Geophysical risk: volcanic activity

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3.2 Geophysical risk: volcanic activity

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3.2.1 Volcanoes and volcanic activity

Volcanoes provide spectacular evidence of the dynamic nature of planet Earth and bring many long-term benefits to society, including rich soils, tourism and geothermal energy. Some erupt frequently and others may appear benign for generations, which means the risk they pose may be underestimated. Understanding the risk first requires characterisation of the volcano and knowledge of the type, magnitude and frequency of past eruptions.

3.2.1.1 Global distribution of volcanoes and volcanoes in Europe

There are about 1 550 known terrestrial volcanoes that have erupted in the past ≈10 000 years and are therefore likely to erupt again in the future; they are described as 'active' (Siebert et al., 2010; Cottrell, 2014).

Volcanic eruptions may cause local to global impacts; in order to understand and mitigate risks, the first step is to recognise a volcano as active and to characterise its past activity.

Most have formed along colliding or diverging tectonic plate boundaries (e.g. the Pacific margins, the Mediterranean, the Lesser Antilles and Iceland; Figure 3.7) and these account for >94 % of known historical eruptions (Siebert et al., 2015); the remainder have formed above mantle 'hotspots' (e.g. Hawaii).

In Europe, volcanism from Spain (Bartolini et al., 2015) to Armenia (Savov et al., 2016) is mainly caused by the convergence of the northward-moving African and Arabian lithospheric plates with the Eurasian plate and microplates in the Aegean Sea and Anatolia (Figure 3.8). In Iceland, volcanism is caused by a combination of rifting at the Mid-Atlantic Ridge and a 'hotspot'. There are 32 volcanoes in Iceland (Ilyinskaya et al., 2015), 47 known volcanoes in continental Europe (Siebert et al., 2010), and many more in autonomous regions, European dependencies and territories in the Atlantic (Canary Islands, Azores, Cabo Verde, Tristan da Cunha, Ascension Island), the Lesser Antilles (Montserrat, Guadeloupe, Martinique, Saba) and the Indian Ocean (La Réunion). About 15 million people in Europe live within just 30 km of an active volcano; of these, more than 2.2 million live within 20 km of the Campi Flegrei caldera in Italy and more than 675 000 live within 10 km of Vesuvius (Siebert et al., 2010).

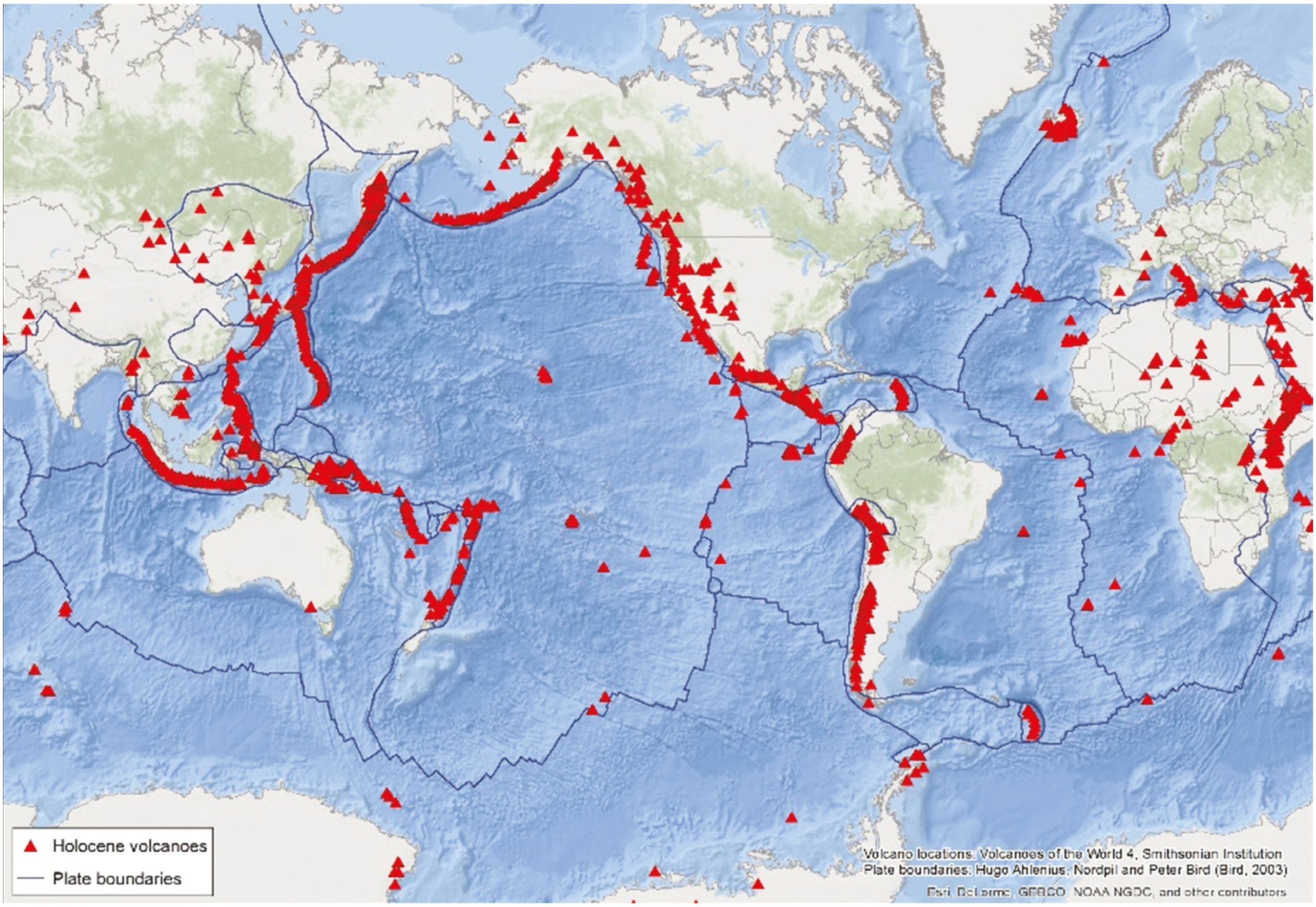
3.2.1.2 Eruption type, duration, frequency and size

