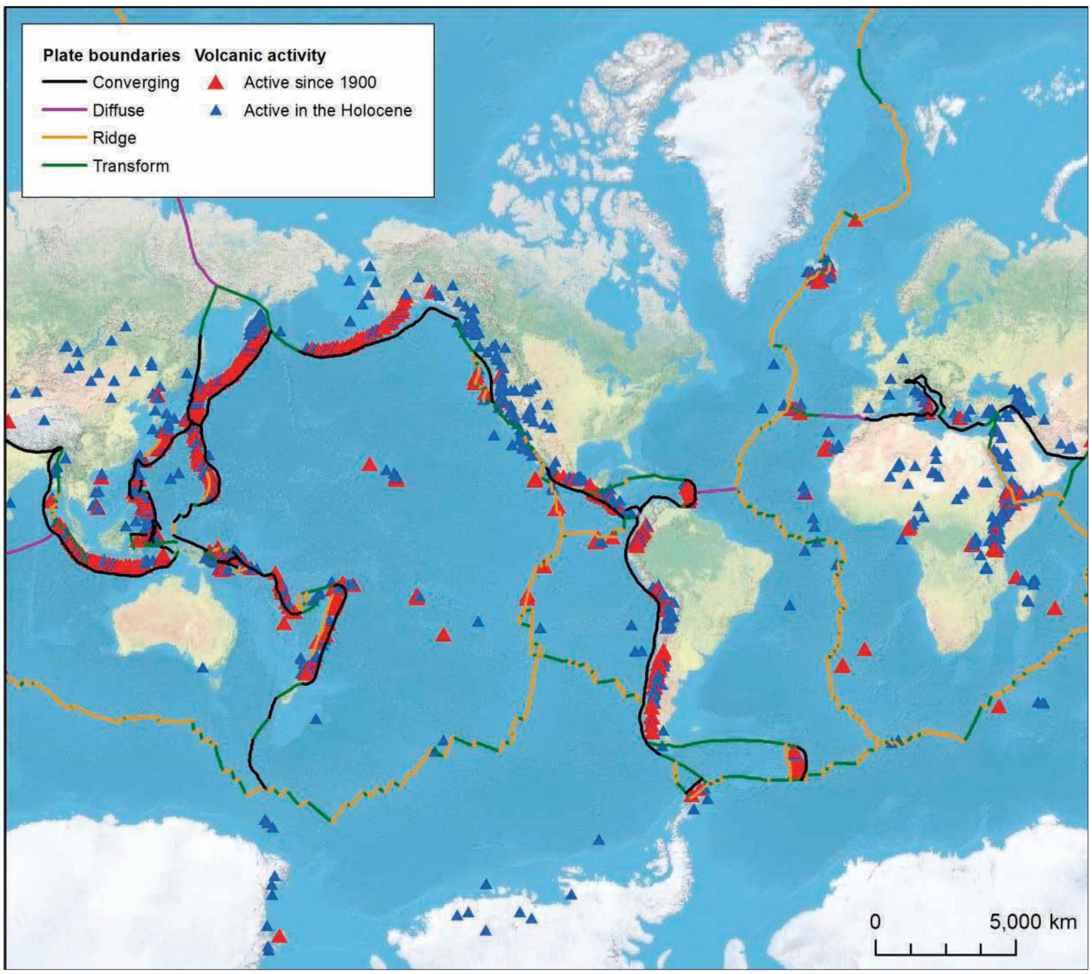

Figure 2.2 Global map of the distribution and status of Holocene volcanoes as listed in VOTW4.22. The distribution of volcanoes also outlines the boundaries of major tectonic plates.

The spatial distribution of volcanoes (Figure 2.2) is now very well understood (Cottrell, 2014) 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.

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2.2.2 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^{o}C. The latter are called *rhyolites* and have temperatures typically in the range 700 to 900^{o}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 (Le Maitre et al., 2002).

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 within plates or where plates rift apart 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.

2.2.3 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 2.3). 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 km. 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

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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.

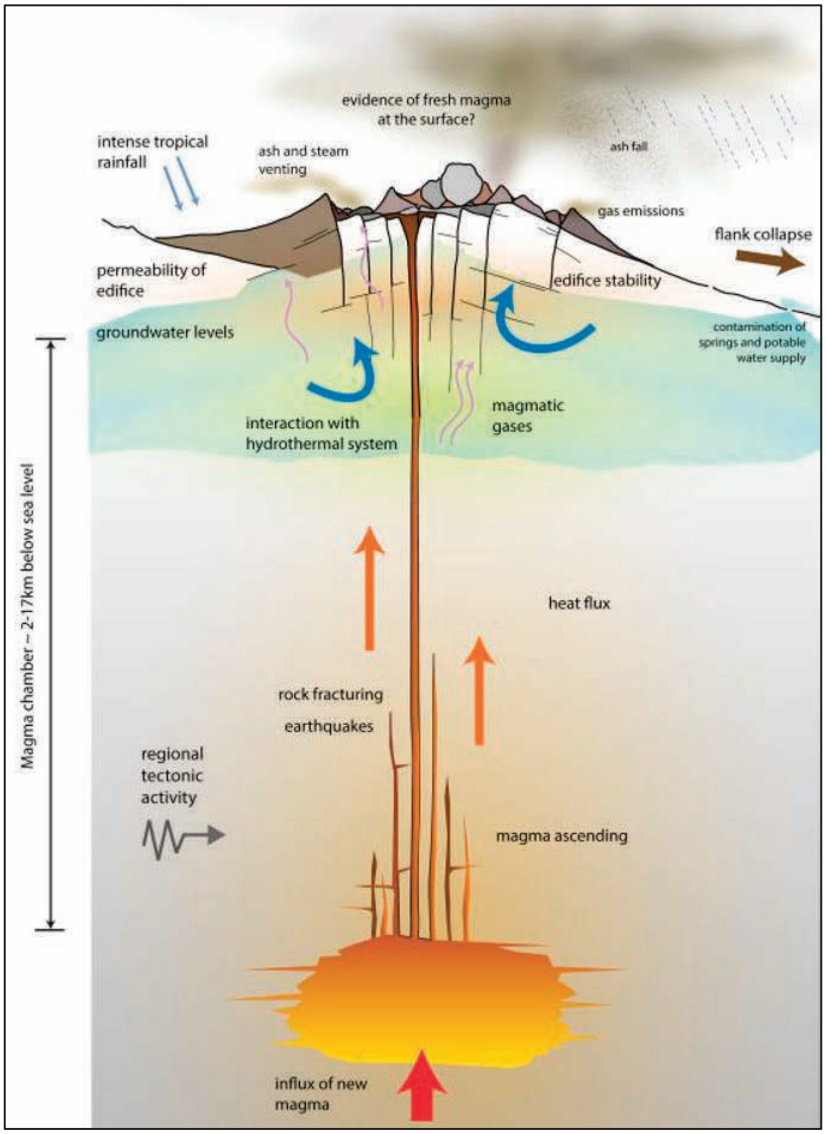

Figure 2.3 Schematic cross-section through a volcano in a tropical setting and its underlying magma chamber illustrating some of the major processes that lead to phenomena that are monitored on active volcanoes. Modified from Hincks et al. (2014). The magma chamber may become pressurised, for example 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

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chambers and in movement of magma and gases from a magma chambers to the surface (Figure 2.3). Recent research is recognising that many volcanic systems involve multiple regions of magma (Figure 2.4) and that there can be other causes of geophysical phenomena at volcanoes, such as movements of ground water (Figure 2.3), which need to be distinguished from manifestations of magma chambers.

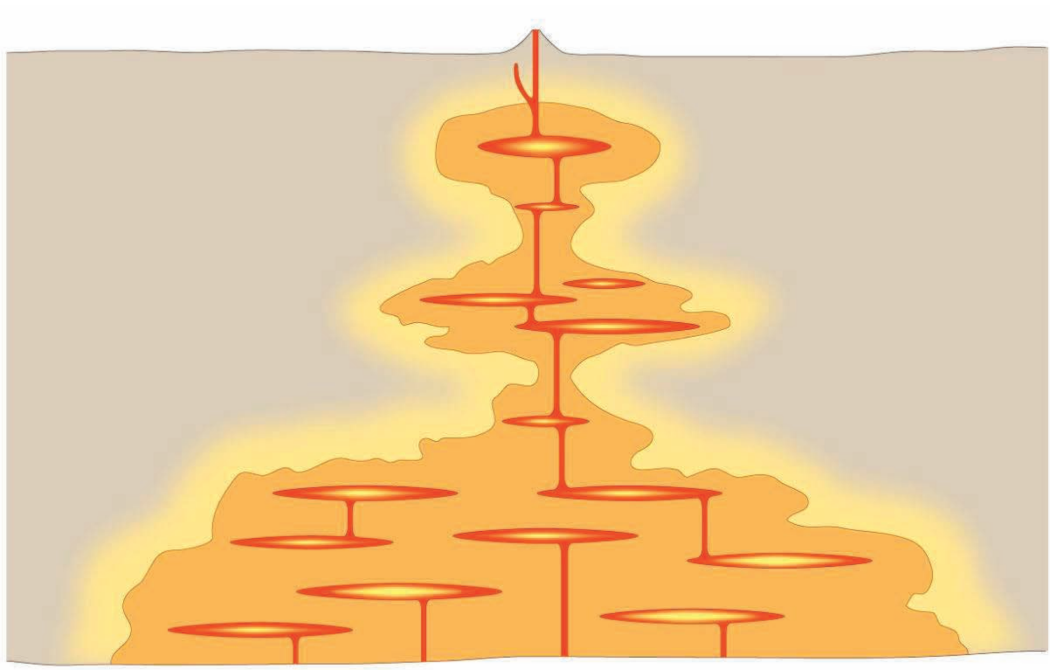

Figure 2.4 Schematic diagram showing a crustal region comprising several magma bodies embedded in hot partially melted rocks at different depths below a volcano. Figure 2.3 shows the uppermost chamber connected to the volcano.

2.2.4 Types of volcanoes

The Smithsonian classification (Siebert et al., 2010, Cottrell, 2014) 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.

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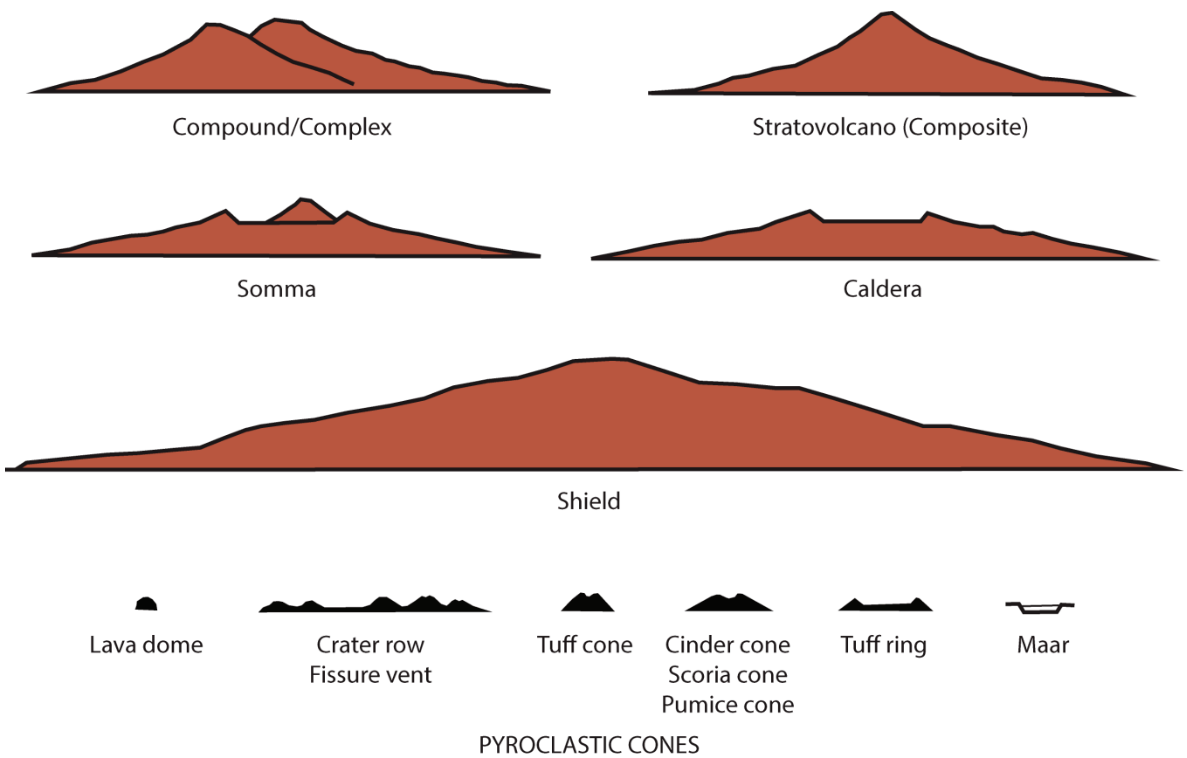

Figure 2.5 Volcanoes take a variety of forms as dictated by their chemistry, eruption style and products. Here the main volcano types are illustrated with a vertical exaggeration of 2:1 for the main edifice constructs and 4:1 for the pyroclastic cones (Siebert et al., 2010). Relative sizes are approximate.

Some common volcano types are illustrated in Figure 2.5. *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 2.6a), 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 basaltic (Figure 2.6b). *Stratovolcanoes*, like Fuji (Japan) and Colima (Mexico), are typically steep-sided and are mixtures of lava and pyroclastic deposits (Figure 2.6c). *Lava dome volcanoes*, like Soufrière Hills Volcano (Montserrat, Eastern Caribbean) are made of mounds of andesitic or rhyolitic lava known as *domes*, together with pyroclastic deposits (Figure 2.6d). *Calderas* are large volcanic craters (1 to more than 50 km diameter) mostly formed by large magnitude volcanic eruptions (Figure 2.6e). 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 (Self & Blake, 2008).

