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Edited by Susan C. Loughlin, Steve Sparks, Sarah K. Brown, Susanna F. Jenkins and Charlotte Vye-Brown
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Chapter 1

An introduction to global volcanic hazard and risk

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Contents

1.1 Introduction

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. The 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). The Volcanoes of the World database collated by the Smithsonian Institution (Siebert et al., 2010, Smithsonian, 2014) is regarded as the authoritative source of information on Earth's volcanism and is the main resource for this study (data cited in this report are from version VOTW4.22).

Chapter 1 provides a short summary of global volcanic hazards and risks intended for a non-technical readership. Chapter 2 provides a more detailed analysis of global volcanic hazards and risks. Chapter 3 focuses on volcanic ash fall hazard and risk. Chapters 4 to 26 provide additional detail and case studies about subjects covered in Chapters 1 and 2. These case studies, along with published literature, provide the evidence base for this work. Summaries of Chapters 4 to 26, and additional case studies 1-3 are provided as an appendix to this chapter.

A complementary report comprising country profiles of volcanism, is provided online in support of this book (Appendix B). The 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.

Loughlin, S.C., Vye-Brown, C., Sparks, R.S.J., Brown, S.K., Barclay, J., Calder, E., Cottrell, E., Jolly, G., Komorowski, J-C., Mandeville, C., Newhall, C., Palma, J., Potter, S., Valentine, G. (2015) An introduction to global volcanic hazard and risk. In: S.C. Loughlin, R.S.J. Sparks, S.K. Brown, S.F. Jenkins & C. Vye-Brown (eds) *Global Volcanic Hazards and Risk,* Cambridge: Cambridge University Press.

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1.2 Background

Volcanic eruptions can cause loss of life and livelihoods in exposed communities, damage critical infrastructure, displace populations, disrupt business and add stress to already fragile environments (Blong, 1984). Currently, an estimated 800 million people live within 100 km of a volcano that has the potential to erupt [Chapter 4]. These volcanoes are located in 86 countries and additional overseas territories worldwide [see Appendix B]*.

The total documented loss of life from volcanic eruptions has been modest compared to other natural hazards (~280,000 since 1600 AD, Auker et al., 2013). However, a small number of eruptions are responsible for a large proportion of these fatalities, demonstrating the potential for devastating mass casualties in a single event (Figure 1.1). Importantly, these eruptions are not all large and the impacts are not all proximal to the volcano. For example, the moderate-sized eruption of Nevado del Ruiz, (Colombia) in 1985 triggered lahars (volcanic mudflows), which resulted in the deaths of more than 23,000 people tens of kilometres from the volcano (Voight, 1990).