Globally, about 70 volcanoes erupt each year and at any one time at least 20 are erupting (Siebert et al., 2010, 2015). Eruptions are complex time-dependent events, which often exhibit distinct phases including effusive (e.g. lava flows/domes) and/or explosive types of activity (e.g. Gudmundsson et al., 2012) over durations of hours to decades (Brown et al., 2015).

Major controls on eruption type include magma chemistry, rheology and volatile content. Eruptions can be measured using magnitude (erupted mass), but volume is often used as a proxy for magnitude for explosive eruptions (e.g. the Volcanic Explosivity Index, see Newhall and Self 1982, Pyle 2015).
Some volcanoes erupt frequently (e.g. Stromboli and Etna), whereas others (e.g. Campi Flegrei) erupt infrequently, with hundreds of years between eruptions (e.g. Selva et al., 2012; Brown et al., 2014). Global data show a power law relationship between magnitude and frequency, such that larger magnitude eruptions are less frequent (Deligne et al., 2010). In order to understand the distribution of eruption types and magnitudes in time and space at a given volcano (and, therefore, the likelihood and type of future

FIGURE 3.7

The locations of known Holocene (past ≈ 10.000 years) terrestrial volcanoes of the world, most of which form near tectonic plate boundaries (Bird, 2003).
Source: Smithsonian Institution (2013)



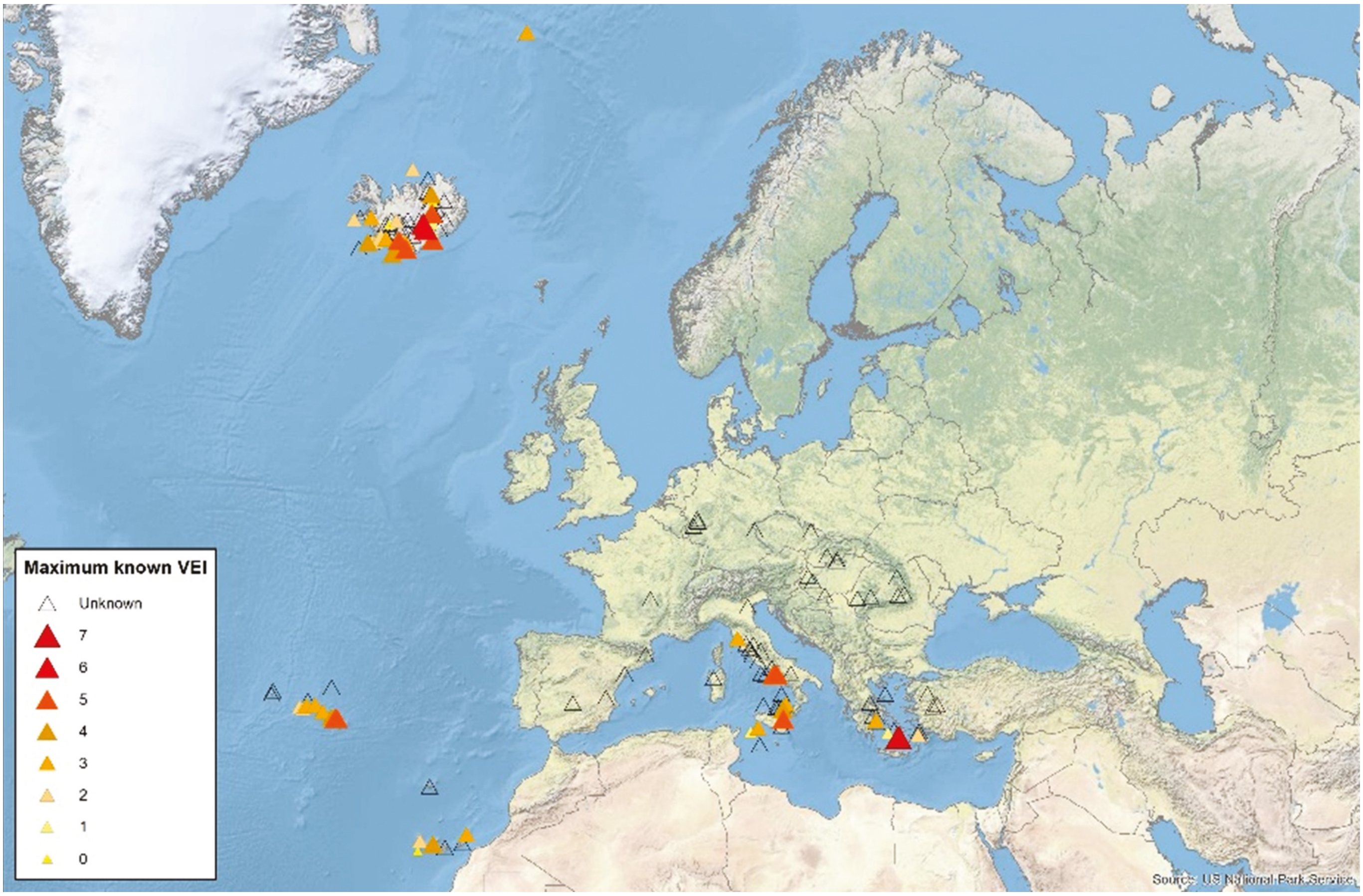
eruptions), geological and geochronological studies are an essential starting point (e.g. Druitt et al., 1999; Orsi et al., 2004; Thordarson and Larsen, 2007; Hicks et al., 2012).

