Assessing Volcanic Hazard: A Review

Joan Martí Molist

Subject: Physical Sciences, Natural Hazard Science, Geology, Geophysics
Online Publication Date: Sep 2017 DOI: 10.1093/oxfordhb/9780190699420.013.32

Abstract and Keywords

Volcanoes represent complex geological systems capable of generating many dangerous phenomena. To evaluate and manage volcanic risk, we need first to assess volcanic hazard (i.e., identify past volcanic system behavior to infer future behavior). This requires acquisition of all relevant geological and geophysical information, such as stratigraphic studies, geological mapping, sedimentological studies, petrologic studies, and structural studies. All this information is then used to elaborate eruption scenarios and hazard maps. Stratigraphic studies represent the main tool for the reconstruction of past activity of volcanoes over time periods exceeding their historical record. This review presents a systematic approach to volcanic hazard assessment, paying special attention to reconstruction of past eruptive history. It reviews concepts and methods most commonly used in long- and short-term hazard assessment and analyzes how they help address the various serious consequences derived from the occurrence (and nonoccurrence in some crisis alerts) of volcanic eruptions and related phenomena.

Keywords: volcanic hazards, hazard assessment, event tree, scientific communication, risk reduction

Introduction

Volcanoes can cause significant losses of human lives and property and their impact can be important at local, regional, and/or global scales depending on the size of the eruption. It is estimated that about 250,000 persons died during the past two centuries as a direct consequence of volcanic eruptions and that, of these, almost 26,000 were killed in the past two decades, above all in developing countries (Blong, 1984; Siebert et al., 2010; Auker et al., 2013). Today, about 500 million people live in regions of the world directly subject to volcanic risk (Auker et al., 2013). Volcanoes directly threaten large population centers and have an important influence on the socioeconomic development of these regions; as well, they can have serious environmental and economic impacts at the global level in the form of climate change (e.g., Toba, Indonesia, about 75,000 years ago) and/or the disruption of global air traffic (2010 eruption of Eyjafjallajökull, Iceland) (Oppenheimer, 2011).
Thus, it is obvious that volcanic risk assessment and management are important scientific, economic, and political concerns, especially in densely populated areas. Appropriate responses to these issues require accurate assessment and mitigation programs; efficient educational and communication programs able to ensure that knowledge and communication on volcanic hazards and risks reach all societal levels, the development of effective programs and tools for forecasting, predicting and managing crises; and the promotion of capacity building and sustainable development in threatened regions. This implies that scientists, engineers, governments, and civil protection agencies, among others, must cooperate and work together.

The evaluation of volcanic risk is extremely complex, since it encompasses several different hazardous natural phenomena. Volcanic eruptions are excellent examples of multi-risk cascading threats due to their intrinsic multi-hazard natures, in which a variety of volcanic (lava flows, fallout, lahars, and pyroclastic flows) and associated hazards (seismic shocks, landslides, tsunamis, or floods) interact or impact sequentially, and to the resulting successive loss of services that usually accompanies them. This multiplicity of phenomena has seriously constrained the evaluation and management of risk in volcanology, despite the fact that advances and improvements in this scientific discipline could be easily exported and applied to almost all types of natural hazards.

To evaluate and manage volcanic risk we need first to assess volcanic hazard, that is, identify how a volcanic system (i.e., an active volcano or volcanic area) has behaved in the past and then use this information to infer how it may behave in the future. This task requires a compilation of all existing geological and geophysical information concerning the eruption style of the volcanic system in question, its eruptive recurrence, the structural constraints on the opening of new vents, and the characteristics and potential extent of its main hazards. All this information can be used to draw up eruption scenarios and hazard maps that will constitute the basis for designing risk management programs, as well as essential material to develop the educational and communication programs that should also form part of a risk reduction process.

From a scientific point of view, considerable progress has been made in recent years thanks to the development of Geographic Information Systems (GIS) and the deployment of increasingly powerful computers and computational models. Recent studies have improved volcanic risk methodology by advancing the basic scientific and technological skills employed in volcanic risk assessment and mitigation, such as computer models, vulnerability databases, and probabilistic risk assessment protocols (Felpeto et al., 2007; Biass et al., 2012; Jenkins et al., 2014; Thierry et al., 2015). However, despite these crucial advances, the evaluation and management of volcanic risk still has three important shortcomings. The first derives from the fact that scientists, volcanological observatories, and Civil Protection Agencies often use different terminologies, methodologies, criteria, and protocols to evaluate, manage, and communicate volcanic risk. This lack of homogeneity often hinders and delays decision making and encumbers communication between members of the scientific and administrative communities. The second issue stems from the need for expertise and scientific background to make proper use of scientific advice,
Assessing Volcanic Hazard: A Review

which precludes the wider use of scientific and technical advances by potential end users outside the scientific community, thereby slowing down the social benefits of such improvements. The third shortcoming is due to the fact that, in many cases, human populations, administrators, mass media, and politicians alike ignore—or are in denial about—the reality of living with volcanoes. In many cases, the absence of basic or advanced educational programs tackling the understanding, evaluation, and mitigation of volcanic risk prevents a society from perceiving volcanoes as a natural threat that can be lived with and even successfully managed, but, at the same time, one that should never be ignored.

In order to help mitigate these problems, this review aims to analyze the main aspects that need to be considered in any volcanic hazard assessment, irrespective of where it is being conducted and by who. It first revises the definition of concepts such as “hazard” and “risk,” and “active” and “extinct” volcanoes, which sometimes cause confusion, particularly among those who are less familiar with the way volcanoes work. It then goes on to describe volcanic and associated hazards, the tasks and methods required when conducting hazard assessment, and how hazard assessment contributes to eruption forecasting and early warning. Finally, it considers a number of other significant questions such as scientific communication and the education and dissemination that is needed for effective volcanic hazard assessment.

**Hazard versus Risk**

Despite having very different meanings, hazard and risk are two terms that are often confused and/or used interchangeably as if they were synonyms. Although this confusion occurs in many contexts, in this section we only refer to hazards and risks of volcanic origin. Volcanic hazard is defined as the probability of a particular area being affected by a destructive volcanic event within a given period of time, whereas risk is the probability or likely magnitude of loss of life, property and/or productive capacity within an area subject to volcanic hazard (Fournier d’Albe, 1979; Blong, 1984; 2000; Tilling, 1989; Peterson and Tilling, 2000). Thus, hazard relates to physical phenomena and their possible recurrence, extent and impact, while risk refers to the potential socioeconomic cost of the impact of a particular hazard or group of hazards. Volcanic hazard evaluation aims to determine which areas are prone to be affected by volcanic events and is essential for designing (and applying) emergency plans and territorial planning. Volcanic risk assessment, on the other hand, tries to evaluate potential costs in terms of, for example, human lives, economic losses, and service breakdowns and is pertinent for planning and undertaking mitigation measures, that is, decision making during crises or for preventing crises from arising.

In simple terms, risk can be expressed as the product of the magnitude of potential losses and the probability that these losses will occur, that is, hazard × value × vulnerability (Fournier d’Albe, 1979). Hazard is the physical event having an impact on a particular area within a specific timeframe and therefore contains implicit spatial (i.e., the probability that the effects of the event will extend over a certain distance or surface area) and
Assessing Volcanic Hazard: A Review

temporal (i.e., the probability that it will occur) probabilities. Value is the combined worth of the number of people, capital value (e.g., land, buildings, and infrastructures) and productive capacity (e.g., factories, power plants, and agricultural land) in the potentially affected area. Vulnerability is a calculation of the proportion of the value that is likely to be lost as a result of a given event. However, as risk is an estimate of a potential cost, this definition may be more appropriately formulated if we also take into account possible mitigation measures, which can be understood as any action (e.g., hazard assessment, territorial and emergency planning, the reduction of physical vulnerability, monitoring, or education) that can be implemented to reduce risk. Therefore, risk can be defined as:

\[
\text{Risk} = \frac{\text{Hazard} \times \text{Vulnerability} \times \text{Value}}{\text{Mitigation measures}}
\]

The enormous human and economic losses caused by unexpected volcanic events can unfortunately be easily illustrated by numerous historical examples (Table 1). Although less frequent in occurrence than other natural hazards, volcanoes do have significant negative consequences on human populations, their economies, and the environment, which may then require long, psychologically, physically, and economically difficult periods of recovery. Thus, despite their potentially high cost, investment in risk-reduction programs is always preferable to merely reacting once disasters have struck.