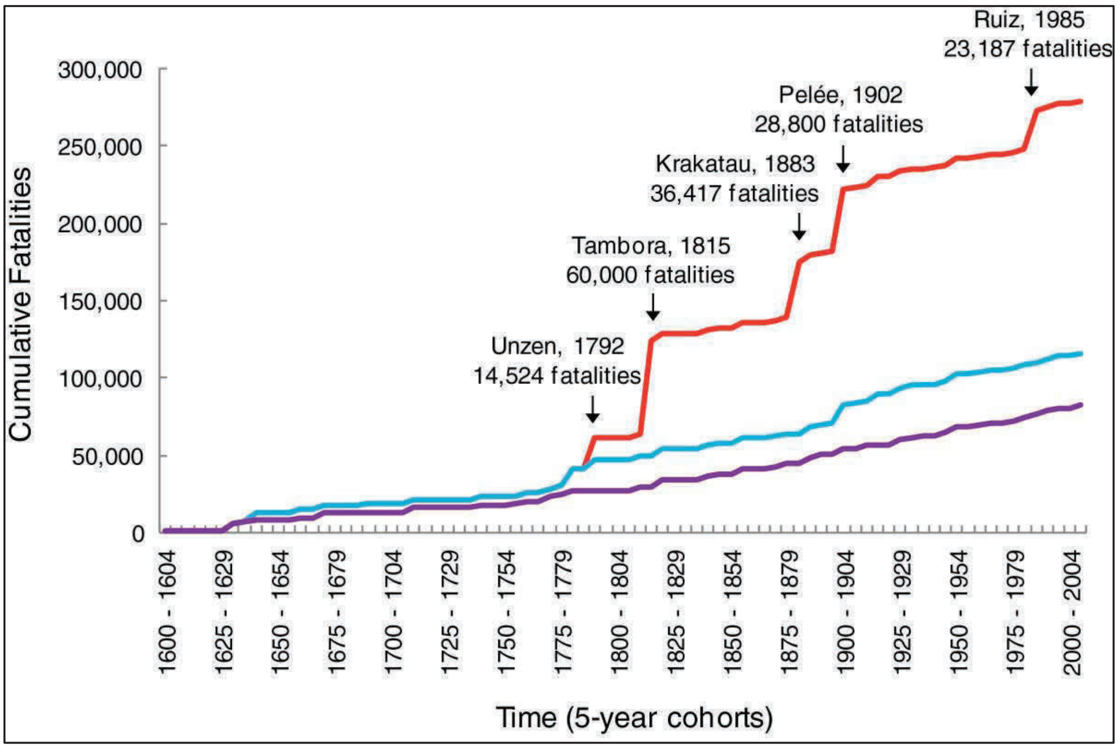

Figure 1.1 Cumulative number of fatalities directly resulting from volcanic eruptions (Auker et al., 2013). Shown using all 533 fatal volcanic incidents (red line), with the five largest disasters removed (blue line), and with the largest ten disasters removed (purple line). The largest five disasters 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. This figure is reproduced as Figure 2.13 in Chapter 2.

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* Appendix B (www.cambridge.org/volcano) comprises country profiles of volcanism.

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Despite exponential population growth, the number of fatalities per eruption has declined markedly in the last few decades, suggesting that risk reduction measures are working to some extent (Auker et al., 2013). There has been an increase in volcano monitoring and resultant improvements in hazard assessments, early warnings, short-term forecasts, hazard awareness, communication and preparedness around specific volcanoes (Leonard et al., 2008, Solana et al., 2008, Lindsay, 2010, Larson et al., 2010, Roberts et al., 2011, Marzocchi & Bebbington, 2012, Wadge et al., 2014). Many volcano observatories are active in vulnerable communities, helping to build awareness of volcanic hazards and risk. They now have a key role in building resilience and reducing risk. It is conservatively estimated that at least 50,000 lives have been saved over the last century (Auker et al., 2013) probably as a consequence of these developments. Unfortunately, many volcanoes worldwide are either unmonitored or not sufficiently monitored to result in effective risk mitigation and therefore when they re-awaken the losses may be considerable. The inequalities in monitoring capacity worldwide and the lack of basic geological information at some volcanoes is demonstrated in the country and regional profiles of volcanism in Appendix B.

Volcanic eruptions are almost always preceded by ‘unrest’ (Potter et al., 2012, Barberi et al., 1984) including volcanic earthquakes and ground movements which can in themselves be hazardous. Volcanic unrest can allow scientists at volcano observatories to provide early warnings if there is a good monitoring network (Phillipson et al., 2013) [Chapters 15 and 18]. Increasingly, effective monitoring from both the ground and space is enabling volcano observatories to provide good short-term forecasts of the onset of eruptions or changing hazards situations (Sparks, 2003, Segall, 2013; Chapter 17). Such forecasts and early warnings can support timely decision-making and risk mitigation measures by civil authorities (Newhall & Punongbayan, 1996, Lockwood & Hazlett, 2013). For example, nearly 400,000 people were evacuated during the November 2010 eruption of Merapi, Indonesia and it is estimated that 10,000 to 20,000 thousand lives were saved as a result (Surono et al., 2012). Nevertheless, there were 386 fatalities reflecting in part the complex contexts in which individuals receive information and make decisions.