3.2.1.3 Causes of volcanic unrest and eruptions

Eruptions are caused by complex processes including magma overpressurisation. Most eruptions are preceded by one or multiple episodes of 'volcanic unrest' as magma moves towards the Earth's surface (Acocella et al., 2015; Parks et al., 2015). The movement of magma through the crust (and its interaction with hydrothermal systems) causes pressure changes, which result in ground deformation and earthquakes, and also induces detectable changes in mass and/or density (Freymueller et al., 2015). During magma ascent, volatiles (gases) separate and are either retained in the magma as bubbles or escape to interact with the hydrothermal system or be released at the surface. (Aiuppa et al., 2013). An episode of volcanic unrest may last for a matter of days to a number of years (average ≈500 days), and understanding the processes driving unrest and eruption is an essential part of effective early warning (Cashman et al. 2013, Sparks and Cashman 2017). Volcanoes that erupt infrequently (e.g. calderas) may experience many episodes of unrest (e.g. De Natale

FIGURE 3.8

Maximum known Volcanic Explosivity Index (0-8) of eruptions at European volcanoes in the past ≈10 000 years, based on the Smithsonian Institution Volcanoes of the World database (VOTW4.22). Volcanoes with unknown eruption histories are marked as black triangles.
Source: Smithsonian Institution (2013)



et al., 2006). In contrast, in a global study of 228 volcanoes active between 2000 and 2011 (many of which erupt frequently) the 'Volcanic unrest in Europe and Latin America' project (VUELCO) funded by the European Union's 7th Framework Programme (FP7) showed that 47 % of documented periods of volcanic unrest led to an eruption (Phillipson et al., 2013). Some episodes of detected unrest may not be caused by magma and may be entirely tectonic or caused by hydrothermal phenomena (e.g. Segall, 2013; Biggs et al., 2009).

3.2.2 Monitoring systems and early warning

Volcano observatories are the official institutions in charge of monitoring volcanoes. They may be dedicated to a single volcano (e.g. the Montserrat Volcano Observatory) or may operate from national institutions and be responsible for multiple volcanoes in a country (e.g. the Icelandic Met Office and Istituto Nazionale di Geofisica e Vulcanologia). Some institutions have responsibility for volcanoes and volcano observatories overseas (e.g. Institut de Physique du Globe de Paris).

Volcano observatories have a key role in early warning. They collect multiple streams of diverse data, analyse the data in near real-time, determine the level of threat and make decisions on, for example, raising alert levels (Villagrán de León, 2012). These decisions must be based on sound evidence (Marzocchi et al., 2012; Bretton et al., 2015). The quality, range and sophistication of monitoring methods has increased dramatically in recent years (Sparks et al., 2012), with advances in computing underpinning improvements in power, speed, data transmission, data analysis and modelling techniques. Long-term monitoring at quiescent volcanoes is necessary to establish baselines, and satellite remote sensing provides many opportunities as the spatial and temporal resolution of data improves (e.g. Harris et al., 2016; Bagnardi et al., 2016). Nevertheless, only a small fraction of the world's 1 550 volcanoes have sufficient ground monitoring and the necessary accompanying institutional capacities to effectively support DRM, despite evidence that volcano monitoring is cost-effective (Newhall et al., 1997).

3.2.2.1 Geophysical monitoring (seismic, deformation, gas, infrasound) and the need for global monitoring

Episodes of unrest are highly variable in character, so forecasting the onset of an eruption remains a significant challenge (Chiodini et al., 2016; Selva et al., 2015; Marzocchi and Bebbington, 2012; Sigmundsson et al., 2010). Accelerating rates of seismicity and deformation may be detected before eruptions (Sigmundsson et al. ,2010; Saltogianni et al., 2014; Cannavò et al., 2015) and tracking the location of volcano-tectonic earthquakes in near real time (Thorkelsson, 2012; Sigmundsson et al., 2015, Pallister and McNutt, 2015; Falsaperla and Neri, 2015) may facilitate eruption forecasting. Long-period earthquakes and micro-earthquakes can be key indicators of imminent eruption, especially during an ongoing eruption (McNutt et al., 2015). Cyclic patterns of activity can also enable forecasting of hazardous events (Voight et al., 1999; Loughlin et al., 2002). Borehole strainmeters have successfully been used to forecast eruptions of Hekla in Iceland (Roberts et al., 2011).

If appropriate monitoring is in place at a volcano, it may be possible to issue short-term forecasts of eruptions and volcanic activity and to provide early warnings for different hazards.

Although satellite passes are not yet frequent enough to use Interferometric Synthetic Aperture Radar (InSAR) as a forecasting tool, it can be used in combination with other data to gain tremendous insights into volcanic unrest and eruption (e.g. Gudmundsson et al., 2016; Spaans and Hooper, 2016). InSAR is useful to detect deformation at remote volcanoes and at regional scales (Biggs et al., 2014; Parks et al., 2015).