An overall risk reduction plan should include several essential programs that work in harmony: (1) a scientific program aimed at improving knowledge of the process and its potential impacts (i.e., hazard assessment); (2) a monitoring program for determining the current state of activity of the process; (3) an educational program, to educate the population about the potential hazards and risks that threaten them; and (4) a management program for designing emergency plans and resilience strategies (Fig. 1). Each of these programs should include a corresponding public communication and outreach section in order to add transparency to the scientific process and to build support, trust, and understanding on the part of the public. These programs must be undertaken when the volcano is at rest or only exhibits a background level of activity, in order to guarantee adequate responses when it reactivates and/or to prepare for a further eruption. To fail to do so is to court disaster.
Therefore, hazard assessment is one of the first steps in estimating risk and risk reduction (Fig. 2). First of all, it identifies how a volcano has behaved in the past, the types of hazards it tends to produce, the extent of those hazards and their potential impact, as well as the volcano’s eruption frequency. Consequently, hazard assessment aims to categorize principal past eruption scenarios and to speculate which scenarios are most likely to occur in the future. In essence, the purpose of volcanic hazard assessment is to anticipate the nature of the next eruption (Sparks et al., 2013). This information will be crucial for land planning and the development of emergency services, two essential actions that reduce risk, respectively, by preventing development in danger areas and identifying safe areas and evacuation routes needed in case of an eruption. In addition, hazard assessment will aid decision making during volcanic crises, as it provides a basis for evaluating potential eruption scenarios and their impacts. Hazard assessment also provides a guide for education programs and dissemination actions focused on explaining to the local population the volcanic hazards they are exposed to. Finally, hazard assessment is a prerequisite for conducting vulnerability analyses and estimating the potential impact and economic losses to societies and the environment in the event of a fresh eruption.
Table 1 Summary of Losses of Some of the Most Deadly Eruptions
## Assessing Volcanic Hazard: A Review

<table>
<thead>
<tr>
<th>Deaths</th>
<th>Volcano</th>
<th>Location</th>
<th>Year</th>
<th>Major Cause of Death</th>
</tr>
</thead>
<tbody>
<tr>
<td>60,000</td>
<td>Tambora</td>
<td>Indonesia</td>
<td>1815</td>
<td>Fallout, tsunamis, PDCs, Starvation</td>
</tr>
<tr>
<td>36,417</td>
<td>Krakatau</td>
<td>Indonesia</td>
<td>1883</td>
<td>Tsunami</td>
</tr>
<tr>
<td>29,025</td>
<td>Mt. Pelee</td>
<td>Martinique</td>
<td>1902</td>
<td>PDCs</td>
</tr>
<tr>
<td>23,080</td>
<td>Nevado del Ruiz</td>
<td>Colombia</td>
<td>1985</td>
<td>Lahars</td>
</tr>
<tr>
<td>16,000?</td>
<td>Vesuvius</td>
<td>Italy</td>
<td>79</td>
<td>Fallout, PDCs</td>
</tr>
<tr>
<td>14,524</td>
<td>Unzen</td>
<td>Japan</td>
<td>1792</td>
<td>Volcano collapse, tsunami</td>
</tr>
<tr>
<td>10,000?</td>
<td>Kelut</td>
<td>Indonesia</td>
<td>1586</td>
<td>PDCs?</td>
</tr>
<tr>
<td>9,350</td>
<td>Laki</td>
<td>Iceland</td>
<td>1783</td>
<td>Starvation</td>
</tr>
<tr>
<td>5,405?</td>
<td>Kilawea</td>
<td>Hawaii</td>
<td>1790</td>
<td>PDCs</td>
</tr>
<tr>
<td>5,110</td>
<td>Kelut</td>
<td>Indonesia</td>
<td>1919</td>
<td>Lahars</td>
</tr>
<tr>
<td>5,000</td>
<td>Tungurahua</td>
<td>Ecuador</td>
<td>1640?</td>
<td>PDCs, lahars?</td>
</tr>
<tr>
<td>Eruptions</td>
<td>Volcano</td>
<td>Country</td>
<td>Year</td>
<td>Phenomena</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------------</td>
<td>-------------</td>
<td>------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>4,011</td>
<td>Galunggung</td>
<td>Indonesia</td>
<td>1822</td>
<td>Lahars</td>
</tr>
<tr>
<td>3,360</td>
<td>Vesuvius</td>
<td>Italy</td>
<td>1631</td>
<td>Lahars, lava flows</td>
</tr>
<tr>
<td>3,000</td>
<td>Awu</td>
<td>Indonesia</td>
<td>1711</td>
<td>PDCs</td>
</tr>
<tr>
<td>3,000?</td>
<td>Merapi</td>
<td>Indonesia</td>
<td>1672</td>
<td>PDCs</td>
</tr>
<tr>
<td>2,957</td>
<td>Papandayan</td>
<td>Indonesia</td>
<td>1772</td>
<td>Landslide</td>
</tr>
<tr>
<td>2942</td>
<td>Lamington</td>
<td>Papua New Guinea</td>
<td>1951</td>
<td>PDCs</td>
</tr>
<tr>
<td>2,806</td>
<td>Awu</td>
<td>Indonesia</td>
<td>1856</td>
<td>PDCs, lahars</td>
</tr>
<tr>
<td>2,500?</td>
<td>Santa Maria</td>
<td>Guatemala</td>
<td>1902</td>
<td>Fallout?</td>
</tr>
<tr>
<td>2,000?</td>
<td>Chichon</td>
<td>México</td>
<td>1982</td>
<td>PDCs</td>
</tr>
<tr>
<td>2,000</td>
<td>Makian</td>
<td>Indonesia</td>
<td>1760</td>
<td>Lahars</td>
</tr>
<tr>
<td>1,900</td>
<td>Ararat</td>
<td>Turkey</td>
<td>1840</td>
<td>PDC, landslide</td>
</tr>
<tr>
<td>1,700</td>
<td>Lake Nyos</td>
<td>Cameroon</td>
<td>1986</td>
<td>Volcanic gases</td>
</tr>
<tr>
<td>1,680</td>
<td>Soufriere St. Vincent</td>
<td>Guadeloupe</td>
<td>1902</td>
<td>PDCs</td>
</tr>
</tbody>
</table>
Assessing Volcanic Hazard: A Review

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Magnitude</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1532</td>
<td>Awu</td>
<td>Indonesia</td>
<td>1892</td>
</tr>
<tr>
<td>1500</td>
<td>Mayon</td>
<td>Philippines</td>
<td>1875</td>
</tr>
<tr>
<td>1491</td>
<td>Asama</td>
<td>Japan</td>
<td>1783</td>
</tr>
<tr>
<td>&gt;1,335</td>
<td>Taal</td>
<td>Philippines</td>
<td>1911</td>
</tr>
<tr>
<td>1,200</td>
<td>Mayon</td>
<td>Philippines</td>
<td>1814</td>
</tr>
<tr>
<td>1,148</td>
<td>Agung</td>
<td>Indonesia</td>
<td>1967</td>
</tr>
</tbody>
</table>

From Siebert et al., 2010.
Active versus Extinct Volcano

Hazard assessment should be conducted in all volcanic areas in which future eruptions are possible. This begs the question: When should a volcano be considered active or potentially active, and when should it be regarded as definitively extinct? There is no consensus in volcanological literature regarding the definition of active and extinct volcanoes, in part due to the fact that volcanoes exhibit very distinct behavior and eruption frequencies, and may be almost permanently active (e.g., Stromboli, Italy; Pacaya, Guatemala), erupt frequently (e.g., Piton de la Fournaise, La Reunion), or have very long recurrence periods (e.g., El Teide, Canary Islands). Recent examples have shown that volcanoes that have been inactive for hundreds and even thousands of years may suddenly erupt with great violence (e.g., Pinatubo, Philippines; Chaiten and Calbuco, Chile). By contrast, we know of volcanic zones that were active from the Middle Miocene to the early Holocene (e.g., the European rift system): Should they now be considered to be extinct because they have not erupted for several thousands of years? The only unquestionable fact is that we do not yet possess the answer to this question.

In general, people do not consider events on a geological time scale, so in many cases volcanoes that have been quiescent for thousands or tens of thousands of years are considered as extinct and, consequently, as volcanoes that we do not need to worry about. This has led to a variety of definitions of extinct volcanoes: a volcano that has not erupted in historical time (Mercalli 1907), or a volcano that has not erupted during the Holocene (Siebert et al., 2010) or, depending on the type of volcano, during any other given time interval (Szakàcs 1994). Each definition possesses a degree of inaccuracy depending on the geographical area involved (the existence or not of a proper historical record) and/or on the type of volcano. Scandone et al. (2016) have recently proposed that a volcano should be considered active if it may potentially erupt again, that is, as long as the factors that provoke an eruption (the availability of magma and a pathway to the surface) are still operative. This implies that the geodynamic conditions that keep the associated magmatic
system alive (i.e., magma supplied from depth to the volcanic system) are still active. Therefore, volcanoes are classified as “active” when they may potentially become active in the future and as “extinct” when it is impossible for them to erupt again. Likewise, Scandone et al. (2016) suggest classifying volcanoes as “awake” when they have been active in historical times and “dormant” when they have exhibited no such activity.