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.

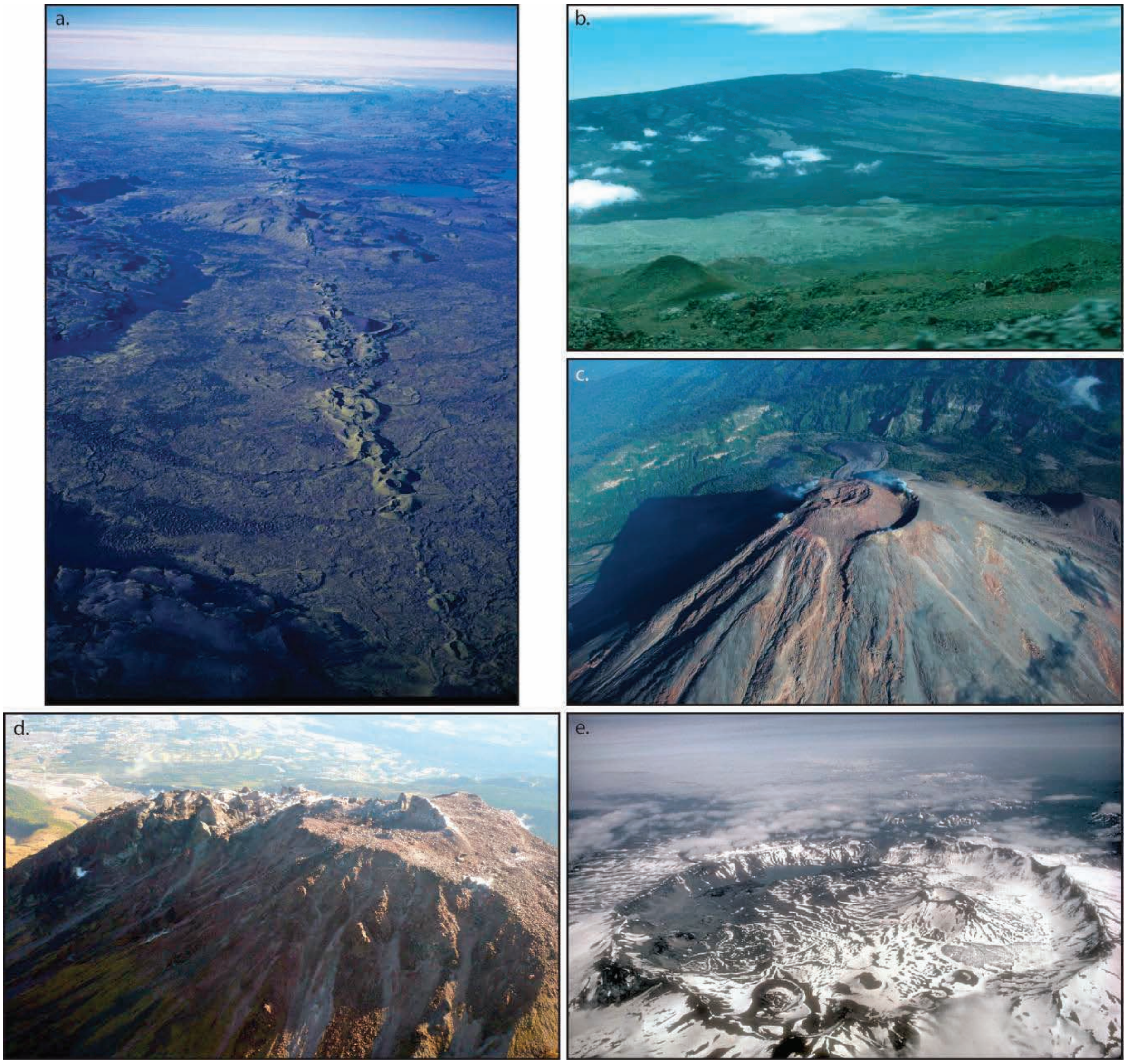

Figure 2.6 Examples of volcano forms. a) Fissure from the 1783 Laki, Iceland, eruption (O. Sigurdsson). b) The Mauna Loa shield volcano, Hawaii (US Geological Survey archive). c) Colima stratovolcano, Mexico. (S. Brown). d) The lava dome at Unzen volcano, Japan (S.Jenkins). e) The 10 km diameter Aniakchak caldera, Alaska (US Geological Survey archive).

2.2.5 Styles of eruption

At the most basic level volcanic activity can be divided into effusion of lava and explosive eruptions (Figure 2.7). 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 2.8a, b) and by interaction of hot erupting magma with water (Figure 2.8c). Lava represents magma that has lost most of the originally

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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 2.8d), while more viscous andesite and rhyolite form much thicker lavas and domes (Figure 2.8e).

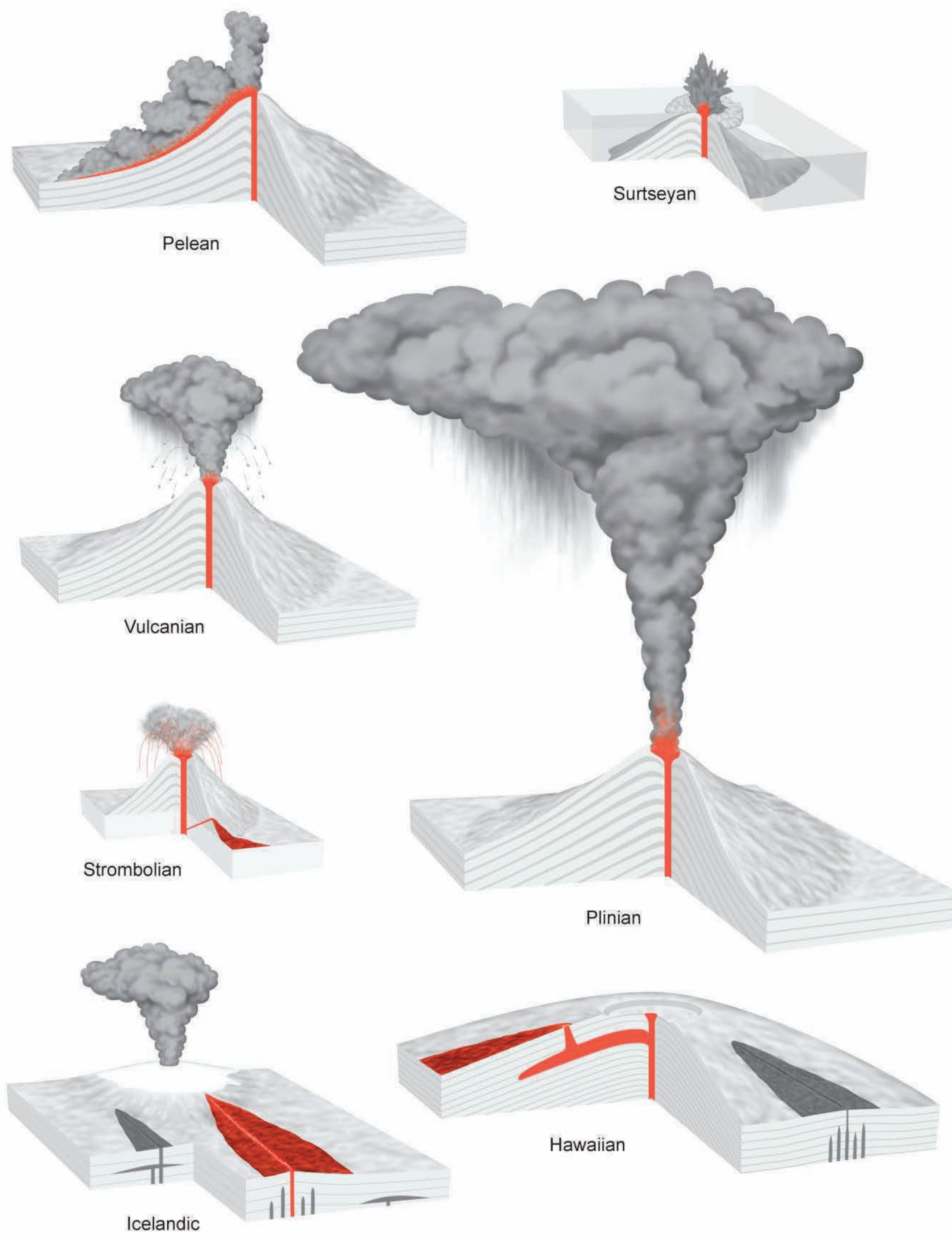

Figure 2.7 Eruption styles vary from effusive lava outflows in Hawaiian style eruptions through to large explosive Plinian eruptions, which can inject ash into the Stratosphere. Here the main eruption styles are illustrated (Artist John Norton in Siebert et al. (2010)). See Figure 2.8 for examples.

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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 2.8b). 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 2.8b). In other cases the mixture is so full of rocks and ash that erupted mixture collapses (Figure 2.8f) and forms a dense flow (called a pyroclastic density current) that moves along the ground under gravity (Figure 2.8g). Over 43% of deaths directly attributed to volcanic hazards are caused by such flows (Auker et al., 2013). Similar flows can be formed with the eruption and collapse of lava domes, which are highly unstable (Figure 2.8h). Volcanic hazards are discussed in Section 4 of this chapter.

(Next page) Figure 2.8 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) A Plinian 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 km 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) A Surtseyan explosive eruption of the submarine Nishino-shima volcano, Japan, 2013 (Japan Coast Guard). d) A Hawaiian style eruption-generated 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 Pelean explosive eruption of Mayon, Philippines (C. Newhall). h) Pyroclastic flow from a dome collapse on Montserrat (H. Odbert).

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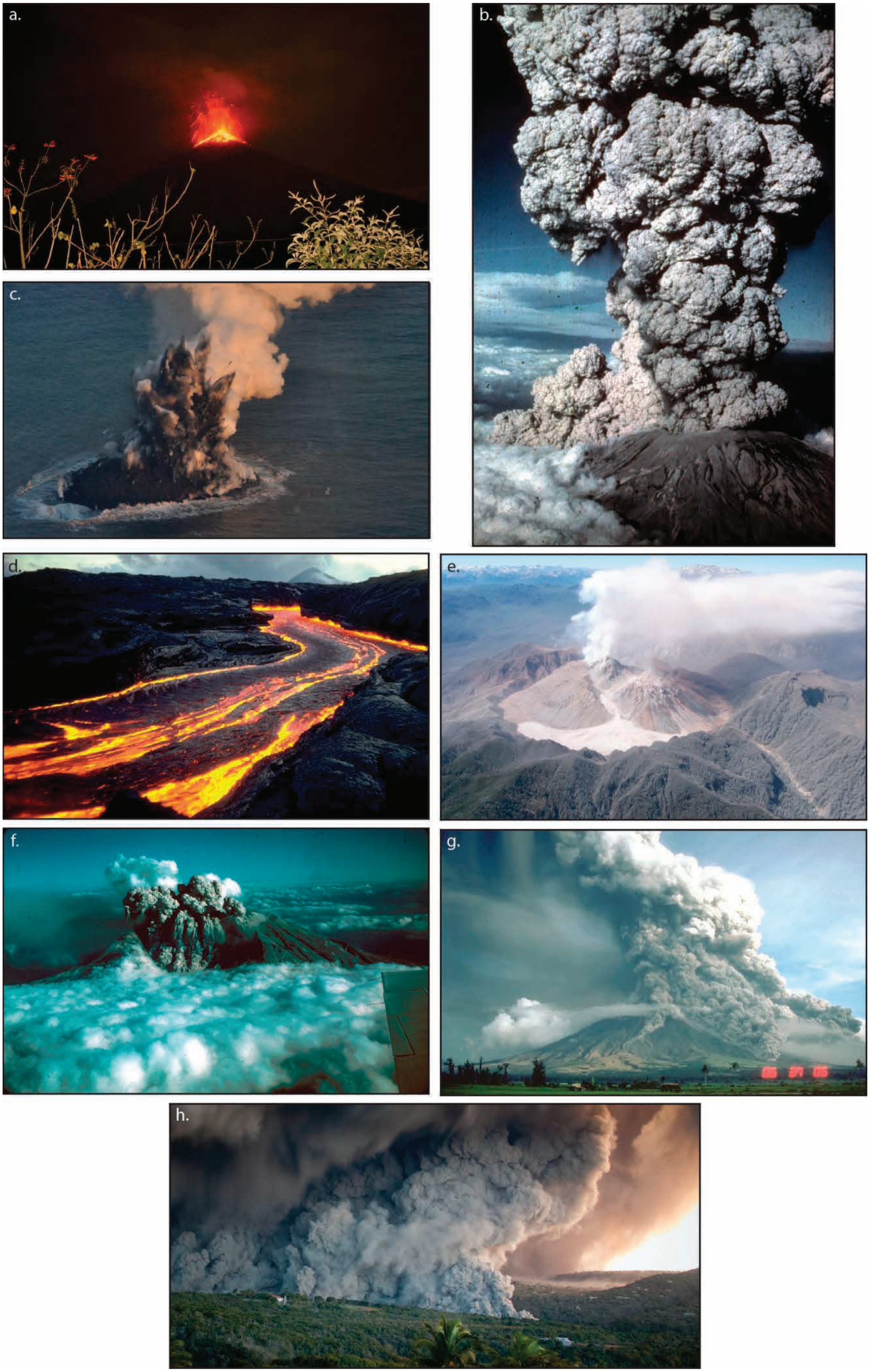

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2.2.6 Size and intensity of eruptions

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 (Brown et al., 2014). 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) (Newhall & Self, 1982), which is used by the Smithsonian Institution to categorise all explosive eruptions based on multiple criteria (Figure 2.9). VEI is on a scale from 0 to 8 and is approximately equivalent to the magnitude (M), 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.