Gas emissions (Silva et al., 2015; Aiuppa et al., 2013; Chiodini et al., 2015), the chemistry, temperature and level of crater lakes and groundwater (Hernández et al., 2007), and the geochemistry and flow rates of glacial rivers (Kristmansdóttir et al. ,1999) may all show detectable changes before and during eruptions. Gas emissions can be monitored using ground-based, airborne or satellite remote sensing (Aiuppa et al., 2007, 2010; Nadeau et al., 2011; Conde et al., 2013). The gas most easily detected and monitored in the atmosphere during eruptions is sulphur dioxide (SO2) (Oppenheimer et al., 2013; Flower et al., 2016).

Petrology and geochemistry can be used in near real time to characterise eruptive materials and understand magmatic properties and dynamics (Hartley et al., 2016; Pankhurst et al., 2014). Rapid analysis of tephra can detect whether or not there is a magmatic component to phreatic (steam-driven) eruptions (Suzuki et al., 2013).

Environmental monitoring such as dissolved constituents in rainwater, ash leachates (Witham et al., 2005) and particulate (air quality) monitoring can potentially provide information about both eruptive behaviour and probable impacts on health, the environment, infrastructure and buildings (Gislason et al., 2015).

3.2.2.2 Additional and emerging monitoring methods

Volcanic infrasound is a technique that detects, locates and characterises shallow or aerial acoustic sources at volcanoes (Fee and Matoza, 2013; Ulivieri et al., 2013). During the H2020 Atmospheric dynamics Research InfraStructure in Europe 2 (ARISE2) project, episodes of lava fountaining at Etna were recorded ≈600 km away, providing evidence that near-real-time notification of ongoing volcanic activity at a regional scale can be achieved (Johnson and Ripepe, 2011; Marchetti et al., 2016).

Establishing mass eruption rate (a parameter needed to effectively forecast ash dispersal) and characterising ash clouds in near real time is a current challenge (Ripepe et al., 2013; Lamb et al., 2015; Marzano et al., 2013, 2016). Monitoring the extrusion rate of lava is crucial to anticipate the evolution of active lava flow fields or stability of lava domes. Time series digital elevation models (DEMs) collected by satellite at Merapi volcano in 2010 (through the International Space Charter), combined with ground monitoring, enabled increasing extrusion rates to be identified, leading to a rise in alert level and timely evacuations that saved thousands of lives (Surono et al., 2012; Pallister and Surono, 2015). Extrusion rates can be established from the ground, unmanned aerial vehicles or aircraft using a variety of methods (e.g. Wadge et al. 2014a, 2014b; Harris et al., 2005).

Characterisation of heat sources (Figure 3.9) during volcanic unrest and eruption can support scientific understanding of eruptive behaviour and timely response (Harris et al., 2016). During the 2014-15 Bárðarbunga eruption in Iceland, the Middle InfraRed Observation of Volcanic Activity (MIROVA) system (Coppola et al., 2015) was used to chart the evolution of the eruption when access was limited and visibility was poor.

In seismology, deterministic eruption forecasting based on the failure forecast method (FFM) is showing potential (Boué et al., 2016).

Time series observations of volcanoes and their emissions using static or video cameras can yield important insights into hazardous processes. Citizen science, including community

FIGURE 3.9

Measuring the temperature of pyroclastic flow deposits in Montserrat (block and ash flow deposits).
Source and Copyright BGS/Government of Montserrat

monitoring, can fill observational and information gaps, raise awareness of hazards and risk, and engage communities at-risk (e.g. Stevenson et al., 2013; Stone et al., 2014; Wallace et al., 2015). During the 2014-15 eruption at Bárðarbunga volcano, Iceland, people could document their experiences of poor air quality due to the gas-rich eruption online (IMO, n.d).

WOVOdat is a searchable, web-accessible global relational database containing time-series monitoring data from more than 100 eruption episodes; this will allow global trends in unrest and eruption data to be interrogated to assist forecasting at individual volcanoes (Venezky and Newhall, 2007; Widiwijayanti et al., 2015).

3.2.2.3 Communication, reporting and alert levels

During unrest or eruption, scientists communicate in a variety of ways (reports, forecasts, alert levels) using a variety of media (email lists, short message service (SMS), social media, television and radio) to suit the needs of information users (Solana et al., 2008; Haynes et al., 2008a; Mothes et al., 2015). Such users are diverse and include civil aviation authorities, civil protection authorities, businesses, tourist operators, the media and the public. Ideally, the content and format of such communications are tailored to users' needs (e.g. Lechner et al., 2017; Doyle et al., 2014) and users have considered in advance their thresholds for action (e.g. Marzocchi et al., 2012; Hicks et al., 2014). During an emergency, joint formal reports can be particularly effective if scientists and civil protection authorities work well together, and if the content and format has been designed specifically with users in mind (e.g. Scientific advisory board of the Icelandic Civil Protection, 2015).

A volcano Early Warning System (EWS) requires that monitoring data are collected and interpreted by scientists, the level of threat is determined

FIGURE 3.10

Summary of alert levels and civil protection system response for Vesuvius volcano, Italy. Alert levels are established by INGV Vesuvio based on changing monitoring parameters. The civil protection system responds in each operative phase according to the alert level and the emergency plan.
Source: authors

ALERT LEVEL	STATE OF THE VOLCANO	ERUPTION PROBABILITY	TIME OF ERUPTION	OPERATIVE PHASE
Base	No significant variation of monitored parameters.	Very low	Undefined	
Caution	Significant change of monitored parameters.	Low	Indefinite, or not less than several months.	I Caution
Warning	Further significant change in monitored parameters.	Medium	From months to weeks	II Warning
Alarm	Appearance of phenomena and/or evolution of monitored parameters suggesting a pre-eruption dynamic.	High	From weeks to days	III Alarm

Operative Phase I: Verification of contingency plans, constant contact between scientists and civil protection, checking of functionality and immediate availability of resources, infrastructure and services needed for subsequent alert levels.