The definition proposed by Scandone et al. (2016) implies that, in order to decide whether or not volcanoes are potentially active, we need to know the current state of local geodynamic activity or, in other words, are regional tectonics and mantle dynamics still sufficiently well connected to produce magma that will feed the volcanic system? Nevertheless, this concept of active volcanoes suggests that the imposing of time constraints may not be the best way of identifying “dormant” volcanoes that may potentially become active in the near future. This also suggests that it is recommendable to conduct hazard assessment in volcanic areas in which there have been signs of tectonic and volcanic activity in recent times, even if there is no evidence of any eruptions.

**Polygenetic versus Monogenetic Volcanism**

Volcanoes are characterized by a wide variety of forms, tectonic settings, compositions, eruption dynamics, and recurrences. Comparison between volcanoes of similar type are useful for establishing common eruptive patterns and for applying generalised definitions (e.g., Vulcanian, Strombolian, or Plinian) that help describe the behavior of a particular volcano, above all when the volcanoes used to draw comparisons have been studied in great detail. However, it is a mistake to assume that a particular volcano will behave in the same or similar way as another since, up to a point, each volcano has its own traits that distinguish it from all others. This is an important concept in volcanic hazard assessment, as it implies that each volcano needs to be studied individually—we cannot assume that a volcano will behave in a predetermined manner just because it belongs to a particular group of volcanoes. For example, we now know that definitions of eruptive behavior such as effusive, explosive, Strombolian, Plinian, Vulcanian, and Pelean that were assumed to characterize certain types of volcano may on occasions be misleading, since a volcano may exhibit explosive and effusive, and/or Strombolian, Plinian, or Vulcanian behavior during different eruptions or even during the same eruption.

When analyzing volcanoes, the whole geophysical system that they form part of must be taken into account. This means taking into account all the geological processes (i.e., magma generation, ascent, accumulation, differentiation and eruption) that allow magma to reach to the Earth’s surface. All these processes must be studied in the framework of regional geodynamics, and all include a series of complex interactions between fluid (magma) and solid (host rock) mechanics. The capacity for magma to form, migrate, and erupt will depend on the stress conditions of each particular situation or system, which will be chiefly controlled by regional and local tectonics, rock and magma rheologies, density differences between magma and host rock, gravity, and topography. Consequently, if our aim is to decipher why a volcano erupts in one way and not in another, it is best to talk about
“volcanic systems” rather than simply “volcanoes,” thereby placing greater emphasis on the complexity of volcanic systems and the importance of understanding the full sequence of processes involved in the functioning of a volcano.

Two basic types of volcanic systems exist: polygenetic and monogenetic. Polygenetic volcanic systems are those that (1) are active for hundreds of thousands or even millions of years; (2) always produce eruptions from the same central vent or vent system and thus construct large volcanic edifices composed of lavas and volcaniclastic products; and (3) may suffer large gravity-induced instabilities throughout their lives, causing sector collapses. These volcanic systems have eruption frequencies ranging from several tens to thousands of years. Good examples of polygenetic volcanic systems include: (1) shield volcanoes (Mauna Kea and Mauna Loa in Hawaii, Nyamuragira in the Congo, and Fernandina in the Galapagos), generally characterized by broad, low-relief volcanic edifices mostly constructed out of lavas and pyroclasts of mafic composition (Walker, 2000); and (2) composite or central volcanoes or stratovolcanoes (e.g., El Teide in Tenerife, Vesuvius in Italy, Mount St. Helens in United States, Piton de la Fournaise in La Reunion, Mt Fuji in Japan, and Chaiten in Chile), consisting of taller volcanic edifices with more abrupt and steeper slopes composed of lavas and volcanoclastic deposits corresponding to more differentiated magmas (Davidson and De Silva, 2000). In both shield and composite polygenetic volcanoes, caldera collapse episodes may also take place (e.g., Las Cañadas caldera in Tenerife, Somma Vesuvius in Italy, and Aira in Japan), in which the central part of the volcanic edifice is foundered by gravity into the associated magma chamber as it decompresses during the course of an eruption (Geyer and Martí, 2014). Caldera collapse episodes in composite volcanoes tend to be highly explosive and represent the main associated hazard. However, collapse caldera systems that bear no relation to shield or central volcanoes may also occur as a response to tectonic activity affecting areas with active magmatism and volcanism (Aguirre-Diaz et al., 2008; Martí et al., 2009) and have given rise to the largest eruptions that have ever occurred on Earth (e.g., Toba, Indonesia; Cerro Galán, Argentine; La Pacana, Chile; Bolaños, México).

Monogenetic volcanism represents the other end member of volcanic systems and is commonly represented by volcanic fields containing tens to thousands of small volcanoes, each the product of a single eruption. They are usually mafic in composition and represent relatively small volume eruptions that produce cinder cones and lava flows, as well as occasional phreatomagmatic deposits due to the interaction between magma and surface water. Basaltic monogenetic volcanic fields (Michoacan-Guanajuato in Mexico, Auckland in New Zealand, Auvergne in France, and La Garrotxa in Spain) are the commonest type of terrestrial volcanism and may be active for several millions of years, with eruption recurrences ranging from several tens to several tens of thousand of years (Wood, 1980; Walker, 2000; Lorenz, 2007; Le Corvec et al., 2013). The distribution of volcanic cones in basaltic monogenetic fields is clearly controlled by regional and local tectonics. The great variety of eruptive styles, edifice morphologies, and deposits in monogenetic volcanoes are the result of a complex combination of internal (magma composition, gas content, rheology, volume, etc.) and external (regional and local stress fields, stratigraphic and rheological contrasts in substrate rock, hydrogeology, etc.) parameters that help charac-
Assessing Volcanic Hazard: A Review

characterize each volcanic system (Tibaldi and Lagmay, 2006; Valentine and Gregg, 2008; Nemeth, 2010; Martí et al., 2012). Monogenetic volcanoes or monogenetic eruptions (i.e., eruptions that only occur once from a particular vent), however, are not only allied to these basaltic fields, since they may also occur in association with polygenetic volcanoes as flank eruptions as on Teide (Martí et al., 2008) and Etna (Neri et al., 2008) and generate lava flows, domes, and/or pyroclastic deposits of more evolved compositions.

The main difference between polygenetic and monogenetic volcanic systems resides in the presence or absence of a shallow magma chamber and the resulting stress fields that characterize them (Fig. 3). In polygenetic systems a zone where magmas preferentially accumulate and evolve (i.e., a magma chamber) before each eruption forms a few kilometers below the top of the volcano. This magma chamber may change position as the volcano evolves but will tend to stay in the same location if the volcano does not change appreciably in shape or size between eruptions and if there are no significant changes imposed by regional tectonics (Pinel and Jaupart, 2004; Gudmundsson and Brenner, 2005; Martí and Geyer, 2009). The magma chamber exerts a stress field on its surroundings that is superimposed on the regional stress field, thereby controlling potential pathways for magma to the surface. In the crust, magma ascent is usually controlled by fractures opening as a result of magma overpressure, whose orientation will depend on the orientation of the stress field (i.e., usually perpendicular to the minimum and parallel to the maximum compressive stresses). An overpressurised magma chamber forces magma to ascend along a preferential path whose position is dependent on the geometry, volume, and position of the chamber. If these parameters do not change from one eruption to the next, the magma’s pathways to the surface will tend to not vary either (Pinel and Jaupart, 2004; Gudmundsson and Brenner, 2005).

By contrast, in monogenetic volcanic systems magma does not accumulate in shallow reservoirs or chambers and tends to rise to the surface from greater depths, usually from the base of the crust or even from the source region or shallower levels in the mantle. Thus, the stress field controlling the magma ascent will only depend on the stress distribution inside the lithosphere and, in particular, on the stress barriers corresponding to rheological and/or structural discontinuities (Menand, 2008, 2011; Gudmundsson, 2011;
Maccaferri et al., 2011; Bolós et al., 2015; Martí et al., 2016). Locally, the stress field may change from one eruption to the next simply because previous intrusions may solidify and block a fracture, thereby creating a new stress barrier that prevents the magma from following the same path as on previous occasions. In fact, examples such as La Garrotxa Volcanic Field in NE Spain (Bolós et al., 2015) illustrate how, despite the existence of a constant, common feeding system at depth during the whole lifetime of the volcanic system, the location of each new eruption is controlled by subordinate shallow fractures that capture magma during the final stages of its ascent to the surface, and thus determine the exact point of eruption. The shallow character of these fractures suggests that the local (shallow) stress field does not have the same control as fractures at much greater depths. Under these circumstances, these shallow fractures can be easily sealed by residual magma that solidifies therein, which thus means that for a subsequent eruptive episode it will be easier to open a new fracture than to reuse a previously sealed one. This coincides with one of the most common features of monogenetic volcanic fields—the formation of proximal clusters of vents in eruptions of the same relative age, which means that in eruptions produced under the same regional stress field, vents will tend to aggregate in the same area but not at the same point.