Long-lived or frequent eruptions pose particular challenges for communities and there are good examples of social adaptation in response to these difficult situations (e.g. Sword-Daniels, 2011). For example, the long-lived but intermittent eruption of Soufrière Hills Volcano in Montserrat (Lesser Antilles), comprised five phases of lava extrusion between 1995 and 2010 (Wadge et al., 2014). The eruption caused severe social and economic disruption, with 19 fatalities on 25 June 1997(Loughlin et al., 2002), and the subsequent loss of the capital, port and airport. The progressive off-island evacuation of more than 7,500 people (two thirds of the pre-eruption population), left a population of less than 3,000 in 1998 (Clay et al., 1999). A strong cultural identity has helped islanders to cope and a state-of-the-art volcano observatory has become established that continues to support development of new methodologies in hazard and risk assessment [Chapter 21]. Tungurahua in Ecuador has erupted since 1999 and innovative incentives to encourage rapid evacuation have been developed. A system of community ‘vigías’ (watchers) support scientists, civil defence and their communities by observing the volcano and organising evacuations of their communities if necessary (Stone et al., 2014). Some of the farmers at highest risk have been allocated additional fields away from the volcano, providing options for retreat in times of threat and uncertainty [Chapter 26]. The preservation or

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rebuilding of livelihoods, critical infrastructure systems and social capital is essential to successful adaptation under these conditions.

The economic impact of volcanic eruptions has recently become more apparent at local, regional and global scales. The 2010 eruption of the Eyjafjallajökull volcano in Iceland caused serious disruption to air traffic in the north Atlantic and Europe as fine volcanic ash in the atmosphere drifted thousands of kilometres from the volcano (Þorkelsson, 2012). The resulting global economic losses from this modest-sized eruption accumulated to about US$ 5 billion (Ragona et al., 2011) as global businesses and supply chains were affected. In the eruption of Merapi, Indonesia in 2010, losses were estimated at US$ 300 million (BNPB., 2011)[Chapters 9 and 10]. Economic losses due to damage of exposed critical infrastructure are unavoidable, but the goal is to minimise them as far as possible through effective long-term planning.

There is often a lack of awareness of volcanic risk both in the proximity of a volcano and further afield, and indeed the risk may not have been assessed at all (Lockwood & Hazlett, 2013). In part this is due to the long duration between eruptions at some volcanoes. Understanding the risks posed by a volcano first requires a thorough understanding of the eruptive history of that volcano, ideally through both geological and historical research (Sparks & Aspinall, 2004). There is still significant uncertainty about the eruption history at many of the world's volcanoes so understanding of potential future hazards, and their likely frequency and magnitude is limited. For example, before the 2008 eruption of Chaitén volcano, Chile, the few studies available suggested that the last major eruption occurred thousands of years ago and little was known of any historical eruptions. The threat appeared low and so the closest monitoring station operated by the national monitoring institution was more than 200 km away. It was only after the 2008 eruption, which resulted in the rapid evacuation of Chaitén town, that new dating was undertaken showing that in fact Chaitén volcano has been more active than previously thought. Had the research been done first, an eruption may have been anticipated (e.g. Lara et al. 2013).

Although volcanoes do pose risks during unrest and eruption, they also provide benefits to society during their much longer periods of repose (Lane et al., 2003, Kelman & Mather, 2008, Bird et al., 2010, Witter, 2012). Volcanic environments are typically appealing: soils are fertile; elevated topography provides good living and agricultural conditions, especially in the equatorial regions (Small & Naumann, 2001); water resources are commonly plentiful; volcano tourism can provide livelihoods; some volcanoes have geothermal systems that can be exploited (Witter, 2012) and some have religious or spiritual significance. These benefits mean that providing equivalent alternatives if evacuation/resettlement is advised can be challenging.

1.3 Volcanoes in space and time

Most active volcanoes (Figure 1.2) occur at the boundaries between tectonic plates (Schmincke, 2004, Cottrell, 2014) where the Earth's crust is either created in rift zones (where tectonic plates move slowly apart) or destroyed in subduction zones (where plates collide and one is pushed below the other). Most volcanoes along rift zones are deep in the oceans along mid-ocean ridges. Some rift zones extend from the oceans and seas onto land, for example in Iceland and the East African Rift valley. The Pacific 'ring of fire' comprises chains of island volcanoes (e.g. Aleutians, Indonesia, Philippines) and continental volcanoes (e.g. in the Andes) that have formed above subduction zones. These volcanoes have the potential to be highly explosive. Other notable subduction zone volcanic chains include the Lesser Antilles in the Caribbean and the South Sandwich Islands in the Southern Atlantic. Some active volcanoes occur in the interiors of tectonic plates above mantle 'hot spots', the Hawaiian volcanic chain and Yellowstone in the USA being the best-known examples.