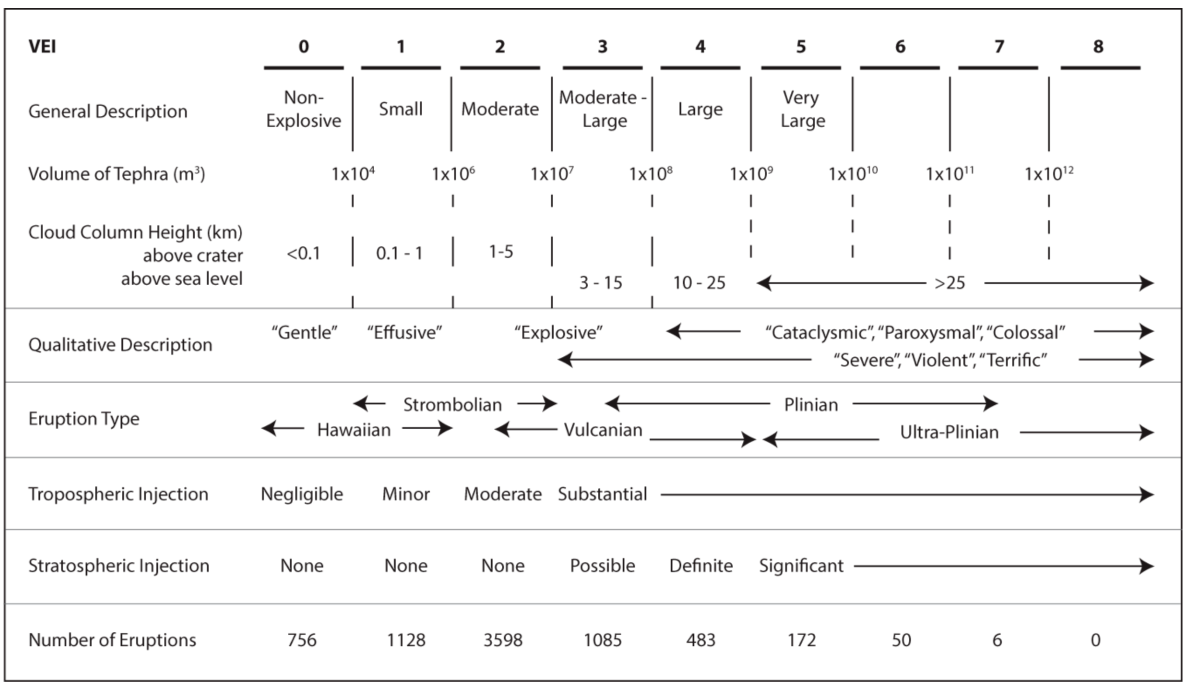

Figure 2.9 Scheme to illustrate the assessment of Volcanic Explosivity Index (VEI) from diverse observations adapted from Newhall & Self (1982) and Siebert et al. (2010). VEI is best estimated from erupted volumes of ash but can also be estimated from column height. The nomenclature of common kinds of 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 2.7). Some of the most common terms are indicated in Figure 2.9 and are qualitatively correlated with VEI and intensity of eruption. The term Plinian comes from the AD79 eruption of Vesuvius and

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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 (Mastin et al., 2009, Bonadonna et al., 2012) which cannot be measured directly. Adjustments are required for wind in the case of weak eruptions (Woodhouse et al., 2013).

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.

2.3 Volcanoes in space and time

Since 1960 the Smithsonian Institution has collated data on the world's active Volcanoes. Their Volcanoes of the World database (Siebert et al., 2010, Smithsonian, 2013) (VOTW4.0) is regarded as the authoritative source of information on Earth's volcanism and is the main resource for this study. Eruption data cited in this book are from VOTW4.22.

2.3.1 Volcano inventory

VOTW4.0 contains a catalogue of 1,551 volcanoes. Their distribution is shown in Figure 2.2. There are 596 volcanoes that have an historical eruption record since 1500 AD, and 866 volcanoes with known Holocene eruptions (the last 10,000 years). There are 9,444 eruptions recorded 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 (Crosweller et al., 2012) 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 (Biggs et al., 2014). 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.

2.3.2 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 (Simkin, 1993). 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 (Deligne et al., 2010, Furlan, 2010, Brown et al., 2014), that is the historical and geological records become less complete back in time. For example statistical studies of the available records (Deligne et al., 2010, Furlan, 2010, Brown et al., 2014) 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.

Table 2.1 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 VOTW4 and the Large Magnitude Explosive Volcanic Eruptions database (LaMEVE) version 2 (http://www.bgs.ac.uk/vogripa/) (Crosweller et al., 2012). The analysis method takes account of the decrease of event reporting back in time (Deligne et al., 2010). Note that the data are for M ≥ 4.

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

Analysis of global data for explosive eruptions shows a decrease in the frequency of eruptions as eruption magnitude increases (Table 2.1), 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 (Self & Blake, 2008) 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.

The global eruption record since 1950 is considered largely complete for eruptions on land. Eruptions of submarine volcanoes are largely undocumented, although 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.

2.3.3 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 (Luhr et al., 1993). 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 [Chapter 5] (Lindsay, 2010). The AVF covers 360 km^2, has over 50 eruptive centres (vents), and over 55 eruptions have occurred here in the past 250,000 years (Figure 2.10). 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.

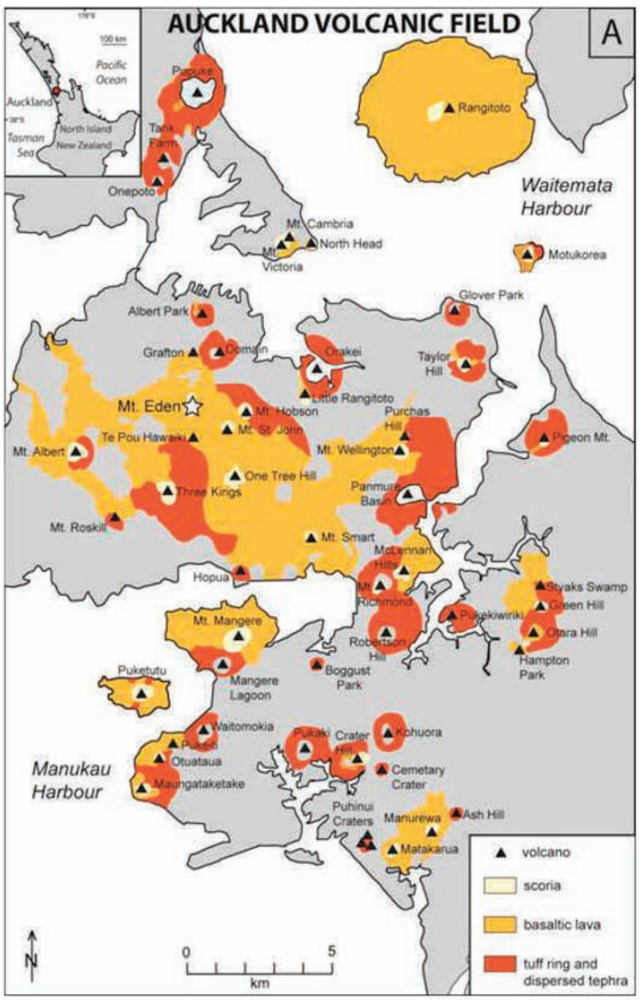

Figure 2.10 a) Map of Auckland Volcanic Field (AVF) showing the distribution of volcanic vents and products in the city of Auckland, New Zealand. Star shows the location of Mount Eden. b) View of Mount Eden looking to the north, highlighting the complete overlap of AVF and city (©Auckland Council). This figure can also be seen in Chapter 5 as Figure 5.1.

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 [Chapter 6]. Millions of inhabitants are directly threatened by three active volcanoes, namely Vesuvius, Campi Flegrei caldera and Ischia (Figure 2.11). The Osservatorio Vesuviano (OV) of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) continuously monitors these volcanoes using

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advanced techniques to record the time and spatial evolution of seismic activity, ground deformation, geochemical signals, and many other potential pre-eruptive indicators. The Osservatorio Vesuviano 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.

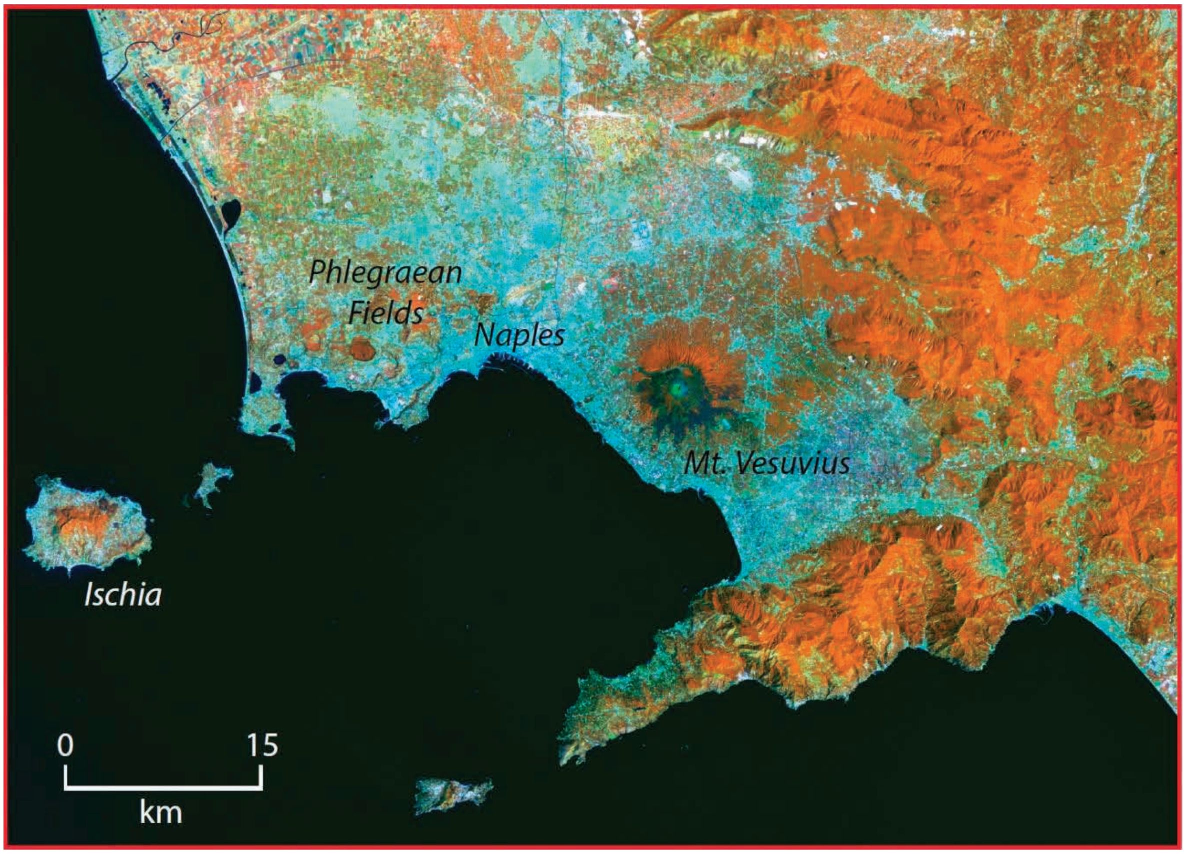

Figure 2.11 Satellite image of the Naples area where over 2 million people live on the flanks of the three active volcanoes of Vesuvius, Campi Flegrei (also known as Phlegraean Fields) and Ischia.

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 (Wadge et al., 2014). 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 (1995-2013) and complex with many different hazards. There were 19 fatalities on 25 June 1997 and the population of the island was reduced through evacuations from about 10,000 to about 3,000, with major economic consequences (Clay et al., 1999).

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 twentieth century [Chapter 7, (Newhall & Punongbayan, 1996a). 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 Chapter 25]. 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 eruption 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 (Lara et al., 2013).

The emergency in 1976 of La Soufrière Volcano, Guadeloupe (Eastern Caribbean) illustrates the difficulty of assessing the outcome of an eruption [Chapter 8, Hincks et al. (2014)]. A major eruption had occurred in the sixteenth 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 (Komorowski et al., 2005). 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 with 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 [Chapters 9 and 10] (Surono et al., 2012). 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 (Surono et al., 2012). The volcanologists recognised unusual and threatening behaviour

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[Chapter 9]. Although the eruption was considered responsible for 367 deaths (Jenkins et al., 2013), 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 [Chapter 10]. 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 onset of the eruption and 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 (Voight et al., 2013). 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 [Chapter 11] (Komorowski, 2003). A basalt lava flow erupted from the crater and inundated the city of Goma producing major devastation and 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 (Baxter et al., 2003). 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 which 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 twentieth 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

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third of Icelanders (~8,000) died from the magnitude 6.7 Laki eruption, largely through famine due to the environmental catastrophe (Thordarson & Self, 2003) 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 (Schmidt et al., 2011). Likewise the Tambora death toll was an estimated 70,000, mostly related to post-eruption famine (Auker et al., 2013). 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 (Robock, 2000). 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 twenty-first 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 (Self & Blake, 2008). 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 (Self & Blake, 2008). Volcanoes capable of super-eruptions include, but are not limited to, Yellowstone (USA), Taupo Volcanic Centre (New Zealand) and Campi Flegrei (Italy). Such eruptions would have severe global impact, but they occur very infrequently, roughly every 130,000 years or so (Table 2.1), although this is 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 (Druitt et al., 2012). 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 eruption in Indonesia that occurred in 1257AD (Lavigne et al., 2013)). Hence, 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 (Self & Blake, 2008).