Operative Phase II: Voluntary evacuation of red zone to alternative accommodation outside the zone of risk. All involved in the emergency plan alert and prepared for Phase III.

Operative Phase III: Evacuation of the red zone within three days.

and a decision to alert stakeholders is made (Fearnley, 2013). Some volcano observatories use Volcanic Alert Levels (VALs) to communicate changes in the status of volcanic activity that imply a changing probability of eruption (Gardner and Guffanti, 2006; Fearnley, 2013; Winson et al., 2014) or changing types of hazard (Potter et al., 2014). Notification of a change in VAL is usually accompanied by situation-specific information in the form of a more detailed report. VALs are developed to suit local situations and, as such, they vary worldwide. Some focus on unrest and eruption forecasting (Figure 3.10) and others acknowledge the changing phenomena and hazards of long-lived eruptions (Potter et al., 2014). In situations in which major and costly mitigation actions are triggered by volcanic EWSs (e.g. the evacuation of urban areas), quantitative, objective and rational scientific decision-making is essential to avoid accusations of 'false alarms' (see Chapter 3.2.3, Hincks et al., 2014).

The global network of nine Volcanic Ash Advisory Centres (VAACs) was set up by the International Civil Aviation Organization (ICAO) following aircraft encounters with ash clouds in the 1980s (Guffanti et al., 2010). Volcano observatories provide reports to VAACs to support the initiation of ash dispersal models and have the option to set an 'aviation colour code' representing the status of volcanoes in the context of likelihood of eruption and potential for ash emissions (Lechner et al., 2017). This system can run in parallel to a VAL system.

In situations on the ground in which it is acknowledged that there may be little time for response , alerts may be sent out to authorities and the public via SMS, telephone, radio or social media (e.g. IMO, 2016; Stone et al., 2014; Mothes et al., 2015). EWSs for lahars and jökulhlaups (glacier floods in Iceland) are variable in terms of components but, in general, require monitoring (e.g. acoustic flow monitors) to detect flows in proximal environments that can alert authorities to sound sirens downstream so that communities can be evacuated.

3.2.3 Volcanic hazard assessment

Volcanic hazards are diverse and they can occur in different combinations and interact in different ways throughout the unrest, eruption and post-eruption period.

Volcanoes generate multiple hazardous processes, the short- and long-term forecasting of which involve diverse methods to anticipate hazard footprints in order to enable anticipation and mitigation of impacts.

Scientists are improving their ability to assess and forecast these hazards, their likely 'footprints', interactions and impacts over different timescales. Short-term and long-term forecasts, to support crisis response and planning, respectively, are based on a variety of different approaches depending primarily on data availability. Deterministic and probabilistic approaches to hazard are used and are appropriate in different circumstances. .

3.2.3.1 Hazard forecasting

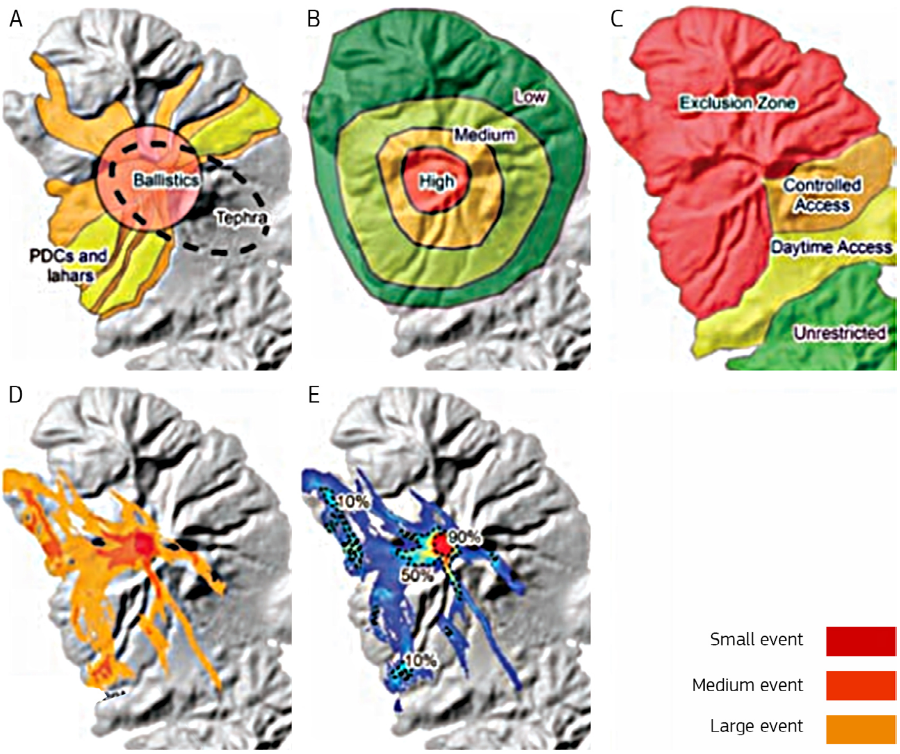
Short-term forecasts can enable communities across broad areas to prepare for imminent hazards and impacts. For example, simple simulations of expected atmospheric dispersal and deposition of volcanic tephra based on monitoring/observation parameters, can be made available (e.g. for Etna at INGV (n.d.) and for Mount St Helens at USGS (2015), Hasegawa et al., 2015). Similarly, short-term dispersal forecasts of SO_2 (which may adversely affect human and live-stock health) can enable mitigation actions to be taken (e.g. Gislason et al., 2015). Such forecasts can also be achieved for lava flows and lahars, and, in some places, mitigation of lava flow impacts has been attempted using engineering measures.