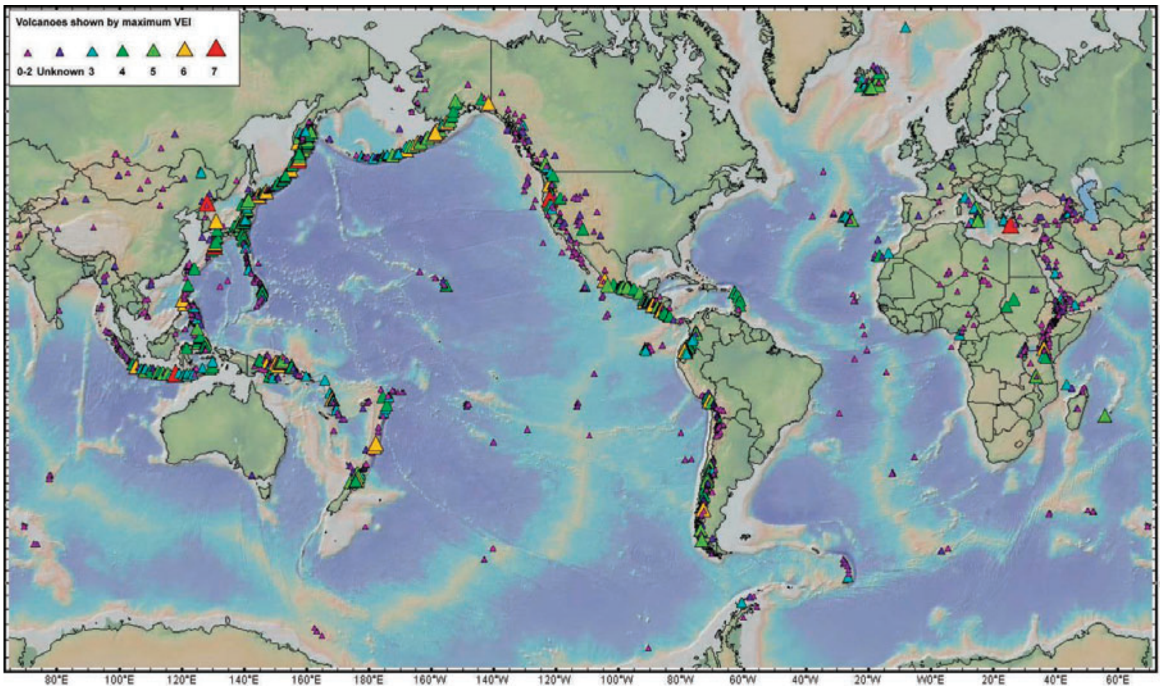

Figure 1.2 Potentially hazardous volcanoes are shown with their maximum recorded Volcanic Explosivity Index (VEI) – a measure of explosive eruption size. Small eruptions (VEI 0-2) and eruptions of unknown size are shown in purple and dark blue. The warming of the colours and the increase in size of the triangles represents increasing VEI. Volcanoes mostly occur along plate boundaries with a few exceptions. There may be thousands of additional active submarine volcanoes along mid-ocean ridges but they don't threaten populated areas. Records are for the Holocene (the last ~10,000 years).

There are many different types of volcanoes in each of these settings, some are typical steep-sided cones, some are broad shields, some of the larger caldera volcanoes are almost indistinguishable on the ground and can only be seen clearly from space (Siebert et al., 2010, Cottrell, 2014). Each volcano may demonstrate diverse eruption styles from large explosions that send buoyant plumes of ash high into the atmosphere to flowing lavas. Each eruption evolves over time, resulting in a variety of different hazards and a wide range of consequent impacts. This variety in behaviours arises because of the complex and non-linear processes involved in the generation and supply of magma to the Earth's surface (Cashman et al., 2013). The subsequent interaction of erupting magma with surface environments such as water or ice may further alter the characteristics of eruptions and thus their impacts. This great diversity of behaviours and consequent hazards means that each volcano needs to be assessed and monitored individually by a volcano observatory.