2.4 Volcanic hazards and their impacts

Volcanoes produce multiple hazards (Blong, 1984, Papale, 2014), 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.

Figure 2.12 Volcanic hazards and their impacts. a) The turbulent eruption column of the 2011 Grímsvötn eruption, Iceland (Ó. Sigurjónsson). b) The 2010 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 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).

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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.

2.4.1 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 (Blong, 1984) 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.

2.4.2 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, 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 chapter on volcanic ash fall hazard and risk is provided (see Chapter 3).

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 2.12b) 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 2.12c). In the 1991 eruption of Pinatubo [Chapter 7] 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 [Chapter 12] (Blong, 1984, Spence et al., 2005, Wilson et al., 2012b). 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 (Wilson et al., 2012b).

Very fine ash at ground level is a health hazard to both animals and humans [Chapter 13] (Horwell & Baxter, 2006, Durant et al., 2010), and can also be readily remobilised by wind which can prolong exposure to airborne ash (Carlsen et al., 2012, Wilson et al., 2012a). Inhalation of fine ash may trigger asthma and other acute respiratory diseases (Horwell & Baxter, 2006), 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 (Kar-Purkayastha et al., 2012). 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 (Cronin & Sharp, 2002); and harmful effects (such as fluorine toxicity to livestock). Famines have occurred following some major eruptions due to destruction of food supplies due to ash fall.

Airborne volcanic ash is a major hazard to aviation [Chapter 14] (Guffanti et al., 2010) 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.

2.4.3 Pyroclastic flows, surges and volcanic blasts

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 2.8g, h) called *pyroclastic density currents*. *Pyroclastic flows* are concentrated avalanches of hot ash, gases and blocks that are typically confined to valleys (Figure 2.8g), 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 100 m/s in some cases) and dynamic pressures (Jenkins et al., 2013).

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 (Blong, 1984, Charbonnier et al., 2013, Jenkins et al., 2013). 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 people. The current took only three minutes to reach the town 6 km 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 km 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 km 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 (Charbonnier et al., 2013, Jenkins et al., 2013, Komorowski et al., 2013). 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 (Carey et al., 1996).

Pyroclastic density currents account for one third of all volcanic fatalities (Auker et al., 2013). 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.

2.4.4 Lahars and floods

Lahars and floods are a major cause of loss of life in volcanic eruptions, accounting for 15% of all historical fatalities (Auker et al., 2013). *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 [Chapter 7].

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 (Voight et al., 2013). Breaching of lakes, notably in craters and reservoirs, is another mechanism that can generate

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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 2.12e), 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.

2.4.5 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 (Siebert, 1984, Voight, 2000). 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, USA, 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 (Siebert, 1984). 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 (Mandeville et al., 1996). Moreover, volcanogenic tsunamis can be destructive tens to hundreds of kilometres from where they were generated. Oceanic islands with gentle slopes, such as 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.

2.4.6 Volcanic gases

Volcanic gases can directly cause fatalities, health impacts, and damage to vegetation, livestock, infrastructure and property [e.g. Chapters 10, 11 and 13]. 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 1,800 fatalities as a result of asphyxiation (Kling et al., 1987). 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 sulfate particles, a major cause of air pollution (Schmidt et al., 2011). 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 [Chapter 11].

2.4.7 Lava

Lava flows (Figure 2.8d) 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 (Auker et al., 2013). In 2002 lava from Nyiragongo (Komorowski, 2003) caused great damage, many injuries and fatalities (Figure 2.12f) [Chapter 11].

2.4.8 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.

2.4.9 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 (Auker et al., 2013). McNutt & Williams (2010) found that lightning has been reported in 10% of VEI 6 eruptions, with smaller eruptions less commonly associated with lightning.

2.4.10 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 chapter. 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 [Chapter 11] 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 2.3.3. 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 twenty-first century.

2.4.11 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 chapter are derived from analysis of this database (Auker et al., 2013).

Volcanic eruptions have caused 278,880 known fatalities (Figure 2.13). 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.

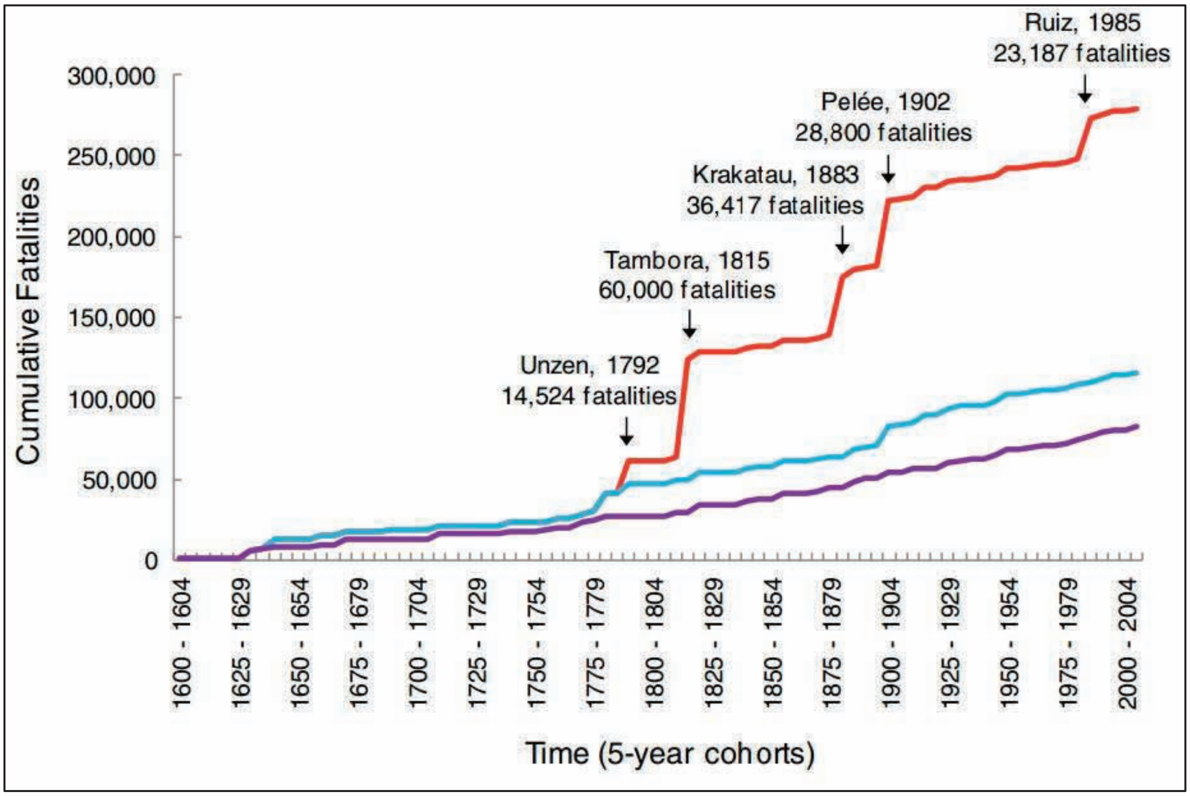

Figure 2.13 Cumulative number of fatalities directly resulting from volcanic eruptions (Auker et al., 2013). Shown using all 533 fatal volcanic incidents (red line), with the five largest disasters removed (blue line), and with the largest ten disasters removed (purple line). The largest five disasters 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 2.14) shows that the most likely eruption size (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.

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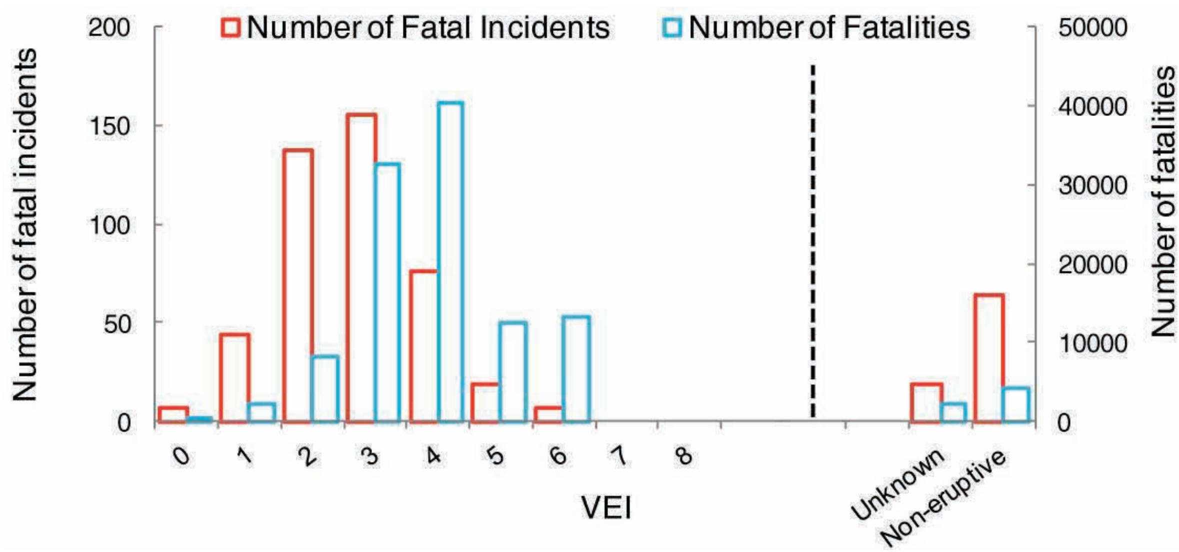
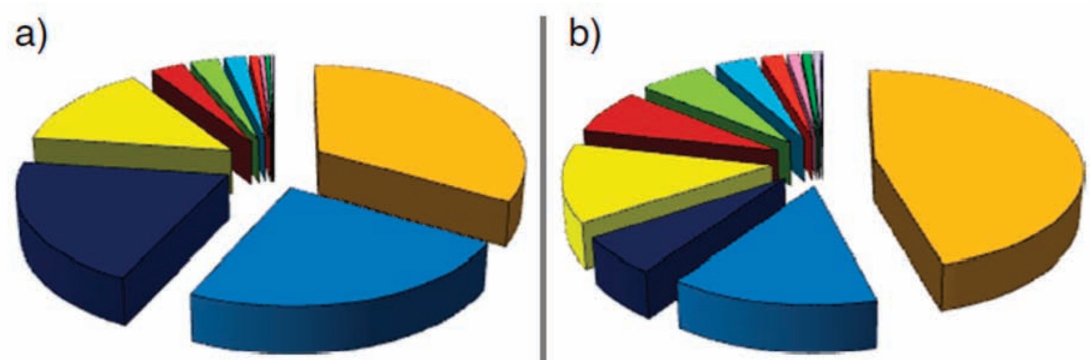


Figure 2.14 Distribution of fatalities and fatal incidents across VEI levels (not including the five largest disasters from statistical analysis of fatalities and eruption magnitude data). The five volcanic disasters with largest fatalities were discarded in order to investigate the relationship of fatalities with magnitude in an unskewed dataset, (Auker et al., 2013).

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 (Auker et al., 2013). 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 (Newhall & Punongbayan, 1996b). 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 2.15 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 [Chapter 7].



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 2.15 a) Distribution of fatalities across fatality causes, for all fatal incidents; b) Distribution of fatalities across fatality causes, with the largest five disasters removed; from Auker et al. (2013).

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2.5 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 (Newhall et al., 1997). Costs of monitoring itself are typically between several tens of thousands USD per year 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 (Mrozek & Taylor, 2002). Other benefits include avoided losses of equipment, goods and anything else that can be moved out of the way or otherwise protected, and matters such as 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 (Clay et al., 1999) 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 Pounds sterling. 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 (Hincks et al., 2014), 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 (Phillipson et al., 2013). 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 (Sigurdsson et al., 2015).

The localised character and individuality of volcanoes gives a special importance to dedicated volcano observatories, which play a key role in monitoring, hazard assessments and early warning around the world [Chapter 15]. 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 volcano observatory 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 volcano observatory may provide interpretations of those data and undertake cutting edge research on volcanic processes. In most cases a volcano observatory will provide volcanic hazards information such as setting Volcanic Alert Levels and issuing forecasts of future activity, and in some instances, a volcano observatory 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 volcano observatories 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 (Sigurdsson et al., 2015). 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.

2.5.1 Monitoring

Instrumental monitoring is the basis of early warning, forecasting and scientific advice to decision-making authorities. Monitoring programmes at volcano observatories 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. Volcano observatories 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 volcano observatories 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

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systems. However, it is fundamental to have good knowledge 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 (Sparks et al., 2012). 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 (Chouet, 1996, McNutt, 2005). 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 2.16) (Þorkelsson, 2012), and enable the pathways for magma ascent to be identified (Figure 2.17). In some cases VT earthquakes can track the migration of earthquakes towards the surface (Toda et al., 2002), 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 pre-existing tectonic faults that are reactivated by increased pore water pressure as intruding magma compresses surrounding country rock.