Volcanic hazard process models still need further development to better simulate key processes; this is especially true for pyroclastic flows, surges and lahars, the assessment of which currently lags behind that of tephra dispersal and fall. The ability to model interacting hazards is also important, such as rainfall-triggered lahars (Jones et al., 2015), eruption column collapse into pyroclastic flows or pyroclastic flows into lahars.

Long-term volcanic hazard assessment is primarily based on characterising the past eruptive activity of a volcanic system and understanding the recurrence rates of eruptions and the range of possibilities for future eruptions. Such assessments are often presented as hazard maps. Ideally, geological and historical studies are needed to establish eruption histories but sometimes such information is not available, further fieldwork is needed, or data simply doesn't exist. For example, fine-grained deposits (e.g. ash fall, surges, lateral blasts) may be missing from the geological record, so thorough consideration of knowledge gaps and uncertainties is paramount in any hazard analysis (e.g. Engwell et al., 2013; Sparks et al., 2013, Bonadonna et al. 2012, 2015). Volcanologists can study analogue volcanoes and global databases to address knowledge gaps (e.g. Ogburn et al., 2015), or use methods such as expert elicitation in order to consider and quantify uncertainties (Aspinall, 2006, 2010). Uncertainty should be acknowledged in all scientific decision-making, forecasts and assessments.

FIGURE 3.11

Synthetic examples (not a real volcano) of the appearance of five hazard map types found during the review:
(a) geology-based map,
(b) integrated qualitative map,
(c) administrative map,
(d) modelling-based map and
(e) probabilistic map.



3.2.3.2 Volcanic hazard maps

Volcanic hazard maps can communicate information about one or a range of hazards including lahars, pyroclastic flows and surges, tephra fall (Macedonio et al., 2008), ballistics, lava flows (Richter et al., 2016), and, sometimes, less frequent hazards such as debris avalanches and monogenetic eruptions. An International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) working group is reviewing current global practice (>200 published hazard maps). They defined five major classes of hazard map and found that >60 % of maps are based primarily on the geological history of the volcano (Figure 3.11), despite incomplete eruption histories that do not represent all past and possible future scenarios. Furthermore, >83 % of hazard maps use a qualitative 'high-medium-low' description to indicate likelihood of impact, but the meanings behind these terms are open to broad interpretation (Calder et al., 2015).

The IAVCEI working group have established that there is no single approach that suits all situations; different approaches may be suitable for different needs. Nevertheless, there is consensus that quantitative, accountable and defendable hazard maps are increasingly needed.

The group aims to collectively define

good practices. Scientific priorities to enhance hazard maps include (1) improved methods for probabilistic analysis, especially for lahar, pyroclastic flows and surges, (2) establishing methods to undertake hazard assessments for data-poor volcanoes and (3) approaches for multihazard, multiscenario probabilistic modelling (Calder et al., 2015). Although probabilistic volcanic hazard maps exist for a few of the world's best studied volcanoes, they are far from being the norm.

Haynes et al. (2007) recognised that maps are rarely well understood by users and that three-dimensional (3D) visualisation can significantly help understanding.

3.2.3.3 Probabilistic volcanic hazard assessment

A variety of methods are used, often in combination, to generate probabilistic volcanic hazard assessments over different timescales.

For example, statistical methods can be used to assess recurrence rates and locations of vents, which, when combined with numerical simulations of volcanic processes (e.g. lava flow emplacement, tephra dispersal and fall), can create hazard curves for specific locations or hazard maps for larger areas (Connor et al., 2015). There may be high uncertainty in vent location, particularly if a volcano has vents distributed across its flanks or the area is a volcanic field comprising multiple eruption centres (Connor et al., 2012; Bebbington and Cronin, 2010).

Because of the variety and potential complexity of volcanic hazards, probabilistc hazard maps commonly attempt to communicate information about only a single hazard at a time (Figure 3.11e). For example, volcanic flows are tyically displayed as the spatial variation of inundation probability over a given period of time. Tephra fall might be assessed using contours of probability given a hazardous threshold of tephra thickness (Jenkins et al., 2015a) or contours of tephra thickness given a certain probability in order to better assess the associated impact (e.g. Bonadonna, 2006; Biass et al. 2014, 2016a). Probabilistic hazards assessments can be local to global in scale.

The first probabilistic assessment of global tephra fall hazard has been attempted for the 2015 United Nations International Strategy for Disaster Reduction (UNISDR) Global Assessment Report, based on a method developed for the regional scale (Jenkins et al., 2012, 2015a).

Once volcanic unrest begins there are multiple potential eruptive outcomes (scenarios) due to the dynamic complexity of volcanic systems. In this situation, probabilistic methods provide a basis for scientists to explore those outcomes, allocate probability estimates to them (Marzocchi et al., 2012; Selva et al., 2010) and communicate them to authorities to support rational decision-making (e.g. Sparks 2003, Marzocchi et al., 2007). The results can be tested using statistical procedures and allow comparisons between volcanoes and other natural and non-natural hazards (e.g. Scandone et al., 1993; Bayarri et al., 2015).