Volcanic eruptions are usually measured by magnitude and/or intensity (Pyle, 2015) but neither is easy to measure, particularly for explosive eruptions. The magnitude of an eruption is defined as total erupted mass (kg), while intensity is defined as the rate of eruption, or mass flux (kg per second). In order to compare the size of different types of eruptions, a magnitude scale is commonly used. A widely used alternative to characterise and compare the size of purely explosive eruptions is the *Volcanic Explosivity Index* (VEI) which comprises a scale from 0 to 8 (Figure 1.3). The VEI is usually based on the volume of material erupted during an explosive eruption (which can be estimated based on fieldwork after an eruption) and also the height of the erupting column of ash (Newhall & Self, 1982). The height of an ash column generated in an explosive eruption can be measured relatively easily and is related to intensity (Mastin et al., 2009, Bonadonna et al., 2012).

In general, there is an increasing probability of fatalities with increasing eruption magnitude, for example, all recorded VEI 6 and 7 eruptions since 1600 AD have caused fatalities (Auker et al., 2013). Five major disasters dominate the historical dataset on fatalities accounting for 58% of all recorded fatalities since 4350 BC (Figure 1.1). The two largest disasters in terms of fatalities were caused by the largest eruptions (Tambora 1850; Krakatau 1883). Nevertheless, small to moderate eruptions can be devastating, the modest eruptions of Nevado del Ruiz (VEI 3) and Mont Pelée (VEI 4) being good examples (Voight, 1990). A statistical analysis of all volcanic incidents (any volcanic event that has caused human fatalities), excluding the five dominant major disasters, highlights the fact that VEI 2-3 eruptions are most likely to cause a fatal volcanic incident of any scale and VEI 3-4 eruptions are most likely to have the highest numbers of fatalities (Auker et al., 2013).

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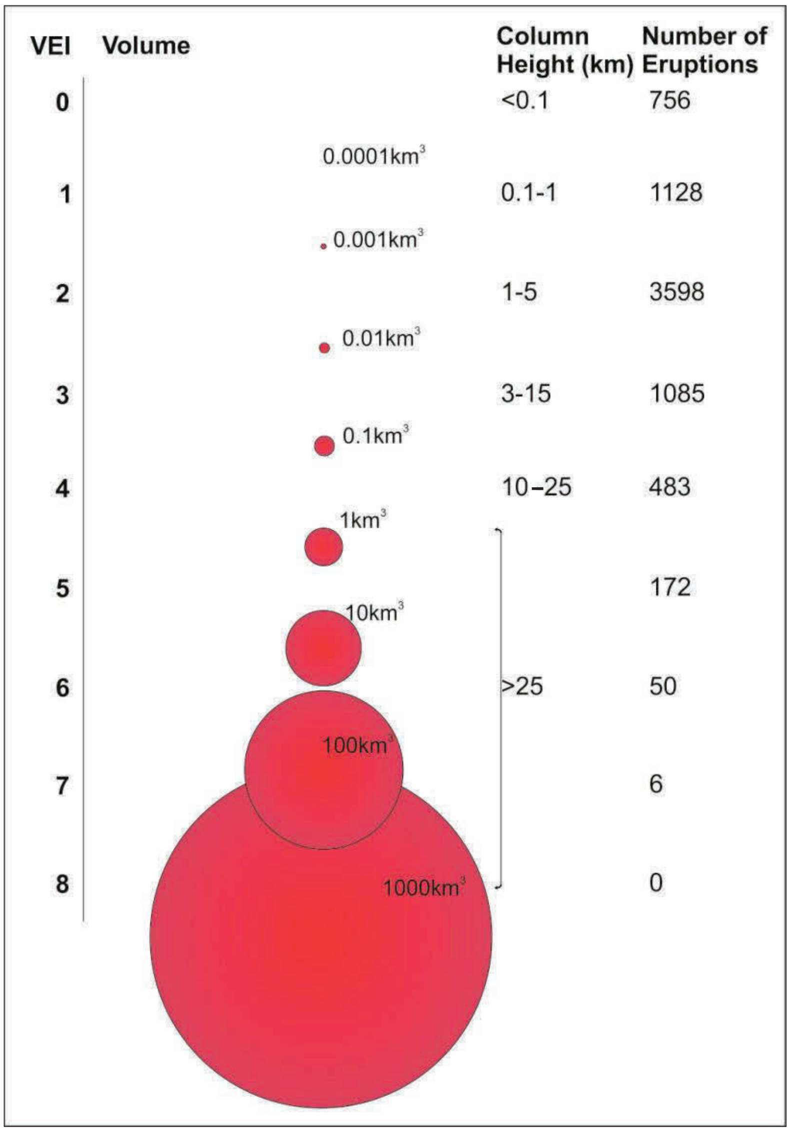