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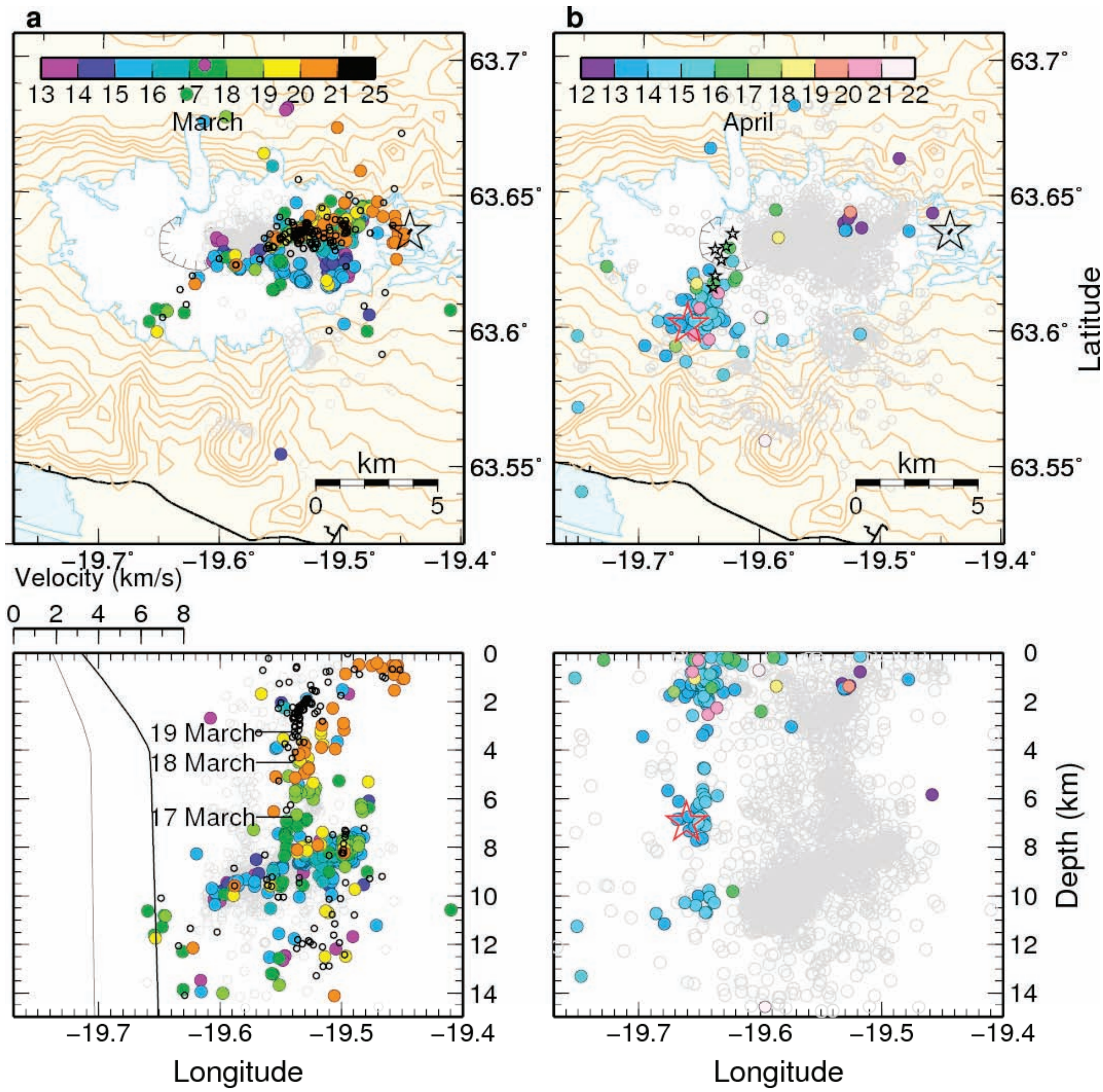

Figure 2.16 Spatial location of earthquakes before and during the eruption of Eyjafjallajökull volcano, Iceland in 2010. a) the flank eruption and b) the summit eruption. a) Earthquakes 4-12 March are gray and 13-24 March coloured or black. A flank eruption site is marked by a star. Crustal velocity 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 Þorkelsson (2012). Diagram from Þorkelsson (2012) courtesy of Sigurlaug Hjaltadottir (Icelandic Meteorological Office).

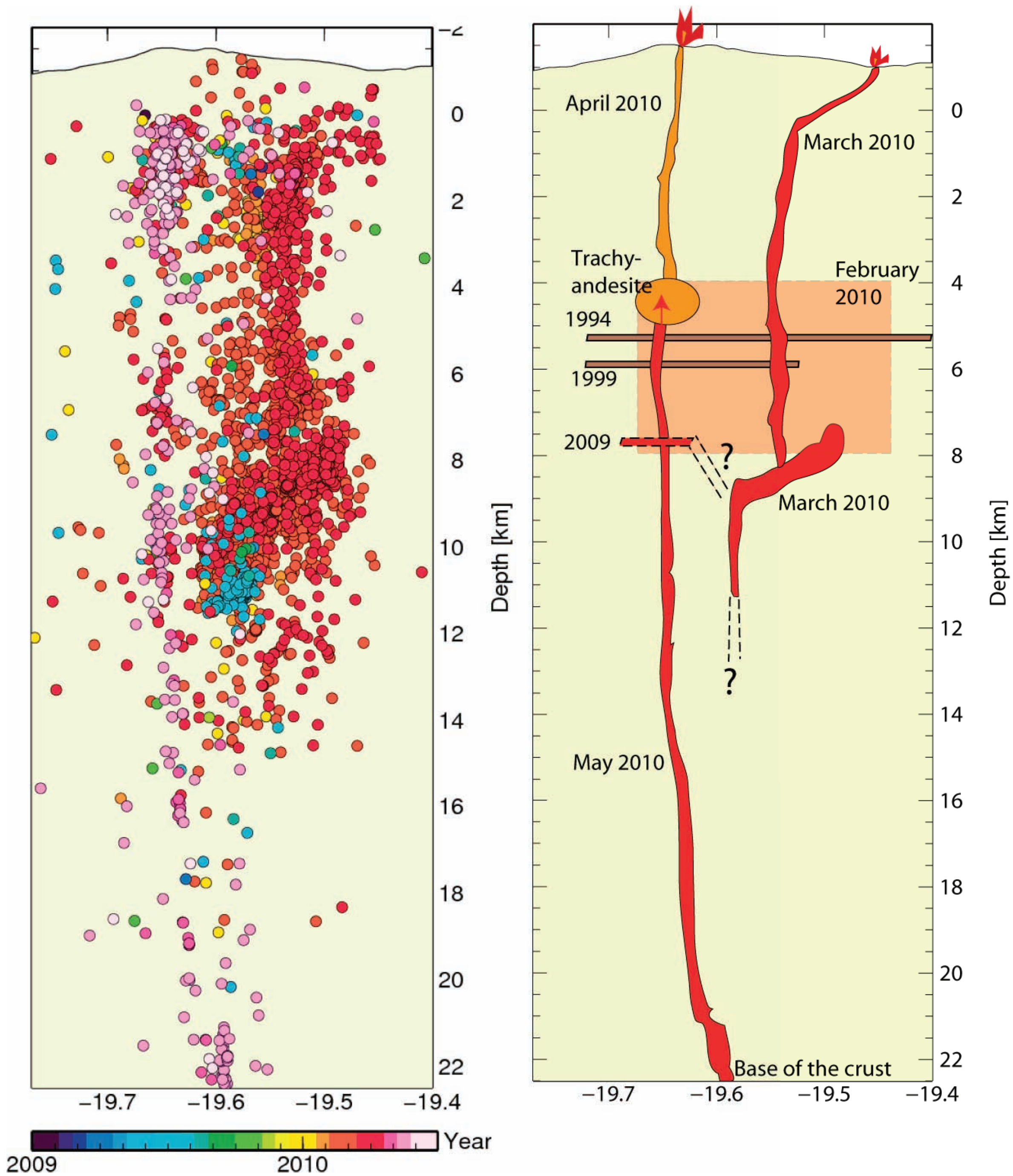

Figure 2.17 A schematic drawing of magma pathways in Eyjafjallajökull during 2009-2010 based on earthquake distribution (left) (Þorkelsson, 2012). Vertical scale is stretched. The red transparent box indicates roughly the extent of the February activity (intrusions), south-east of the main clusters. Diagram from Þorkelsson (2012)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

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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 [Chapter 16]. 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.

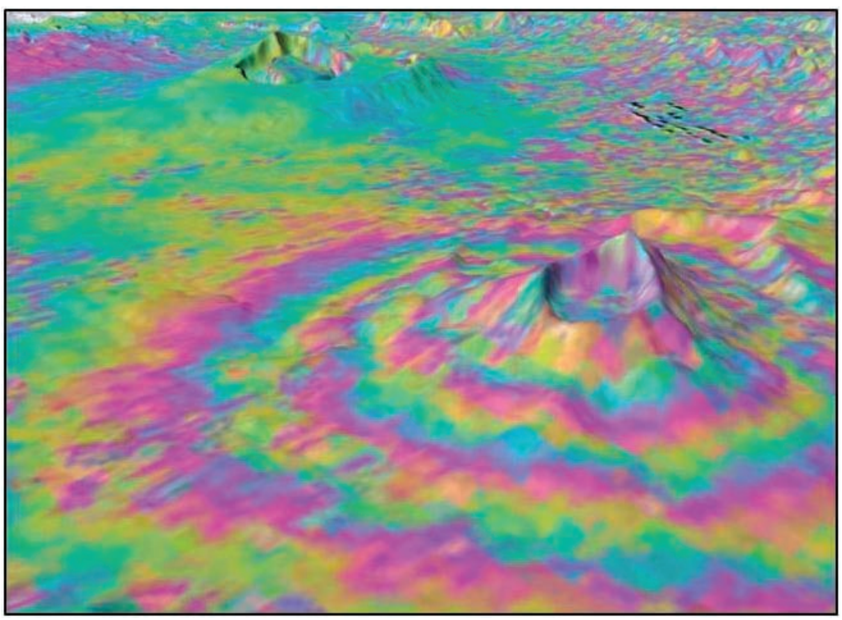

Figure 2.18 This InSAR image (Sparks et al., 2012) shows a pulse of uplift during 2004 to 2006 at Mount Longonot, Kenya, a volcano previously believed to be dormant. The image, from the ESA satellite Envisat, is draped over a digital elevation model from the Shuttle Radar Topography Mission. Each complete colour cycle (fringe) represents 2.8 cm of displacement towards 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* (Dzurisin, 2003). 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 (Larson et al., 2010). Nowadays electronic distance measurements using lasers and networks of GPS stations have largely replaced labour-intensive precise levelling 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 [Chapter 17] have resulted in a major advance in the ability to detect ground movements (Figure 2.18). 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 (Biggs et al., 2014), 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 2.18; Chapter 17) (Biggs et al., 2009, Sparks et al., 2012). 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 volcano observatories.

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 [Chapter 17] (Aiuppa et al., 2010, Nadeau et al., 2011). 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 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 [Chapter 7] (Newhall & Punongbayan, 1996a). 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 (Wadge et al., 2014). 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 (Aiuppa et al., 2010).

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 4 and 5 May (Figure 2.19), while ash output did not increase until several hours after the gas emissions (Figure 2.20). This ash-production phase caused widespread disturbance to European airspace during most of the following week.

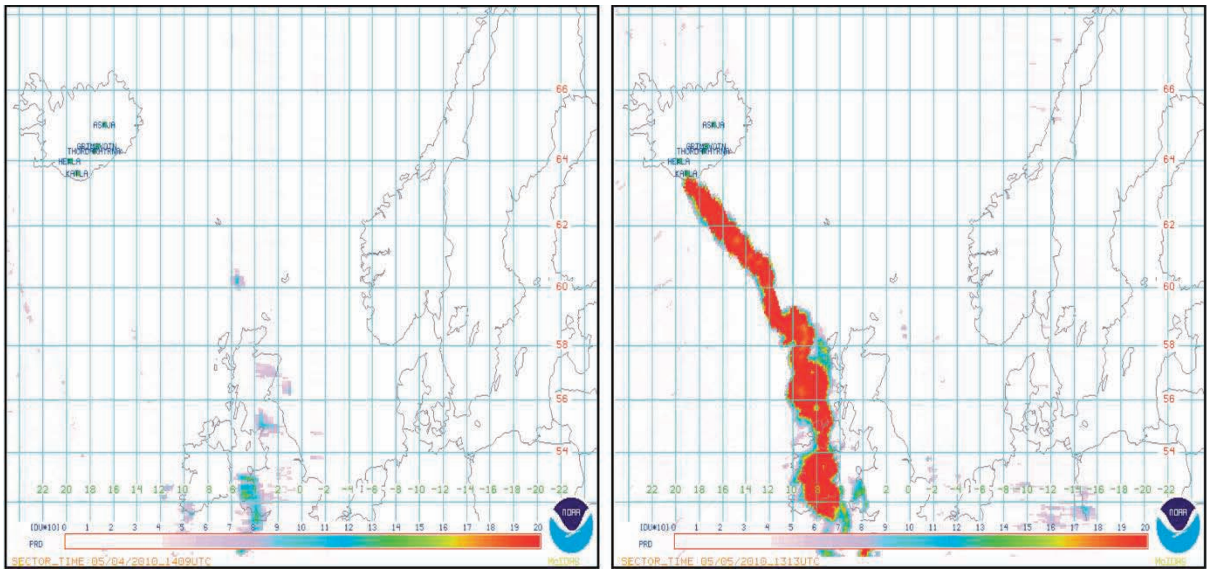

Figure 2.19 SO_2 emissions measured from satellites during the 2010 eruption of Eyjafjallajökull, Iceland. a): Low SO_2 emissions measured on 4 May 2010, 14:09 UTC (OMI satellite, NOAA). b) Drastic increase in SO_2 measured on 5 May 2010, 13:13 UTC (OMI satellite, NOAA).