Current probabilistic approaches build on the idea of event trees (Newhall and Hoblitt, 2002) and on Bayesian statistics (e.g. Papadopoulos and Orfanogianaki, 2005). The probability estimates allocated to each outcome/scenario might be empirical, or be based on expert discussion and elicitation, numerical simulations or a combination of methods (e.g. Aspinall, 2006, 2010; Marzocchi and Bebbington, 2012). These methods are also useful if applied regularly at long-lived or frequently active volcanoes where probabilities change and assessments can be compared over time (Pallister et al., 2010; Wadge and Aspinall, 2014). Similar approaches have now been applied at Vesuvius (Neri, 2008), Teide-Pico Viejo, Tenerife (Martí et al., 2008), and Auckland Volcanic Fields, New Zealand (Lindsay et al., 2010). The same principle has also been developed to generate tools (e.g. Marzocchi et al., 2008).

3.2.4 Volcanic risk assessment and mitigation

3.2.4.1 Vulnerability and exposure

Vulnerability is complex, dynamic and spatially variable with many facets including systemic, social, functional and economic vulnerability (e.g. Enhancing resilience of communities and territories facing natural and na-tech hazards (ENSURE) project, Menoni et al., 2012). Exposure contributes to vulnerability (Cutter 2013) and includes the people and assets exposed to the hazards. Volcanic unrest and eruptions tend to unfold over weeks to years, thereby enhancing the dynamic complexity of factors that contribute to vulnerability and exposure (Galderisi et al., 2013; Zuccaro et al., 2014).

Volcanic tephra fall is the hazard that most frequently affects large populations and assets and has reasonable vulnerability estimates in risk models (Spence et al., 2005; Jenkins et al., 2015). Jenkins et al. (2014), as part of the Mitigate and Asses risk from Volcanic Impact on Terrain and human Activities (MIA-VITA) project, developed guidelines and methodologies for carrying out initial physical vulnerability assessments. This built on previous projects including the SPeeD project at Vesuvius and the EXPLORIS project (e.g. Zuccaro et al., 2008; Marti et al., 2008). Jenkins et al. (2015) categorised tephra fall impacts by sector and considered the relationship between hazard intensity (in that case ash thickness) and damage or disruption to each sector (buildings, critical infrastructure, agriculture). More data need to be collected to inform estimates of physical vulnerability of buildings and infrastructure, through: (1) collection of post-eruption damage data (e.g. Baxter et al., 2005; Wilson et al., 2011; Biass et al., 2016a, 2016b; Charbonnier et al., 2013; Jenkins et al., 2015b), (2) experimental testing of materials failure, or (3) using theoretical calculations of material strengths (e.g. Jenkins et al., 2014). Damage data and experimental data remain sparse so theoretical calculations can contribute to the development of vulnerability functions, which provide the probability of a certain level of damage as a function of hazard intensity (Jenkins et al., 2014; see also Chapter 2.4).

A dynamic pressure scale for building

FIGURE 3.12

Soufrière Hills Volcano and Plymouth, the capital of Montserrat, in October 1997.

damage by pyroclastic surges (Baxter et al., 2005), developed after experiences in Montserrat (Figure 3.12) and at Mount St Helens, has contributed to simulation work at Vesuvius and other European volcanoes in the EXPLORIS project (Baxter et al., 2008).

Studies on social vulnerability in volcanic risk are increasing in number and showing the value of semi-quantitative and qualitative assessments (e.g. Sword-Daniels, 2011; Sword-Daniels et al., 2014). Hicks and Few (2015) showed that during long-term eruptions, coping capacity, maintenance of well-being, recovery of losses and rebuilding of livelihoods are highly variable within populations and tend to be linked to preceding socioeconomic conditions (Birkman, 2007). Socio-economic impacts are most likely to be experienced by those with pre-existing and inter-related sociocultural, political and economic vulnerabilities (Wisner et al., 2012; Gaillard 2008). Volcanic activity can have a disproportionate effect on livelihoods and economy because of high systemic vulnerability (Wilson et al., 2011, 2014; Jenkins et al., 2015a).

Comprehensive quantitative assessment of the impacts of all types of volcanic hazard is relatively new but is most advanced for tephra fall (Craig et al., 2016; Elissondo et al., 2016; Wilson et al., 2011, 2012, 2014; Magill et al., 2013). Socioeconomic impacts due to tephra fall are most likely to be documented in long-lived eruptions (e.g. Sword-Daniels, 2011; Sword-Daniels et al., 2014).

3.2.4.2 Risk assessment methodologies

Volcanic risk assessment is not as advanced as assessment of other hazards such as flooding, earthquakes and tropical cyclones. For the long-lasting eruption at Soufriere Hills Volcano, Montserrat, volcanic risk has been assessed in a regular and consistent way for 20 years (Aspinall et al., 2002; Aspinall, 2006; Wadge and Aspinall, 2014). After deriving event scenario probabilities and their uncertainties by elicitation, risks and uncertainties are quantified using Monte Carlo modelling, and the risk is presented as (1) societal risk expressed quantitatively as a curve of the probability of exceeding a given number of fatalities, (2) individual risk given as an annualised probability of death (from the volcano) for any person living in a specific area and (3) occupational risk given for people working under certain conditions in specific areas.