Figure 1.3 VEI is best estimated from volume of explosively erupted material but can also be estimated from column height. The typical eruption column heights and number of confirmed Holocene eruptions with an attributed VEI in VOTW4.22 are shown (Siebert et al., 2010).

In total there are 1,551 volcanoes in the Smithsonian Institution database VOTW4.22, of which 866 are known to have erupted in the last 10,000 years (the Holocene). Since 1500 AD, there are 596 volcanoes that are known to have erupted. Only about 30% of the world's Holocene volcanoes have any published information about eruptions before 1500 AD, while 38% have no records earlier than 1900 AD. Geological, historical and dating records become less complete further back in time. 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.

The record since 1950 is believed to be almost complete with 2,208 eruptions recorded from 347 volcanoes. The average number of eruptions ongoing per year since 1950 is 63, with a

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minimum of 46 and maximum of 85 eruptions recorded per year. On average 34 of these are new eruptions beginning each year.

Going further back in time, the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database (Crosweller et al., 2012) lists 3,130 volcanoes that have been active in the last 2.58 million years (Quaternary period), and some of these may well be dormant rather than extinct. Many of these volcanoes remain unstudied and much more information is needed to understand fully the threat posed by all of the world's volcanoes. There are also thousands of submarine volcanoes, but the great majority of these (with one or two exceptions) do not constitute a major threat.

Estimating the global frequency and magnitude of volcanic eruptions requires this under-recording to be taken into account (Deligne et al., 2010, Furlan, 2010, Brown et al., 2014). Statistical analysis of global data for explosive eruptions (with under-recording accounted for) shows that as eruption magnitude increases, the frequency of eruptions decreases (Table 1.1).

Table 1.1 Global return periods for explosive eruptions of magnitude M (where $M = \mathrm{Log}_{10}m - 7$ and m is the mass erupted in kilograms (Pyle, 2015)). The estimates are based on a statistical analysis of data from VOTW4.22 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.This table is reproduced as Table 2.1 in Chapter 2.

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	5.0
≥6.0	72	10
≥6.5	380	18
≥7.0	2,925	190
≥7.5	39,500	2,500
≥8.0	133,350	16,000

Volcanoes that erupt infrequently may surprise nearby populations if monitoring is not in place, and eruptions may be large. For example, Pinatubo, Philippines, (Newhall & Punongbayan, 1996) was dormant for a few hundred years before the large eruption in 1991 [Chapter 7], so populations, civil protection services and government authorities had no previous experience or even expectation of activity at the volcano. Conversely, some volcanoes are frequently active and local communities have learned to adapt to these modest eruptions (e.g. Sakurajima, Japan; Etna, Italy; Tungurahua, Ecuador [Chapter 26]; Soufrière Hills volcano, Montserrat (Sword-Daniels, 2011)). Very infrequent, extremely large volcanic eruptions (i.e. VEI 7-8+) have the potential for regional and global consequences and yet we have no experience of such events in recent historical time (Self & Blake, 2008). The super-eruptions that took place at Yellowstone (Magnitude M=8 or more) have a very low probability of occurrence in the context of human society (Table 1.1).

1.4 Volcanic hazards and their impacts

Volcanoes produce multiple primary and secondary hazards (Blong, 1984, Papale, 2014) that must each be recognised and assessed in order to mitigate their impacts. Depending upon volcano type, magma composition, eruption style, scale and intensity at any given time, these hazards will have different characteristics and may occur in different combinations at different times. The major volcanic hazards that create risks for communities include those outlined below:

Ballistics. Ballistics (also referred to as volcanic bombs) are rocks ejected on ballistic trajectories by volcanic explosions. In most cases the range of ballistics is a few hundred metres to about two kilometres from the vent, but they can be blasted to distances of more than 5 km in the most powerful explosions. Fatalities, injuries and structural damage result from direct impacts of ballistics, and those which are very hot on impact can start fires.