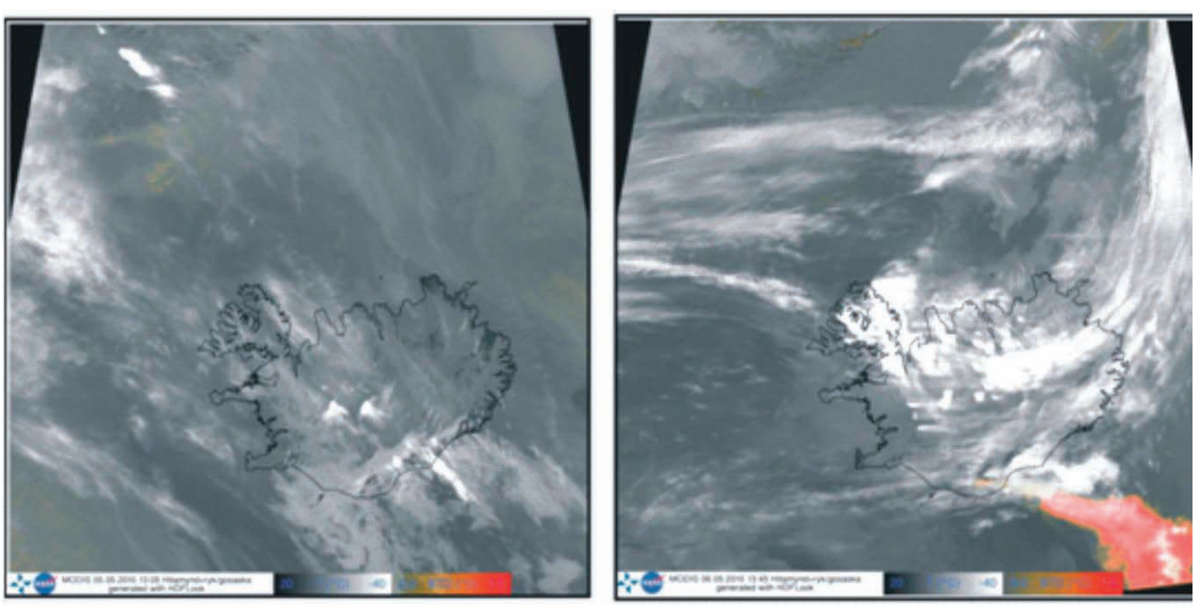

Figure 2.20 Ash output from Eyjafjallajökull volcano, Iceland in 2010. a) Low ash output on May 5th 13:05 UTC does not coincide with the high SO_2 gas flux (Figure 2.19b). b) Ash output has increased when measured on 6 May 13:45 UTC, several hours after the increase in SO_2 output. MODIS satellite, NOAA, processed by IMO.

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Near real-time gas measurements (including satellite and ground-based monitoring) are augmented by studies of volcanic rocks, which trap gases prior to eruption (Edmonds, 2008), 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 (Johnson & Ripepe, 2011) and borehole strain meters (Roberts et al., 2011). 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 (Lesparre et al., 2012).

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 (Punongbayan et al., 1996). Pattern recognition is commonly a key element of using monitored data (Sparks, 2003, Segall, 2013). In 1997 the combination of earthquake swarms, deformation measured by tiltmeter, 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 (Voight, 1999).

2.5.2 Volcanic unrest

Almost all eruptions are preceded by periods of *volcanic unrest* [Chapter 18], 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

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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 (Phillipson et al., 2013) 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 (Dzurisin, 2003, Phillipson et al., 2013, Segall, 2013, Biggs et al., 2014) 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 (Biggs et al., 2014).

Systematic studies of ~200 volcanoes using satellite data show that after 18 years, 54 had experienced deformation and of these 25 had erupted (Biggs et al., 2014). 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 (www.wovodat.org). 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 volcano observatories.

2.5.3 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 (Auker et al., 2013) suggests that at least 50,000 lives were saved during the twentieth century, and Voight et al. (2013) notes that a similar number have already been saved in the three decades that postdate the tragedy at Nevado del Ruiz.

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 [Chapters 7 and 9] (Sparks, 2003, Sparks & Aspinall, 2004). 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 (Marzocchi & Bebbington, 2012).

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.

2.5.4 Volcano observatories

A volcano observatory 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 [Chapter 15]. The fact that most volcano observatories face similar problems and challenges has led to increasing collaboration between volcano observatories and the formation of the World Organisation of Volcano Observatories (WOVO; http://www.wovo.org/). There are over 100 members of WOVO. The exact constitution and responsibilities of a volcano observatory may differ country-by-country, but it is typically the source of authoritative short-term forecasts of volcanic activity and information on volcanic hazards.

There are a variety of models of volcano observatory. 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 Istituto Nazionale Geofisica and Vulcanologia, Italy, are examples. Some observatories, such as 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.

Volcano observatories 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.

Volcano observatories are involved in all parts of the risk management cycle. In times between eruptions observatories 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, volcano observatories 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

(Durant et al., 2010). The extent of involvement of volcano observatories in decision-making varies greatly between different countries. A volcano observatory 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, volcano observatories 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, volcano observatories 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 (Loughlin et al., 2002, Voight et al., 2013).

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.

2.5.5 Volcano observatories and aviation safety

Since the start of commercial airline travel in the 1950s, 247 volcanoes have been active, some with multiple eruptions. There were at least 129 encounters of volcanic ash by aviation from 1953-2009 (Guffanti et al., 2010), including a number of very near major catastrophic accidents. Two of the most significant encounters occurred in the 1980s which resulted in total engine shut-down, and 16 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 VAACs [Chapters 12 and 14]. They provide volcanic ash advisories to the aviation community for their own geographical area of responsibility (Figure 2.21).

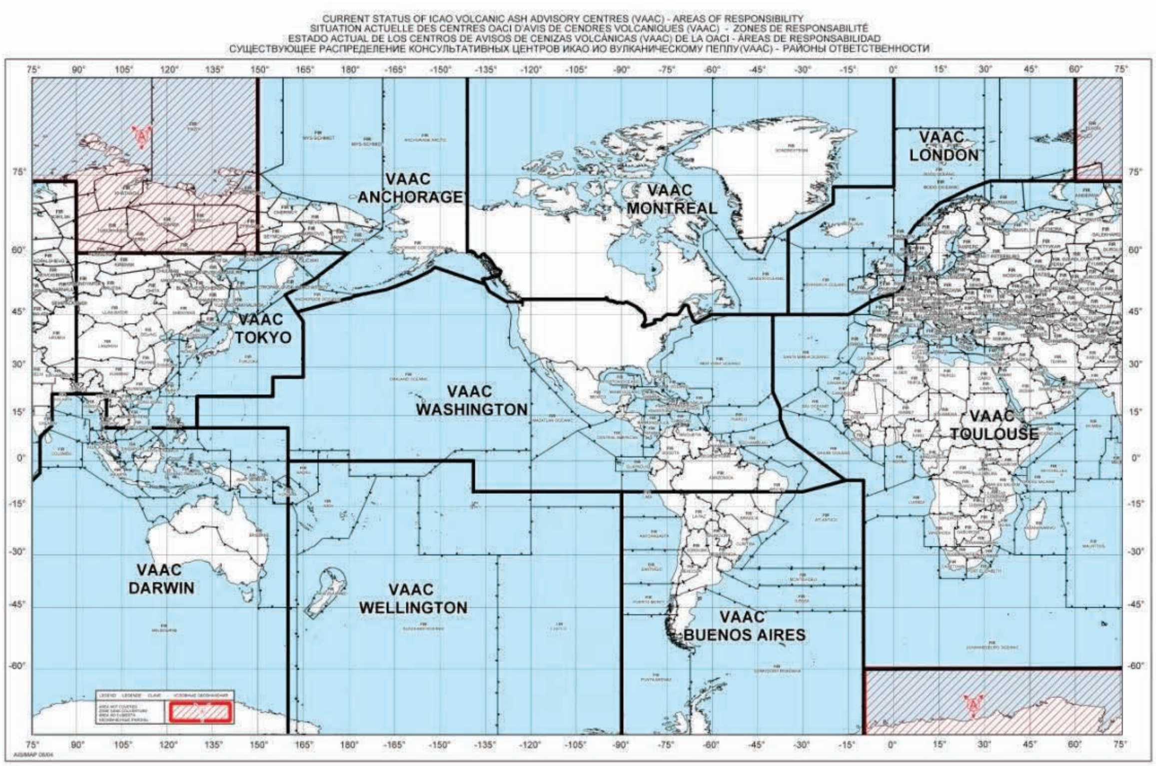

Figure 2.21 Map showing areas of responsibility of the nine Volcanic Ash Advisory Centres (ICAO). This figure can also be seen in Chapter 14, as Figure 14.1.

There are several different alerting systems used worldwide [Chapter 14], each with the aim to update those in local population centres close to the volcano and the aviation community (see Section 2.7.2). The United States Geological Survey (USGS) uses one notification (aviation colour code) specifically for the aviation sector (Neal & Guffanti, 2010), and another (volcano alert system) for hazards that might affect the surrounding population (Gardner & Guffanti, 2006). ICAO adapted its international aviation colour code system from that of the USGS.

Minimising aviation impact requires rapid notices from volcano observatories 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 (Bonadonna et al., 2012) 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 Operations Group (IAVWOPSG) preceded and continues the work of the IVATF. Globally, there can be many erupting volcanoes that are potentially hazardous to aviation. Therefore, the VAACs 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.

Volcano observatories 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,

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the volcano observatory 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 observatory to VAAC communication channel was significantly improved based on the experience from the 2010 eruption, but it must be noted that not all volcano observatories worldwide have well-defined relationships with their regional VAAC. One of the main roles of WOVO has been to link more volcano observatories with VAACs to enhance communication between volcano observatories 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.

2.5.6 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 Chapter 19) 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 [Chapter 19]. 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 has been undertaken here. 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 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 this work, 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, e.g. 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 volcano observatory.
- Some monitoring: 1 to 3 or fewer seismometers dedicated to volcano monitoring, and a volcano observatory 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 volcano observatory 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 to 3 seismometers and the majority of these volcanoes have this seismic monitoring alone. About 35% of historically active volcanoes have four or more seismometers within 20 km distance and most of these volcanoes also have GPS stations, tiltmeters, or other deformation instruments.

2.5.7 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 [Chapter 17]. 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 volcano observatories (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 volcano observatories. 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

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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 [Chapter 17]. 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.

2.6 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 (Sparks, 2003). 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 (Sparks, 2003, Sparks et al., 2012). 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, is unique in some respects and requires dedicated investigation. This diversity has led to different methods being developed and applied in hazard and risk assessment in different places (Sparks & Aspinall, 2004, Marzocchi & Bebbington, 2012, Sparks et al., 2013). 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.

2.6.1 Hazards maps

At many volcanoes, hazards assessments take the form of maps, which may be qualitative, semi-quantitative or quantitative in nature [Chapter 20]. Most are based upon a geological and historical knowledge of past eruptions over a given period of time (Tilling, 1989). 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 entirety), 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 (Auker et al., 2013), 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 (see Chapter 3).

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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, pyroclastic density currents or 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 worldwide 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 [Chapter 16] (Figure 2.22). 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.

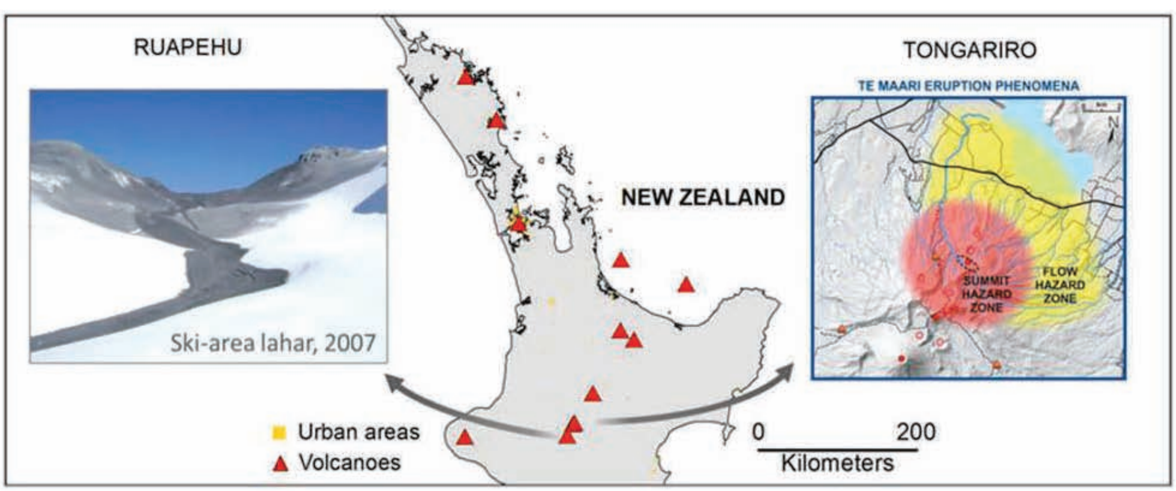

Figure 2.22 Risk management at two volcanoes in New Zealand. The comprehensive Tongariro hazard map can be found at www.gns.cri.nz/volcano*. This figure can also be seen in Chapter 16, as Figure 16.1.*

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Drawing lines on maps to demark safe from unsafe zones sounds easy in principle, but is difficult in practice 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 (Bonadonna et al., 2012).

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.

2.6.2 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) (Marzocchi & Bebbington, 2012, Sparks et al., 2013, Hincks et al., 2014), could

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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 [Chapter 12]. 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 (Jenkins et al., 2012). 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 2.23).

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 1,000 km), Jakarta’s risk is dominated by population exposure, and Port Moresby’s risk by the vulnerability. Chapter 3 presents a much more detailed assessment on ashfall hazard and risk.