The explanation of the monogenetic eruptions that sometimes occur on the flanks of central volcanic edifices, forming what are known as parasitic cones, may be analogous to the case of basaltic fields: A possible change in the position of the magma chamber or to the formation of a subordinate batch of magma creates its own stress field, thereby modifying the stress trajectories defined by the main (or the previous) magma chamber (Martí and Geyer, 2009).

The ability of a volcanic system to form shallow magma chambers that control stress distribution at shallower levels and thus, the position of eruption vents seems to be linked to the complex relationship existing between magma production and ascent rates, lithosphere structure, and the regional and local tectonics in each particular geodynamic setting in which magmatic and volcanic systems develop (Jellinek and De Paolo, 2003; Gudmundsson, 2011). A more in-depth discussion of this topic is beyond the scope of this review. Needless to say, the difference between polygenetic and monogenetic volcanic systems and the influence of regional and local stress fields in determining, in each case, where a new eruption will occur are crucial in volcanic hazard assessment, as they determine the position of the potential vent for the next eruption and, consequently, the most probable eruption scenarios in each case.

**Direct and Indirect Volcanic Hazards**

Volcanic hazards are inherently complex, difficult to predict, rarely present a single hazardous threat, and often result in cascading risks. Volcanic hazards are the toughest geophysical hazards to assess due to their intrinsic multi-factor nature, in which different volcanic (lavas flows, fallout, lahars, and pyroclastic flows) and associated hazards (seismic shocks, landslides, tsunamis, and floods) interact or impact sequentially (Table 2). The
cascading impact of volcanic hazards may also lead to successive failure in services. Therefore, when evaluating the potential impact of volcanic eruptions it is essential to consider their multi-hazard nature and the possibility that such hazards may become cascading events with similarly cascading consequences. This implies that we must develop knowledge of their cause–effect relationships and not treat each hazard individually as a separate event. The first step in a hazard assessment process is thus to understand what direct and indirect hazards can derive from a volcanic eruption (Fig. 4).

*Figure 4* Causes/effects relationships between the main direct and indirect volcanic hazards (see Table 2)
<table>
<thead>
<tr>
<th>Type of Hazard</th>
<th>Hazard</th>
<th>Nature and Main Characteristics</th>
<th>Main Physical Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct hazards</td>
<td>Lava flows</td>
<td>Nonfragmented magma, continuous non-Newtonian flow</td>
<td>Gravity, topography, temperature, viscosity, eruption rate</td>
</tr>
<tr>
<td></td>
<td>Ballistics</td>
<td>Particles ejecta directly from the vent during explosive phases, ballistic emplacement</td>
<td>Gravity, density, air friction, explosion intensity, ejecta angle</td>
</tr>
<tr>
<td></td>
<td>Fallout</td>
<td>Magma and rock fragments transported into the atmosphere by eruption clouds, deposited as individual particles</td>
<td>Gravity, density, particle size and shape, air friction, atmosphere structure (density and viscosity), diffusivity, wind velocity</td>
</tr>
<tr>
<td></td>
<td>PDCs (dilute)</td>
<td>Magma and rock fragments deposited in mass, transported by highly turbulent, gas-rich pyroclastic density currents formed by gravitational collapse of eruption columns, gravitational collapse of domes and lavas, or laterally directed blast explosions</td>
<td>Gravity, grain-size distribution, momentum, temperature, particle/gas ratio, juvenile pyroclasts/lithics ratio, topography, flow regime, total mass</td>
</tr>
<tr>
<td>PDCs (dense)</td>
<td>Magma and rock fragments deposited in mass, transported by turbulent to laminar, gas-rich to gas-poor pyroclastic density currents formed by gravitational collapse of eruption columns, or gravitational collapse of domes and lavas</td>
<td>Gravity, grain-size distribution, temperature, momentum, particle/gas ratio, juvenile pyroclasts/lithics ratio, topography, flow regime, total mass</td>
<td></td>
</tr>
<tr>
<td>Lahards</td>
<td>Slurry of pyroclasts, rock debris and water that originates on the slopes of volcanoes during eruptive activity. Water comes from melting of ice and snow by hot volcanic ejecta; crater lakes and other surface waters; water in the groundwater and geothermal systems; and torrential rains.</td>
<td>Gravity, topography, solid/water ratio, grain-size distribution, yield strength</td>
<td></td>
</tr>
<tr>
<td>Debris avalanches</td>
<td>Rockfalls, rockslides, and debris avalanches, which can move rapidly downslope and which originate immediately before, during, or immediately after an eruption</td>
<td>Gravity, topography, bulk density</td>
<td></td>
</tr>
<tr>
<td>Floods</td>
<td>Low-density, normal stream flows primarily that may originate from lahars when they reduce particle concentration of syn-eruptive heavy rainfall</td>
<td>Gravity, topography, grain size, water content, yield strength, bulk density</td>
<td></td>
</tr>
</tbody>
</table>
Volcanic gases | Magmatic gases that mix with atmospheric air | Density, temperature, meteorological conditions, atmospheric properties
---|---|---
Phreatic explosions | Explosive disruption of shallow hydrothermal systems, mostly generating ballistic eject and relatively short ash clouds | Gravity, density, air friction, explosion intensity, ejecta angle
Indirect hazards | Earthquakes | Ground shaking and movements caused by seismic shocks of magnitudes usually <5, associated with magma movement and readjustment of the volcanic systems during eruptions
---|---|---
Tsunamis | Long period, shallow water waves generated by the sudden displacement of water caused by volcanic or volcano-tectonic earthquakes, volcanic explosions, or collapse or subsidence of volcanic edifice, or debris avalanches, lahars, or pyroclastic flows entering water bodies | Gravity, shoreline and bathymetric configuration, the velocity of the sea floor deformation, the water depth near the impact source, and the efficiency with which energy is transferred from the impact (volcanic explosion, edifice collapse, earthquake, ...) to the water column.
<table>
<thead>
<tr>
<th>Secon­daris de­bris flows</th>
<th>Slurry of pyroclasts, rock debris, and water that originates on the slopes of volcanoes after a volcanic eruption</th>
<th>Gravity, topogra­phy, solid/water ra­tio, grain-size dis­tribution, yield strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posterup­tion ero­sion and sedimen­ta­tion</td>
<td>In mass remobilization of volcanic material by heavy rainfall and other posteruption causes</td>
<td>Gravity, topogra­phy, grain size, wa­ter content, yield strength, bulk den­sity</td>
</tr>
<tr>
<td>Atmospheric ef­fects</td>
<td>Local changes of at­mospheric dynamics (rainfall, shock waves, lighting) caused by the entrance of ash parti­cles and gases into the atmosphere surrounding the erupting vol­cano</td>
<td>Eruption cloud characteristics, at­mosphere char­acteristics</td>
</tr>
<tr>
<td>Climatic ef­fects</td>
<td>Regional to global ef­fects on climate caused by the formation of aerosols by the injection of volcanic gases and ash particles in the high atmosphere</td>
<td>Size of the erup­tion, columns height, gases com­position, total mass injected, winds strength and direc­tion</td>
</tr>
<tr>
<td>Famine and de­sease</td>
<td>Destruction of food supply by the immediate loss of livestock and crops, and by the longer term (years to decades) loss of agricul­tural productivity of farm lands buried by eruptive materials.</td>
<td>Size of the erup­tion, columns height, gases com­position, total mass injected, atmo­sphere structure and dynamics, winds strength and direc­tion</td>
</tr>
</tbody>
</table>
### Aircraft encounters with volcanic ash

Ingestion of silicate ash into the aircraft’s jet engines when operating in volcanic ash clouds. Ash ingestion degrades engine performance and, in the worst case, causes engine flame out and loss of power.

<table>
<thead>
<tr>
<th>Aircraft encounters with volcanic ash</th>
<th>Ingestion of silicate ash into the aircraft’s jet engines when operating in volcanic ash clouds. Ash ingestion degrades engine performance and, in the worst case, causes engine flame out and loss of power.</th>
<th>Engines characteristics, grain size, composition and shape of ash particles, concentration of ash in atmospheric air</th>
</tr>
</thead>
</table>

Adapted and expanded from Blong, 1984 and Tilling, 2005).
Intuitively, explosive eruptions have the potential to produce more serious hazards than effusive eruptions. Although this is true in most cases, we must take care when conducting hazard assessment, since it is crucial to fully appreciate all the physical phenomena driving such a large diversity of potential outcomes. The reconstruction of the past eruptive history of a volcano and a comprehensive understanding of the physics of volcanic processes allow us to identify the possible eruption scenarios that a volcano may produce, and to determine which have been the most frequent in the past and so may be the most probable in the future. This is the essence of volcanic hazard assessment.