Volcanic ash and tephra. Explosive eruptions and pyroclastic density currents (see below) produce large quantities of intensely fragmented rock, referred to as tephra. The very finest fragments from 2 mm down to nanoparticles are known as 'volcanic ash' and can be produced in huge volumes. The physical and chemical properties of volcanic ash are highly variable and this has implications for impacts on health, environment and critical infrastructure [Chapters 12 and 13], and also for the detection of ash in the atmosphere using remote sensing. Falling volcanic ash may cause darkness and very hazardous driving conditions, while concurrent rainfall leads to raining mud. Even relatively thin ash fall deposits (≥ 1 mm) may threaten public health (Horwell & Baxter, 2006, Carlsen et al., 2012) damage crops and vegetation, disrupt critical infrastructure systems (Spence et al., 2005, Sword-Daniels, 2011, Wilson et al., 2012, Wilson et al., 2014), transport, primary production and other socio-economic activities over potentially very large areas. Ash fall creates major clean-up demands (Blong, 1984) [Chapter 12], which need to be planned for (e.g. the availability of large volumes of water for hosing, trucks and sites to dump ash). The accumulation of ash on roofs can be hazardous especially if it is wet; for example, the collapse of roofs during the 1991 Mount Pinatubo eruption killed about 300 people [Chapter 7]. Unfortunately, volcanic ash fall can also be persistent during long-lived eruptions, giving crops, the environment and impacted communities limited chance to recover (Cronin & Sharp, 2002). Remobilisation of volcanic ash by wind can continue for many months or even years after an eruption, prolonging exposure (Carlsen et al., 2012, Wilson et al., 2012).

Volcanic explosions inject volcanic ash into the atmosphere and it may be transported by prevailing winds hundreds or even thousands of kilometres away from a volcano. Airborne ash is a major hazard for aviation (Guffanti et al., 2010) [Chapter 14]. For example, 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. Forecasting the dispersal of volcanic ash in the atmosphere for civil aviation (Bonadonna et al., 2012) is a major challenge during eruptions and is the role of Volcanic Ash Advisory Centres supported by volcano observatories [Chapter 12].

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The potentially wide geographic reach of volcanic ash, the relatively high frequency of explosive volcanic eruptions and the variety of potential impacts make volcanic ash the hazard most likely to affect the greatest number of people [Chapter 3].

Pyroclastic flows, surges and blasts. These are hot, fast-moving flows (Figure 1.4) that may originate from explosive lateral blasts, the collapse of explosive eruption columns or the collapse of lava domes (Calder et al., 2002). *Pyroclastic flows* are concentrated avalanches of volcanic rocks, ash and gases that are typically confined to valleys, and *pyroclastic surges* are more dilute turbulent clouds of ash and gases that can rapidly spread across the landscape and even travel uphill or across water (Carey et al., 1996). 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). Volcanic blasts can destroy or cause severe damage to infrastructure, vegetation and agricultural land (Blong, 1984, Jenkins et al., 2013, Charbonnier et al., 2013), and can even remove soil from the bedrock (Wadge et al., 2014). The spectrum of flow types are sometimes collectively referred to as *pyroclastic density currents.* They are the most lethal volcanic hazard accounting for one third of all known volcanic fatalities. They travel at velocities of tens to hundreds of kilometres per hour and have temperatures of hundreds of degrees centigrade.

Figure 1.4 Pyroclastic flows from the 1984 explosive eruption of Mayon, Philippines (C. Newhall).

Eyewitnesses have reported that pyroclastic flows and surges make little sound so may offer no warning of their advance if they are not seen (Loughlin et al., 2002). Surviving a pyroclastic density current is very unlikely. Those who have survived in buildings at the margins of dilute currents have been very badly burned, thus the only appropriate response to the threat of an imminent pyroclastic density current is evacuation. Pyroclastic density currents account for one third of all historical volcanic fatalities (Auker et al. 2013).