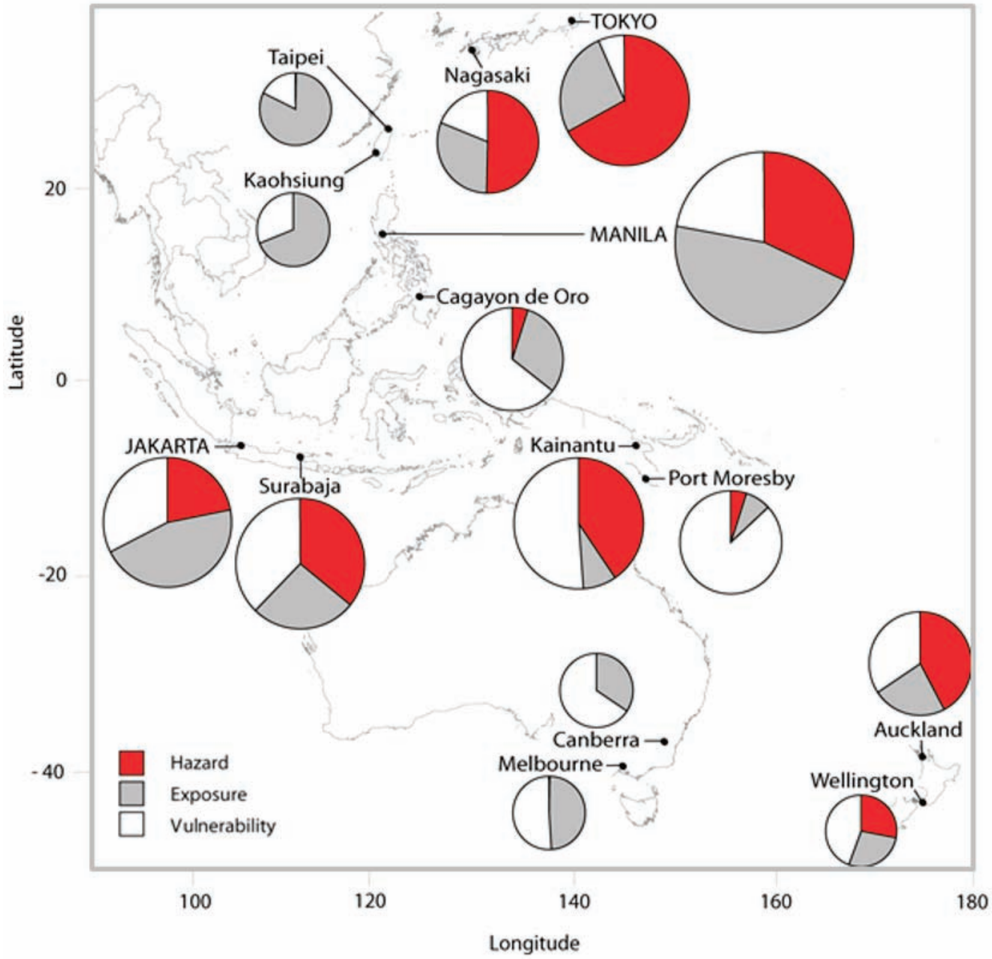

Figure 2.23 Relative contributions of the three factors comprising overall risk score for cities in the Asia-Pacific region (see Chapters 3 and 12).This figure can also be seen in Chapter 12, as Figure 12.3.

2.6.3 Event trees

Event trees are useful logical frameworks for discussing probabilities of possible outcomes at volcanoes showing unrest or already in eruption [Chapter 18] (Newhall & Hoblitt, 2002, Sparks & Aspinall, 2004). They can be valuable for discussion between scientific teams but also with authorities and the public. Each branch of an event tree leads from a necessary prior event to a more specific outcome and is allocated a conditional probability, e.g. given the occurrence of an earthquake swarm the probability of an eruption is estimated. The probability estimates might be based on past and current activity (empirical), expert elicitation (Aspinall, 2010), numerical simulations, or a combination of methods. The probabilities can be revised regularly as knowledge or methodologies improve or when the character of volcanic activity changes. Event trees have been successfully used at many eruptions worldwide since the 1980s, including the eruption of the Soufrière Hills Volcano, Montserrat (Sparks and Aspinall, 2004). Event trees are also commonly used in Volcano Disaster Assistance Program (VDAP) responses to volcanic emergencies [Chapter 25].

2.6.4 Exposure and vulnerability

There can be many different kinds of loss as a consequence of volcanic eruptions including: loss of life and livelihoods (Kelman & Mather, 2008, Usamah & Haynes, 2012), detrimental effects on health [Chapter 13], destruction or damage to assets (e.g. buildings, bridges, electrical lines and power stations, potable water systems, sewer systems, agricultural land) (Blong, 1984); economic losses; threats to natural resources including geothermal energy (Witter 2012); systemic vulnerability and social capital. Each of these will have its own specific characteristics in terms of exposure and vulnerability (Spence et al., 2005, Wilson et al., 2012b).

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 (Wisner et al., 2004) and can be expected to affect the outcome for populations at risk in several ways (Figure 2.24). 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 [Chapter 4]. However, many countries such as 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 (Spence et al., 2005) and to what extent transport systems enable rapid evacuation.

Social vulnerability is defined (Adger, 2006) 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

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geographically, socially or politically, often suffer the most from natural hazards (Dibben & Chester, 1999, Gaillard, 2007, 2008, Lavigne et al., 2008). 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 (Bird et al., 2010). 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 (Crosweller & Wilmshurst, 2013).

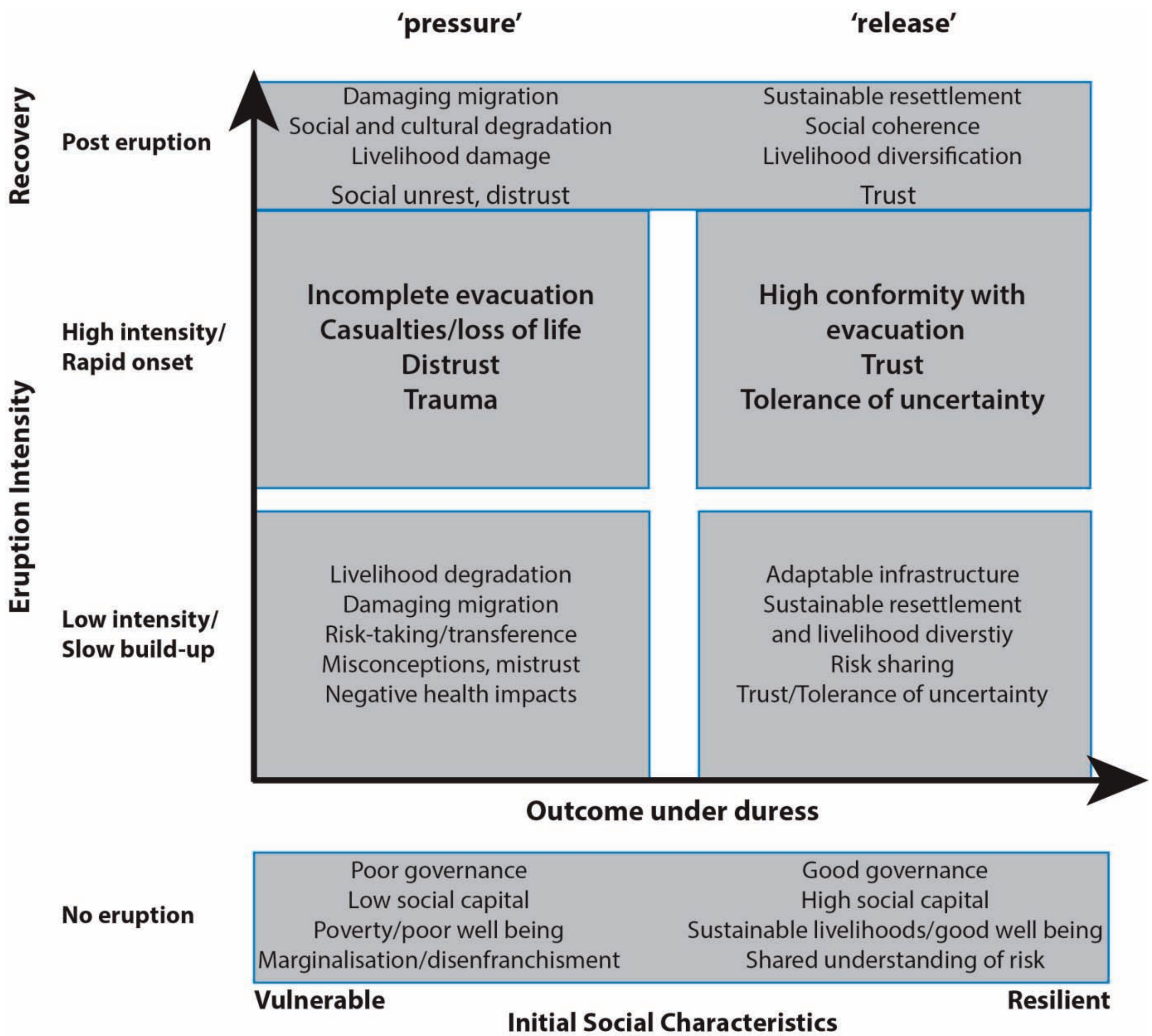

Figure 2.24 Summary of outcomes associated with the interaction of differing population types with volcanic hazards at differing stages of an eruptive cycle. The 'response' phase of volcanic crises has been sub-divided according to intensity and duration. Low-intensity, slow-building or long-duration 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. Image (C) J.Barclay, modified from Barclay et al. (2015).

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 (Small & Naumann, 2001). 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, (Seitz, 2004); Ecuador (Lane et al., 2003); Indonesia (Laksono, 1988), Tonga (Lewis, 1999)).

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 (Clay et al., 1999), and some sought peace and quiet at their homes in the evacuated zone or continued to farm, resulting in 19 unnecessary deaths in 1997 (Loughlin et al., 2002). Concerns about looting also cause people to delay evacuation and return frequently to at-risk areas.

A health and vulnerability study for the Goma, Democratic Republic of Congo, volcanic crisis in 2002 (Baxter et al., 2003) considered human, infrastructural, geo-environmental and political vulnerability following the spontaneous and temporary evacuation of 400,000 people at the onset of the eruption [Chapter 11]. 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 [Chapter 10] and in 2002 in the city of Goma [Chapter 11] 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 [Chapter 8] 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; Chapter 7) 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 (Integrated Research on Disaster Risk, Forensic Investigations of Disasters: 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 (Sword-Daniels, 2011) 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.

2.6.5 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 [Chapter 21] (Wadge & Aspinall, 2014). 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 (Aspinall, 2010); 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 2.25) 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 2.26) 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.

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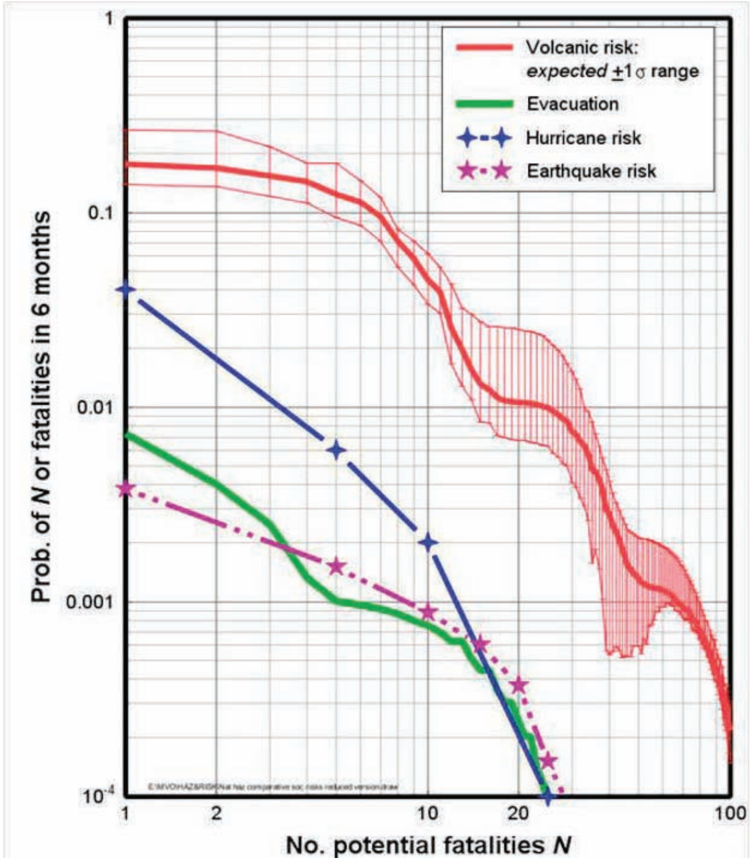

Figure 2.25 The F-N plot from 2003 for the Soufrière Hills Volcano, Montserrat shows the probability of N or more fatalities due to the volcano (red, with uncertainty), the reduced risk if the main at-risk area is evacuated (green) and comparative hurricane and earthquake risks. The curves are compared with societally accepted risks from regional earthquakes and hurricanes on Montserrat. Figure modified from Wadge & Aspinall (2014) see Figure 21.1 and Chapter 21 for further details.

These risk assessments have been used to inform critical decisions on Montserrat, including evacuation and re-occupation (Figure 2.25), and development of management controls on sand mining (Figure 2.26). 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, Chapter 26) 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.

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Concern about the risk to human health from volcanic ash [Chapter 13] motivated an example of a fully quantitative probabilistic risk assessment on the exposure of population on Montserrat to very fine respirable ash (Hincks et al., 2005). 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 multi-disciplinary character of risk assessments, where diverse experts are needed. Figure 2.27 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.

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 (Spence et al., 2005). 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.

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.