Hazardous events occurring during or shortly after an eruption (i.e., within minutes to several days) are regarded as direct volcano hazards (Tilling, 2005) and include lava flows, lava domes, tephra fallout, ballistic projectiles, pyroclastic density currents (PDCs), lahars, sector collapses, and the emission of volcanic gases.

Lava flows constitute the commonest volcano hazard resulting from a nonexplosive eruption, especially in basaltic systems (Tilling, 2005). These flows come in many shapes and sizes and have a wide range of surface morphology (pahoehoe, aa, blocky, etc.), whose differences are mainly controlled by variations in magma viscosity and supply rates at the time of the eruption. The principal constraint on lava emplacement is topography, therefore flows will tend to invade the lowest lying areas. Viscosity depends on magma composition, gas content, crystallinity, and temperature, and rises as the silica content increases: Lavas from mafic magmas (basaltic) are less viscous (more fluid) than those originating from more evolved magmas. Differences in viscosity, effusion rates and ground slopes will determine the initial thickness of a lava flow and the total distance it extends. At low effusion rates (<10 m$^3$/sec), basaltic lava tends to produce many small flows that puddle and pile up near the vent, whereas at higher rates (101–103 m$^3$/sec) flows can move tens of kilometers and cover hundreds of square kilometers at velocities of up to several kilometers per hour (Tilling, 2005). In some extreme cases, such as the Columbia River Basalts in the United States, the flow discharge rate has been estimated at $1 \times 10^6$ m$^3$/sec, and the resulting lava flows cover tens of thousands of square kilometers (Swanson et al., 1975).

More viscous magmas (e.g., andesite, dacite, rhyolite, phonolite) may also form lava flows, which tend to be shorter and thicker than basaltic lava flows, when they are sufficiently degassed. Normally, when they erupt effusively, these magmas have much lower effusion rates than mafic magmas and the resulting lava flows emplace at much lower velocities, at up to several hundreds of meters per hour. On occasions, the effusive emplacement of viscous magmas may give rise to the formation of lava domes over the vent area or even almost solidified spines or plugs extruding from eruption conduits.

When lava flows emplace at relatively low velocities they do not represent a significant hazard for people or animals. However, they are highly hazardous for property and infrastructures due to their highly destructive capacity—the bulldozer effect—and their high temperatures. When emplacing over snow or ice, which they melt, they can cause highly destructive inundations known as jökulhlaups (from their name in Icelandic).
During explosive eruptions magma is fragmented and expelled into the atmosphere as fragments known as pyroclasts or tephra that take on different forms (e.g., angular, rounded or subrounded) and range in size from microns to meters across. As well, the rocks that form the walls of the eruption conduit may be partially fragmented and ejected with the erupting magma, therefore varying proportions of cold solid rock may be thrown out with magma fragments during explosive eruptions. Large fragments fall back to the ground in the proximity of the volcanic vent (proximal hazards), whereas finer fragments—ash-size particles—are carried away by the wind (distal hazards) and may cover large areas. The largest fragments (bombs and blocks) tend to be ejected ballistically and emplace around the vent at a maximum distance of a few kilometers. Finer fragments are incorporated into the mixture of gases and tephra expelled by the eruption conduit and form an eruption column reaching from a few hundred meters to several tens of kilometers in height, depending on the initial kinetic energy of the jet, the mass eruption rate and the capacity of the mixture to become buoyant due to the entrainment, heating, and expansion of atmospheric air (Wilson et al., 1978) (Fig. 5). The highest part of the column is transported by winds for distances that depend on wind velocity, the column height and the size and density of the tephra fragments. Tephra typically becomes finer-grained and forms thinner deposits as it travels 10s to 1,000s km downwind from the eruptive vent.
The size of the area covered by a tephra fall depends on the magnitude (total erupted mass) and intensity (mass eruption rate) of the eruption and the wind strength and direction. These areas will vary in size from just a few tens to hundreds of thousands of square kilometers, and the largest eruptions can even affect whole continents. The hazard represented by tephra fall will depend on the thickness of the deposits that accumulate on the ground, and will affect plants, animals, properties, infrastructures, and population to different extents, depending on the vulnerability of each particular element (Blong, 1984; Ayris and Delmelle, 2012). Nevertheless, significant destruction only generally results in areas affected by tephra fall that is several centimeters thick, which causes roofs to collapse, interrupts power networks, disrupts human infrastructures (e.g., water, waste-treatment, power, transportation, and communication systems) and damages or kills vegetation including crops (Blong, 1984; Tilling, 2005; Ayris and Delmelle, 2012). The significant amount of noxious gases and other components carried by tephra, which represent
an important health hazard for persons and animals, must also be taken into account (Blong, 1984; Baxter, 1990). Moreover, volcanic ash in the atmosphere can contaminate large volumes of airspace and remain suspended for days to weeks and presents a hazard to aircraft in the air as well as communities on the ground (Casadevall, 1994).

On occasion, eruption columns become unstable due to changes in the eruption dynamics and all or part of them lose their buoyancy; this causes the column to collapses and generates gravitational currents of hot pyroclasts and gases that flow away from the vent at great velocities controlled by topography (Sparks et al., 1978; Druitt, 1998; Parfitt and Wilson, 2008). These tephra flows—known as PDCs—constitute the potentially most dangerous proximal volcanic hazard due to their high emplacement velocities, great temperatures and transport capacity, and their overall destructive capacities. However, PDCs do not only form after column collapse and may also occur directly after explosions of silicic magmas, phreatomagmatic eruptions of mafic magmas, or through the gravitational collapse of viscous lava domes and flows, and in all cases represent a significant hazard for affected areas. PDCs are suspension currents that range from highly dilute to highly concentrated, and from highly turbulent to laminar, and their mobility and runout distances will depend on the initial momentum of the flow, particle concentration, temperature, and the flow regime (Druitt, 1998). The total distances travelled by PDCs vary from a few to more than 100 kilometers. The affected area will either be restricted to the main valleys and gullies around the volcano or will embrace larger areas whose extent will depend on the parameters—the initial density, temperature, and velocity of the flow—that control its ability to overcome topographic barriers. Unlike lava flows, the main impact of PDCs on static and moving objects is exerted by dynamic pressure (Pittari et al., 2007), which is directly dependent on their density and velocity. In addition, PDCs may cause asphyxiation, burial, and incineration or, as occurs with lavas, may mix with surface water or snow- and ice melt to form secondary explosions and/or destructive lahars and floods that affect valleys farther downstream (Tilling, 2005).

Lahars or volcanic mudflows are flows of poorly sorted heterogeneous debris, primarily consisting of volcanic rocks of all sizes mixed with water (Crandall, 1971; Vallance, 2000). Such flows are called primary when they occur during eruptive activity and secondary when they are posteruption (Tilling, 2005). The water that transports debris in lahars derives from ice or snow melted by hot tephra, surface water (e.g., rivers or lakes), geothermal water, rainfall, or even condensation from water vapor in the PDCs. Like PDCs, lahars vary in terms of the amount of solid particles they transport and range from very dense to very dilute; likewise, their emplacement characteristics and mobility will depend on the flow density (Crandall, 1971; Vallance, 2000; Tilling, 2005). Lahars are very destructive volcanic hazards that are usually confined to the valleys and gullies draining the volcano. They may reach velocities of several tens of meters per second and travel hundreds of kilometers in distance (Lavigne et al., 2000; Vallance, 2000).

Another important direct volcanic hazard is the volcanic debris avalanches caused by a sector collapse of a volcanic edifice: Gravitational instability triggered by the emplacement of magma below the surface, a seismic shock or heavy rainfall can cause large
masses of rock and soil to fall, slide or flow very rapidly down the slopes of the volcano (Ui et al., 2000). These events may occur during the course of an eruption, as occurred on May 18, 1980 on Mount St. Helens in the United States (Voight et al., 1981). Due to the steep slopes that characterize many large volcanoes, such avalanches are often highly mobile and can run for several tens of kilometers (Siebert, 1996). They are highly destructive and often produce indirect hazards such as water waves or tsunamis when they come into contact with lakes or the sea.

Finally, it is also important to consider the direct volcanic hazards derived from the presence of poisonous gases in erupting magmas (Williams-Jones and Rymer, 2015). During volcanic eruptions, gases such as CO$_2$, CH$_4$, SO$_2$, F, and Cl may occur in proportions dependent on magma composition. They may be present at the vent or be associated with other volcanic products, or be incorporated into the eruption columns and be transported away by winds, mixed in with fine ash particles. Their toxicity and concentration will define the potential hazard that they represent.