An example of a volcanic risk model is the KazanRisk loss model (riskfrontiers.com/kazanrisk.htm), which uses numerical dispersal modelling of ash fall in Greater Tokyo to estimate potential losses associated with building damage, clean-up and reductions in agricultural productivity. At regional to global scales, the CAPRA risk modelling platform (ecapra.org) has been used to provide preliminary estimates of potential building damage around active volcanoes in the Asia-Pacific Region using simplified volcanic hazard outputs from a statistical emulator (Jenkins et al., 2015a). Because some crucial aspects of vulnerability must be assessed qualitatively, there is a need to find innovative ways to integrate qualitative with quantitative data to assess volcanic risk (Hicks and Few, 2015). Novel interdisciplinary approaches are now being developed (e.g. STREVA project) that combine volcanological techniques, probabilistic decision support and social science methods to ensure that the benefits of even uncertain and incomplete knowledge are acted upon to reduce risk (e.g. Hicks et al., 2014; Barclay et al., 2014). Stirling (2010) highlighted that different analytical methods suit different epistemic conditions and acknowledging the state of knowledge is a good start in enabling effective risk analysis and communication..

'Forensic analysis' of past disasters provides a strong basis for learning (e.g. Voight 1990, Loughlin et al. 2002, Thordarson and Self, 2003; Bird et al., 2010; Ragona et al., 2011), and longitudinal studies can reveal valuable insights into causal processes behind impacts and disasters (e.g. Integrated Research on Disaster Risk FORIN project 2011). Such approaches are also being applied to understand recovery processes that are complex and can last for decades (Sword-Daniels et al., 2015).

3.2.4.3 Civil Protection, scientists and risk management

Volcano observatories and civil protection authorities, working together as well as with the public, have reduced fatalities due to volcanic activity worldwide. At least 50 000 lives were saved in the 20th century (Auker et al., 2013) and even more have been saved since 1985 (Voight et al., 2013).

Mutual understanding and trust develop with an investment of time and effort (Haynes et al., 2008a, 2008b) and it is too late to start when an emergency begins. Effective communication and decision-making during a rapidly changing emergency situation (Fischoff, 2013; Doyle et al., 2014) will be facilitated by good planning, preparation and response protocols (Doyle et al., 2015; Bretton et al., 2015). Interdisciplinary and transdisciplinary approaches can bring a wide range of methods and experiences together (e.g. communities, scientists, authorities) to facilitate better understanding, analysis and communication of hazard and risk (Hicks et al., 2014; Barclay et al., 2014, 2015).

Volcanic unrest and eruptions can be prolonged, which may cause disruption and have long-term socioeconomic impacts. Tephra fall can cause damage and disruption across sectors and has potential health impacts (Horwell and Baxter, 2006; Carlsen et al., 2012); therefore, planning for clean-up and recovery is essential (Hayes et al., 2017).

Preparedness for volcanic unrest and eruption often takes the form of contingency plans,which can be practised (Figure 3.13) by scientists, authorities and other stakeholders, including the public (Hicks et al., 2014). Different types of exercises have been reported around the world (Figure 3.13), ranging from the training of small groups to international reaction-chain exercises (Lindsay et al., 2010; Ricci et al., 2013). In high-risk urban settings (e.g. Naples), there are significant costs to mitigation actions, even to exercises, so direct and indirect costs and benefits need to be carefully considered to support decision-making (Marzocchi et al., 2012; Woo, 2014).

FIGURE 3.13

An evacuation exercise for the entire population of Tristan da Cunha, South Atlantic.
Source: photograph courtesy of Anna Hicks

The 2010 eruption of Eyjafjallajökull volcano in Iceland demonstrated that even small eruptions can have global impacts (Ragona et al., 2011). Therefore, international collaboration is essential to ensure that lessons learned and scientific progress are translated into planning and preparation across all sectors (Schmidt et al., 2011, 2015; Bonadonna et al., 2012).

3.2.5 Conclusions and key messages

Partnership

Long-term collaboration and effective partnerships between scientists (operational and research) and civil protection authorities are particularly important for effective evidence-based risk management and emergency response. The recent FUTUREVOLC and MEDSUV projects (FP7) showed how Europe-wide research partnerships can support such national and Europe-wide DRM efforts in particular. Engagement with users of scientific and civil protection advice can improve the format and content of outputs, enhancing understanding, uptake and effective decision-making at all levels. The knowledge and experience of those at risk is increasingly recognised as important and their involvement in the design and development of DRM strategies can be highly effective.

Knowledge

Hazard, impact, vulnerability, loss and recovery data are sparse in volcanology but are needed to produce better hazard and risk assessments. Detailed study of all future eruptions and their impacts is needed. Despite an overall need for increased quantification in volcanic risk, interdisciplinary collaboration is recommended to capitalise on both quantitative and qualitative approaches to risk, particularly in situations in which data are scarce. Progress in process understanding is needed to enable better anticipation of hazardous events. Frameworks for the optimal combination of hazard and vulnerability analysis across multiple temporal and spatial scales is needed for comprehensive risk assessments and proactive policies of risk reduction.

Innovation

There is an ongoing need for development in monitoring techniques, integrated analysis of ground and space data, hazard and vulnerability assessment methodologies and interdisciplinary/transdisciplinary science. A next important step for the volcanology community as a whole is to enhance innovation in hazard and risk assessment strategies. There is an increasingly urgent need for near-real-time global monitoring and a reporting platform to support the anticipation of volcanic events that have wide-reaching or humanitarian impacts. This will require collaborative approaches and innovative integration of data in a wide variety of formats and at different spatial and temporal resolutions.

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