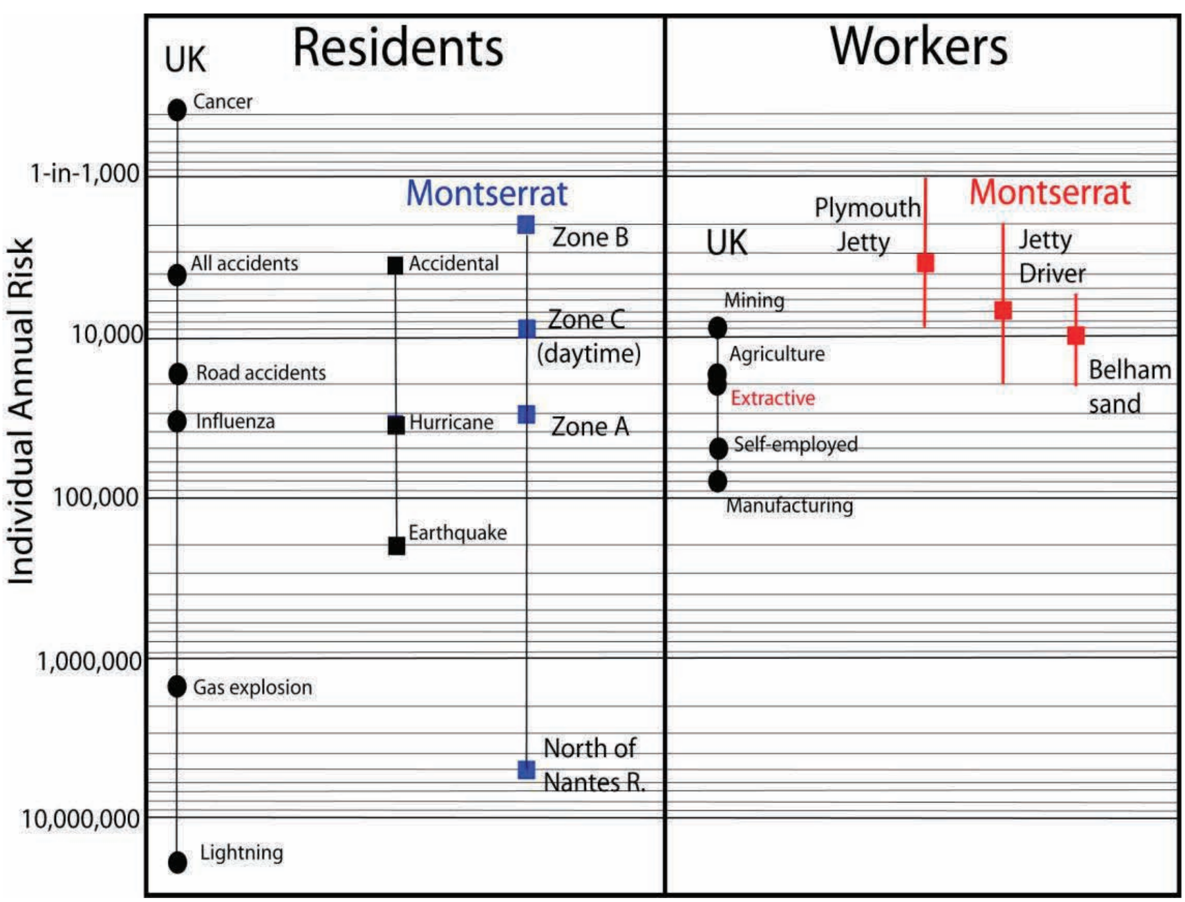

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Figure 2.26 (previous page) An individual risk ladder from 2011 for the Soufrière Hills Volcano, Montserrat is shown with both residential zone risk levels and work-related risk levels plotted, with uncertainties. Comparative values from familiar circumstances are shown for reference. Figure modified from Wadge & Aspinall (2014): see Figure 21.1 and Chapter 21 for further details.

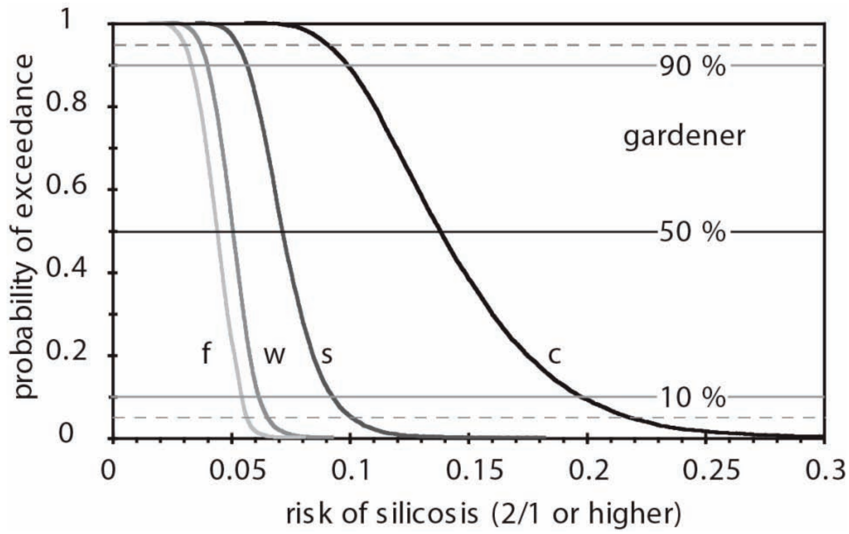

Figure 2.27 Probability of exceedance curve for risk of silicosis (classification ≥2/1) for gardeners, calculated from simulated cumulative exposures: see Hincks et al. (2005) for key to curves, which are for specific Montserrat locations. The study involved Monte Carlo sampling of probability distributions 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. This figure can also be seen in Chapter 13 as Figure 13.2.

2.6.6 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.

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 Chapter 22. The index builds on previous index approaches (Ewert et al., 2005, Aspinall et al., 2011). The supplementary online report (Appendix B) 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. There are 328 volcanoes with 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 in the eruption record. 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. Research is ongoing investigating the use of the well known, classified volcanoes, to inform the hazard assessment at the poorly known, unclassified volcanoes, for example through the identification of analogous volcanoes. However, this would be associated with significant uncertainties and will not substitute for a thorough understanding of individual systems.

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 VOTW4.0 and uses evidence from historic fatalities to derive a single value. The methodology [Chapter 4] extends previous concepts (Ewert & Harpel, 2004; Aspinall et al. 2011). Volcano population data derived from VOTW4.0 is used to calculate PEI, which is then divided into seven levels from sparsely to very densely populated areas to provide an ordinal ranking indicator. The PEI 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.

Here 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 that 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 (Appendix B) plots of VHI versus PEI provide a way of understanding volcanic risk. Indonesia and the Philippines are plotted as an example (Figure 2.28). Volcanoes with insufficient information to calculate VHI should be given serious attention and their relative threat can be assessed through PEI. Being unclassified does not mean a volcano is not hazardous. There are 288 unclassified volcanoes with a high PEI (PEI5-7), indicating volcanoes of potentially high risk.

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.

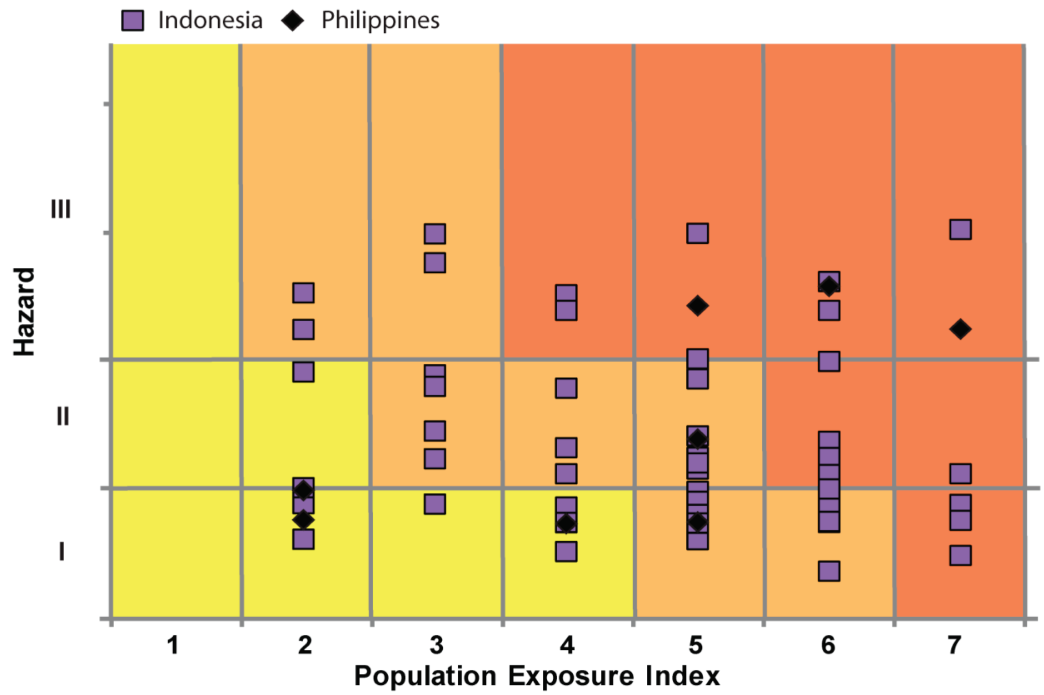

Figure 2.28 Plot of volcanic Hazard Index (VHI) and Population Exposure Index (PEI) for Indonesia and the Philippines, comprising only those volcanoes with adequate eruptive histories to calculate VHI. The warming of the background colours is representative of increasing risk through Risk Levels I to III.

2.6.7 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 (Bright et al., 2012) 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 Chapter 23.

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 (1)

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 2.2 shows the distribution of Measure 1 between the 20 highest scoring countries.

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Table 2.2 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.

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

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 2.3 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 (Auker et al., 2013).

Table 2.3 Regional ranking using Measure 1 and known historical fatalities with the ten largest disasters removed. 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 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)

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:

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

The top 20 countries according to this measure are listed in Table 2.4.

Table 2.4 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.

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

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 2.5.

Table 2.5 Ranking by region using Measure 2. Note the Kuril Islands region is not included.

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

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.

2.7 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; for example eruptions at Chilean volcanoes frequently affect neighbouring Argentina, primarily through ash dispersal (Appendix B; Viramonte et al. 2001). 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 (e.g. post-eruptive lahars of Pinatubo [Chapter 7]), 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.

2.7.1 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 [Chapters 7 and 10]. 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 a 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 [Chapter 8] (Hincks et al., 2014). Here a 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 (Newhall et al., 1999). 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 six of the scientists was overturned in appeal in 2014.

2.7.2 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 (Fearnley, 2013, Potter et al., 2014) 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 (Chapter 16). 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 [Chapter 9]. Merapi is one of the most active volcanoes in Indonesia. The 2010 Merapi eruption affected two provinces and four regencies and led to evacuation of about 400,000 people (Surono et al., 2012). Indonesia applies four levels of warnings for volcano activity (Figure 2.29). 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		

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Figure 2.29 (Previous page) 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 Chapter 10). 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 [Chapter 9] (Surono et al., 2012). All monitoring parameters exceeded levels observed before and during previous eruptions of the late twentieth 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.

2.7.3 Effective communication and relationships

Communication is a critically important aspect of volcanic risk reduction [Chapter 24]. 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. This is too late to be learning about hazards and risks and to get 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 (Haynes et al., 2008b, Solana et al., 2008, Barclay et al., 2014). 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, 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 (Bird et al., 2010), 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.

2.7.4 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. Chapters 7, 10 and 11). 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. Chapter 19]. 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 Program (VDAP) of the US Geological Survey has, for almost three decades, supported scientists and institutions in many countries during volcanic emergencies [Chapter 25]. 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 [Chapter 11].

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 (Newhall et al., 1999) went some way to addressing this concern (Section 2.7.1), 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 volcano observatory, 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 [Chapter 14] 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 Meteorological 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.

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2.7.5 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 [Chapter 10] is well known for a capacity building programme 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 programmes must consider not only "normal" but also unusually large eruptions (Mei et al., 2013). Another example of building capacity [Chapter 16] is provided by improvements to lahar warnings and hazard information for visitors to the ski areas on Mt Ruapehu, New Zealand (Figure 2.22). 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 (Leonard et al., 2008). The communication tools were improved by repeating these activities annually and tracking perceptions of visitors through time in response to real events (Potter et al., 2014).

Cost-benefit analysis (Woo, 2014) 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).

2.7.6 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 (Haynes et al., 2008a).

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 [Chapter 8] in Section 2.7.1 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 (Leonard et al., 2008, Marzocchi & Woo, 2009) and this has been applied at Naples (Chapter 6). Another example of an analysis of the costs and benefits of evacuation has been carried out at Auckland, New Zealand (Chapter 5). 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 three 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 (Chapter 26). 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 (Loughlin et al., 2002), 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 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 (Loughlin et al., 2002). 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 (Kelman & Mather, 2008, Usamah & Haynes, 2012) 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.

2.7.7 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 such as 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 volcano observatories and communities at risk.

Priority for Action 3 focuses on using knowledge, innovation and education to enhance disaster risk reduction 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

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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 [see Supplementary Case Study 1 in the appendix to Chapter 1]. 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 [see Supplementary Case Study 2 in the appendix to Chapter 1]. 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 to 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.

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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.

2.8 The way forward

Here we have highlighted the wide range of hazards posed by volcanoes and described 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, although 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

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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

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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.

Action 2.1 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 in earth science, remote sensing, social science, atmospheric science and 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 volcano observatories and with the EO community (for validation purposes). Progress toward this goal has been slow but steady and some volcano observatories 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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