In addition to these direct hazards, volcanic eruptions may also involve a range of phenomena—some associated with eruptions, some not—that also need to be taken into account when conducting volcanic hazard assessment. These may include (Table 2) (Blong, 1984; Tilling, 2005) ground tremors and movements caused by volcanogenic earthquakes; tsunamis generated by eruption-induced collapse, debris avalanche, or the slump of a volcanic edifice; “secondary” debris flows and floods triggered by heavy rainfall and other post-eruption factors; post-eruption erosion and sedimentation; atmospheric effects (electrical discharges, shock waves); climate change; post-eruption famine and disease; and, in recent decades, damage to aircraft flying through volcanic ash clouds. The possibility that these phenomena will occur is part of any hazard analysis. In particular, it is crucial to investigate the potential cause and effect relationships between direct and indirect hazards, as they may increase the vulnerability of the element exposed when a different sequence of hazards impact on the same area, thereby increasing the volcanic risk.

Most direct and indirect volcanic hazards have predictable impacts during or shortly after an eruption. However, some indirect impacts may occur and persist long after the eruption has ceased, of which the most significant are the atmospheric and climate changes caused by the expulsion of volcanic ash and gases (mainly SO$_2$) into the high atmosphere during highly explosive eruptions (Tilling, 2005; Self, 2005). SO$_2$ forms an aerosol layer of sulphuric acid droplets, which tends to cool the troposphere by reflecting solar radiation and to warm the stratosphere by absorbing radiated heat from the Earth. The 1815 Tambora eruption in Indonesia, which led to the so-called “Year Without Summer” in 1816, marked by severe frosts in July and crop failures, is a good example of this effect (Stommel and Stommel, 1983).
Size and Duration of Volcanic Eruptions

An intrinsic concept that is usually taken for granted by experts and nonexperts alike when discussing hazardous natural phenomena is that larger and longer events will generate greater hazards and so have greater implicit risk. In volcanology this is true for the size (magnitude) of the eruption but not necessarily for the duration. In fact, large explosive eruptions tend to be much shorter than small eruptions in monogenetic volcanoes. This is because the intensity (eruption rate) is much larger in the first than in the second case. These two concepts—the magnitude and intensity of volcanic eruptions—are important when assessing hazard and are discussed in the following text.

The magnitude of a volcanic eruption indicates the size (but not its total energy, as is the case of earthquakes) of the eruption and is expressed as the total mass of magma erupted calculated on a logarithmic index of magnitude, defined as: magnitude = log\(_{10}\) (erupted mass, kg) - 7 (Pyle, 2000). The intensity of volcanic eruptions is a measure of the amount of material erupted per unit of time, and is measured by a similar logarithmic index defined as: intensity = log\(_{10}\) (mass eruption rate, kg/s) + 3 (Pyle, 2000). In the case of magnitude, the total volume of magma erupted is measured as dense rock equivalent, that is, the volume of dense magma (molten rock) without gas bubbles or lithic fragments derived from the country rock. However, when calculating the intensity we must bear in mind all the material (vesiculated magma, gas, rock fragments) erupted per unit of time. Normally, in explosive eruptions there is a correspondence between magnitude and intensity such that larger eruptions have higher intensities. As well, there is a positive correlation between intensity and the height of the eruption column that normally accompanies these eruptions, and larger intensities imply taller eruption columns. However, this may not be the case in effusive eruptions in which larger erupted volumes do not necessarily imply higher eruption rates or the presence of eruption columns.

Newhall and Self (1982) proposed an index for ranking the degree of explosiveness of volcanic eruptions that combines magnitude and intensity. These authors’ Volcanic Explosivity Index (VEI) is used to classify volcanic eruptions on a logarithmic scale from 0 to 8 and to calculate their potential hazard (see Table 3), given that larger, highly explosive eruptions have a much higher destructive potential than small, poorly explosive ones. This implies that eruptions with higher VEIs generate hazards that will have a greater impact on potentially affected elements, and will cover wider surface areas and reach further. This is why VEI is used as a standalone indicator of the degree of potential hazard.
### Table 3 Volcano Explosively Index

<table>
<thead>
<tr>
<th>VEI</th>
<th>Ejecta Volume (bulk)</th>
<th>Classification</th>
<th>Description</th>
<th>Plume height</th>
<th>Frequency</th>
<th>Troposphere injection</th>
<th>Ionosphere injection</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&lt;10,000 m³</td>
<td>Hawaiian</td>
<td>Effusive</td>
<td>100 m</td>
<td>constant</td>
<td>negligible</td>
<td>none</td>
<td>Kīlauea, Piton de la Fournaise, Erebus</td>
</tr>
<tr>
<td>1</td>
<td>&gt;10,000 m³</td>
<td>Hawaiian / Strombolian</td>
<td>Gentle</td>
<td>100 m–1 km</td>
<td>daily</td>
<td>minor</td>
<td>none</td>
<td>Nyiragongo (2002), Raoul Island (2006), Stromboli Island—(continuous since Roman times to present)</td>
</tr>
</tbody>
</table>
### Assessing Volcanic Hazard: A Review

<table>
<thead>
<tr>
<th>Category</th>
<th>Volume</th>
<th>Type</th>
<th>Distance</th>
<th>Frequency</th>
<th>Intensity</th>
<th>Hazard</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>&gt;100,000 m³</td>
<td>Strombolian / volcanian / Hawaiian</td>
<td>1-5 km</td>
<td>weekly</td>
<td>moderate</td>
<td>none</td>
<td>Unzen (1792), Cumbre Vieja (1949), Galeras (1993), Sinabung (2010)</td>
</tr>
<tr>
<td>3</td>
<td>&gt; 10,000,000 m³</td>
<td>Vulcanian / Peléan / Sub-Catastrophic</td>
<td>3-15 km</td>
<td>few months</td>
<td>substantial</td>
<td>possible</td>
<td>Nevado del Ruiz (1985), Soufrière Hills (1995), Nabro (2011)</td>
</tr>
<tr>
<td>No.</td>
<td>Volume (km³)</td>
<td>Type</td>
<td>Distance (km)</td>
<td>Duration (yr)</td>
<td>Magnitude</td>
<td>Relevance</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>--------------</td>
<td>-----------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>-----------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>&gt;0.1</td>
<td>Peléan / Plinian/Sub-plinian</td>
<td>&gt;10</td>
<td>≥1</td>
<td>Substantial</td>
<td>Definite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cataclysmic</td>
<td>Plinian or sub-Plinian</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>&gt;1</td>
<td>Peléan/Plinian</td>
<td>&gt;10 Plinian</td>
<td>≥10</td>
<td>Substantial</td>
<td>Significant</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paroxysmic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mayon (1814), Pelée (1902), Galunggung (1982), Eyjafjallajökull (2010), Vesuvius (79), Fuji (1707), Tarawera (1886), St. Helens (1980), Puyehue (2011)
<table>
<thead>
<tr>
<th></th>
<th>&gt;10 km³</th>
<th>Plinian / Ultra-Plinian/ Ignimbrite</th>
<th>Colossal</th>
<th>&gt;20 km</th>
<th>≥100 yrs</th>
<th>substantial</th>
<th>substantial</th>
<th>Veniaminof (c.1750 BC), Huaynaputina (1600), Krakatoa (1883), Novarupta (1912), Pinatubo (1991)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>&gt;100 km³</td>
<td>Ultra-Plinian/ Plinian/ Ignimbrite</td>
<td>Super-colossal</td>
<td>&gt;20 km</td>
<td>≥1,000 yrs</td>
<td>substantial</td>
<td>substantial</td>
<td>Mazama (c. 5600 BC), Thera (c. 1620 BC), Mount Rinjani (1257), Tambora (1815)</td>
</tr>
</tbody>
</table>
## Assessing Volcanic Hazard: A Review

<table>
<thead>
<tr>
<th>VEI</th>
<th>Volume (km³)</th>
<th>Eruption Type</th>
<th>Distance (km)</th>
<th>Age (yrs)</th>
<th>Size</th>
<th>Size</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>&gt;1,000 km³</td>
<td>Ignimbrite/Plinian/Ultra-Plinian</td>
<td>&gt;20 km</td>
<td>≥10,000 yrs</td>
<td>vast</td>
<td>vast</td>
<td>La Garita caldera (26.3Ma), Yellowstone (640,000 BC), Toba (74,000 BC), Taupo (24,500 BC)</td>
</tr>
</tbody>
</table>

VEI, Volcano Explosively Index.

Adapted from Newhall and Self, 1982, Siebert et al., 2010, and VEI glossary entry, 2015.
Assessing Volcanic Hazard: A Review

The other concept required in hazard evaluation is the duration of the volcanic eruption, which in some ways works in an opposite sense to the magnitude and intensity scales: The most voluminous and intense paroxysmal eruption phases tend to last less time (from a few hours to a few days, see Simkin and Siebert, 2000), while some small, nonexplosive eruptions may continue for several weeks or even months or years.

Long-Term versus Short-Term Hazard Assessment

In hazard assessment, it is imperative to distinguish between long- and short-term assessments, which can be defined in terms of the expected characteristic time in which the process displays significant changes. Long-term assessment is based on historical and geological data, as well as on simulation models of possible hazards, and refers to the available time window before an unrest episode occurs in a volcanic system that currently shows no signs of unrest (Marzocchi et al., 2010; Sobradelo et al., 2013). Long-term hazard assessment is basically used for territorial planning and defining emergency plans. By contrast, short-term assessments concentrate on the unrest phase, when complementary information resulting from the combination of long-term analysis and real-time monitoring data is used to update the status of the volcanic hazard (Blong 2000; Marzocchi et al., 2008; Sobradelo and Martí, 2015; Bartolini et al., 2016). Short-term evaluation helps forecast where and when the eruption will take place and the most likely eruptive scenarios to result from such an eruption.

Long-term volcanic hazard assessment uses quantitative analysis of past volcanic activity—as well as geological mapping and structural and petrologic studies—and a determination of the physical volcanological parameters of past eruptions to model possible hazards and eruption scenarios. These parameters include, among others, magma volume and rheology, mass discharge rates, and pre-eruption volatile content of the feeding magma. Therefore, once all the relevant geological information has been gathered, we are in a position to establish how a volcanic system has behaved in the past, when it became active, and identify all possible eruption scenarios that the system has produced.

Short-term hazard assessment is undertaken when the volcano enters an unrest phase (i.e., a reactivation marked by an increase in volcanic activity above background level) and consists of long-term hazard assessment complemented by continuous up-to-date monitoring data. When a new episode of volcanic unrest occurs, scientists’ main concern is to forecast whether or not the increase in activity will lead to an eruption and, if so, which eruptive scenario is most likely (Selva et al., 2014; Sobradelo and Martí, 2015; Bartolini et al., 2016). Continuous monitoring can identify the different stages in the evolution of an unrest episode by detecting increases in activity revealed by changes in monitored geophysical and geochemical parameters. However, determining when these parameters will peak or pass a threshold, after which point an eruption is inevitable, is at present all but impossible. Every volcano has its own characteristics (internal structure, rock rheology, magma composition, etc.) that generate different maximum values or
thresholds for the monitored parameters before it erupts. The same volcano may even behave differently each time it erupts, and its eruptive episodes may be preceded by unrest periods that differ from the patterns that occurred during the evolution of previous eruptions. The situation is even more complex in the case of volcanoes that have been dormant for long periods and have not erupted in historical time, since no records will exist to suggest how a future eruption should be prepared for.

The evolution of an unrest episode will depend on the causes of the unrest (magmatic, tectonic or geothermal), which will give different outcomes (magmatic eruption, phreatic explosion, sector failure or others) in a range of locations with different possible eruption magnitudes, products, scope, etc. (Sobradelo and Martí, 2010, 2015). Each particular scenario is expected to result from a particular pattern in precursory activity. However, there are factors in each scenario that cannot be anticipated merely by studying monitoring data, but which can be projected by examining the products of past events. Thus, precise eruption forecasting needs to be based on a combination of previously acquired long-term hazard assessment and real-time volcano monitoring data.

Spatial and Temporal Analyses

As indicated, the definition of a volcanic hazard implies a calculation of the spatial and temporal probabilities that a new volcanic event—and its resulting impact—will take place. Therefore, hazard assessment must attempt to identify the main physical mechanisms controlling the predicted phenomena that will determine their extent, potential impact, and destructive capacity, as well as the time framework in which they occur.

Spatial analysis aims to determine the position of vents based on knowledge of past eruptions, the existence of structural controls on vent distribution, the characterisation of products from previous eruptions, and their spatial interrelations (Felpeto et al., 2007; Martí and Felpeto, 2010; Bartolini et al., 2013). This information will provide the basis for establishing the probability of vent opening (i.e., volcanic susceptibility) and the probability of invasion (i.e., laterally and longitudinally) by new eruptive products. Temporal analysis complements spatial analysis by establishing the relative temporal position of each eruption (volcanic stratigraphy) and, whenever possible, its geochronology by means of radiometric dating. This enables us to identify temporal patterns in the eruptive behavior of the volcanic system such as clusters of eruptions or episodes of quiescence between eruptions and, if absolute ages are available, the eruption frequency or recurrence (i.e., the temporal probability of an eruption) (Sobradelo et al., 2013).

Field studies of the products of past eruptions aim to identify the type of eruptions that a volcanic system has generated in the past, characterize the succession of volcanic deposits represented in each eruption, and reconstruct the sequence of eruptive and depositional events that formed them (Cas and Wright, 1987; Martí and Folch, 2005). Volcanological field studies aim to determine the relative stratigraphy (or geochronology) and distribution of the different units that form a particular eruption sequence. A volcanic eruption may encompass several phases and pulses, each giving rise to different prod-
ucts; for example, an eruption may produce a Plinian column, which generates units of fallout deposits and then, as its collapses, produces PDCs of differing characteristics. The deposits produced by each phase or pulse will exhibit different lithological, sedimentological, and stratigraphic characteristics, and be distributed at different sites around the volcano. Plinian fallout deposits will be widely distributed and tend to mantle the surrounding topography, while PDC deposits habitually accumulate in low-lying areas. After deposition, eruptive products may be affected by other geological processes (e.g., erosion, reworking, and resedimentation) and form secondary volcanic deposits (e.g., Pinatubo 1991 eruption, Philippines; Newhall and Punongbayan, 1996). Primary and secondary deposits from a particular eruption appearing in the geological record may exhibit complex stratigraphic relationships that depend on the characteristics of the eruption, topography, and environment in which the eruption took place.

Field studies aim to provide the necessary information for identifying the products and phases of a particular eruption, and to separate them from nonvolcanic processes (Cas and Wright, 1987; Martí and Folch, 2005). Geological mapping can be used to determine the areal distribution of volcanic units at regional to local scales, depending on the size of the eruption, and will determine which combination of photogeological or remote sensing and direct field reconnaissance is required. Stratigraphic correlations are necessary to confirm the distribution of deposits and also to characterize lateral variations in thickness, geometry, and lithology occurring in each unit or facies. Stratigraphic studies are also important for distinguishing groups of deposits from different eruptions or volcanic centers, and for establishing their relative geochronology. Field lithological studies of volcanic deposits are needed to design appropriate sampling policies for related mineralogical and geochemical studies. Moreover, identifying sedimentological characteristics such as grain size distribution and sedimentary structures is crucial when determining the emplacement mechanisms of deposits. Where direct observation of an eruption is lacking, a clear interpretation of the lithological nature and stratigraphic position of each volcanic deposit will provide the basis for understanding a particular eruption and predicting a volcano’s potential future behavior (Martí and Folch, 2005).

Understanding the sequence of deposits resulting from a volcanic eruption becomes ever more complex as the age of the deposits increases, since posteruptive processes may remove or transform the primary deposits, and products from other eruptions can become incorporated into the stratigraphic sequence (Cas and Wright, 1987; Smith, 1987). Stratigraphic criteria such as widespread paleosoils or erosion and alteration surfaces that permit the unequivocal recognition of eruption sequences are thus desirable. Such criteria can also be useful when reconstructing the long-term evolution of volcanic systems, identifying volcanic cyclicity, and for making future volcanic activity more predictable. Stratigraphic correlations between outcrops are also necessary to identify the provenance and thickness variations in volcanic deposits. In this case, the use of isopachs and isopleth maps are useful for constraining the source vent for each deposit (Cas and Wright, 1987). However, the exact location of eruptive vents cannot always be identified,
particularly in complex volcanic fields where the activity of several volcanoes may coincide in both time and space.

Although stratigraphic studies are vital, the determination of the absolute age of a volcano’s deposits will help greatly in the reconstruction of its eruptive history. Absolute age determinations, typically estimated using isotopic compositions, allow us to identify different eruptions and possible cycles of eruptions. However, the determining of the absolute age of a deposit is not always possible, and will depend on the dating technique used and the nature and alteration state of the sample. The establishment of the relative age scheme of a group of volcanic products using volcanic stratigraphy methods (Groppelli and Martí, 2013) should thus always be undertaken before radiometric methods are used to determine the chronology of a sequence.

Structural studies of active volcanoes represent another important subject in hazard-oriented studies. The pathways used by magma as it rises to the surface and opens eruptive vents are controlled by geological discontinuities and local and regional stress configurations (Martí and Felpeto, 2010). In general, the stress regime and fracturing style are modulated by a combination of regional and local stress fields. The local stress of volcanic edifices is, in turn, controlled by a combination of the force of gravity and the underground pressure of magma. Regional stress and fracturing also provide important pathways for the rise of magma stored at depth or in magma chambers located at shallow crustal level, as occurs, for instance, beneath caldera structures (Martí and Geyer, 2009; Martí and Felpeto, 2010; Menand, 2011; Gudmundsson, 2011).

Petrologic studies are also a well-established fundamental component of basic methods of assessing volcanic hazards (Martí and Folch, 2005; Cashman and Sparks, 2013). They contribute substantially to the definition of magma rheology and the way the feeding system of the volcanic edifice works. The definition of a conceptual model of how magma rises, is stored, and reaches the surface puts precise limits on the “degree of freedom” of a volcano’s eruptive style (Pallister et al, 2008; Andujar et al., 2010). In general, good petrological knowledge of a volcanic system (including the nature and behavior of the volatile components) should provide valuable information on the eruptive behavior; given that the feeding system represents the “engine” of the volcano (Cashman and Blundy, 2000; Blundy and Cashman, 2008). Thus, a good match between volcanological and petrological knowledge is an important indication that the conceptual models adopted to explain eruption behavior are reliable. It is, however, important to note that the true value of petrological studies is directly correlated to their integration into stratigraphic and structural studies, that is, sampling must be conducted on all the eruptive units that erupted during a predefined time interval.

**Susceptibility Analysis**

Volcanic susceptibility (Martí and Felpeto, 2010) is an essential part of spatial analysis and consists of determining the spatial distribution of future vents based on the distribution of past vents. When conducting volcanic hazard assessment, it is important to deter-
mine which points in the area of interest may host new vents, given that the location of the vent will govern possible eruptive scenarios. As commented in the discussion of polygenetic and monogenetic volcanic systems, composite volcanoes tend to erupt through central vents, while monogenetic systems tend to have an apparently random distribution of vents. However, when we look in detail at both systems we observe that this generalisation is not quite as accurate as it may seem. In fact, many composite volcanic systems such as El Teide in Tenerife (Martí and Felpeto, 2010; Martí et al., 2012) and Etna in Sicily (Cappello et al., 2012) have produced eruptions from both central and parasitic vents situated on their flanks, with similar frequencies in both cases. As well, clusters of vents may appear in monogenetic systems if their spatial distribution is analyzed under a temporal perspective (Martin et al., 2004; Connor et al., 2000; Connor and Conway, 2000; Gailbaud et al., 2012; Bolós et al., 2015).

Magma in the lithosphere is transported through dykes using pre-existing or newly formed fractures (Gudmundsson, 1990; Rubin, 1995). Dyke propagation and subsequent eruptions in a volcanic system are controlled by magma overpressure, buoyancy forces, and stresses in the host rock. In composite volcanoes the directions of dyke intrusions escaping from a shallow magma chamber are determined by the stress distribution around the chamber (Gudmundsson, 1988; Muller et al., 2001; Pinel and Jaupart, 2004; Gudmundsson and Brenner, 2005). Thus, these systems tend to present more regular patterns in vent opening: If no change occurs in the position, shape, and size of the magma chamber before each eruption, the stress field controlling dyke propagation will be very similar in all eruptions. However, changes in magma chamber parameters (Martí and Geyer, 2009) or morphological changes in the volcano due to sector collapse (Tibaldi, 2004) may induce a redistribution of stress inside the volcano and thus a change in the position of the vents in the subsequent eruption. By contrast, in monogenetic systems characterized by deep magma chambers, most of the stress controls on dyke propagation are exerted by magma overpressure, regional stresses, and the presence of stress barriers caused by structural and rheological changes in the lithosphere. These latter changes may vary from one eruption to the next due to the blocking of previous paths by magma solidification, which will mean that the position of the vents will probably change, albeit maintaining a certain proximity if no significant changes in regional stresses occur. In both polygenetic and monogenetic systems, fluctuations in regional stress fields may induce changes in the position of vents between different periods of volcanic activity in the same system. Nevertheless, these changes will normally take longer to occur than the length of the period of time usually considered in long-term hazard assessments.

Therefore, the appearance of a new vent will be determined by the path that the magma uses to reach the surface and to identify its exact position we need to identify the path the magma will follow. Although we know that magma will choose the easiest route to reach the surface (i.e., the path in which the least energy investment is required), we do not yet possess any direct criteria that enable us to determine paths a priori. This would require detailed 3D knowledge of the stress distribution inside volcanic systems, which is still an impossibility. Even so, there are several direct and indirect sources of data that can provide relevant information. Field structural data including in situ stress-field mea-
measurements (usually measured using boreholes), the location of eruptive vents, and structural alignments (fractures, faults, cone alignments and dykes) constitute the main obtainable direct sources of data. Indirect data can be obtained from theoretical 3D stress field models and structural geophysical data (gravimetric, magnetic, seismic, etc.). These structural elements provide an indication of the corresponding state of stress of the volcanic system when they formed. Therefore, the most recent features should give the best idea of the current stress field, while older features such as dykes, which are normally only exposed after long periods of erosion, may provide data on past stress fields that will not necessarily coincide with the current ones. The principle that new vents will not form far from existing ones is normally accepted in monogenetic volcanic fields (Connor et al., 2000; Martin et al., 2004; Jaquet et al., 2008). The use of direct structural data such as alignments and the location of past eruptive centers implies an assumption that the general stress field has not changed significantly since the formation of the vents. In other words, we should restrict our volcanic hazard assessment to the time period during which the main stress field is believed to have been constant, and only structures that originated during that period should be considered. Therefore, susceptibility analysis should consider all these structural elements and give them the correct weight when they are used to calculate the current stress field.

Two time scales have to be considered in susceptibility analyses. The first consists of long-term hazard assessment and examines the structural criteria that provide direct information on the internal structure of the volcanic field, including its past and present stress fields (Martí and Felpeto, 2010; Marzocchi et al., 2010). The second scale corresponds to the computation of volcanic susceptibility in short-term analyses (from days to a few months) during unrest episodes, and includes those structural aspects that can be inferred from volcano monitoring, as well as the results of long-term volcanic susceptibility analysis (Marzocchi et al., 2008; Sobradelo and Martí, 2015; Bartolini et al., 2016). Estimation of both long- and short-term volcanic susceptibility has an implicit high degree of uncertainty, particularly in the long term in monogenetic fields, due to the impossibility of determining a priori which path the magma will choose to reach the surface. In long-term analyses that only use structural information, the precision of the results obtained will depend on the number of structural elements considered and their ages. Therefore, we need to base our assessment on good datasets that give statistical meaning to our results. In the case of short-term estimates, monitoring data help refine the expected position of a new vent, and, in particular, the location of seismicity and ground deformation can be used to identify the position of magma as it approaches the surface (Marzocchi et al., 2008; Sobradelo and Martí, 2015; Bartolini et al., 2016). Nevertheless, depending on the characteristics of the volcanic system, significant uncertainty will still be associated with forecasts.

To estimate volcanic susceptibility we use probabilistic methods based on structural (long term) and monitoring (short-term) data to identify areas with the greatest probability of hosting new vents rather than attempt to identify precise future vent locations. If the spatial distribution of vents in a volcanic system is completely random (i.e., a process with no spatial memory), a homogeneous Poisson process (i.e., events occur at a constant rate)
can be used to estimate the probability that a point will contain one or more new vents (Martí and Felpeto, 2010). However, in many cases, the distribution of volcanic centers is clearly not random, as vents tend to cluster. In these cases, a nonhomogeneous Poisson process (i.e., events occur at variable rates) is the simplest alternative for modelling this type of clustered random data (Martí and Felpeto, 2010). Assuming that the regional stress field for the study area and the time period considered has not and will not change significantly, the first step consists of collating all available datasets (Fig. 6). For each dataset, a probability density function (i.e., the relative likelihood that a random variable has a given value) should be defined, which represents the spatial recurrence rate if only one dataset is considered. Furthermore, for each dataset, two parameters should be assessed: the relevance and the reliability.

The relevance of a structural element describes its relative significance in the data considered in the evaluation of the volcanic susceptibility. As explained, the structural elements used to calculate volcanic susceptibility are stress indicators; nevertheless, some are better than others and, depending on the age of each element, some may be more representative of the current stress state. Overall, although all structural elements provide useful information for deducing the evolution and present configuration of the stress field in the volcanic system, individually, some may be more significant than others. However, establishing the significance of each element is not a straightforward task and will depend on the subjective opinion of each expert. One method of assigning a relevance value to each structural element is to use an elicitation of expert judgment procedure (see Aspinall, 2006; Bevilacqua et al., 2015). It should be noted that these values are assessed for the type of data without taking into account the quality of the data or even whether or not the data are available.

The quality of the available data defines their reliability for use in the assessment of volcanic susceptibility (Martí and Felpeto, 2010). Data such as tectonic lineations and vent locations that can be directly obtained in the field should be totally reliable. However, the quality or the degree of confidence of data obtained by indirect methods such as theoreti-
cal models of stress fields, structural geophysical data, and monitoring data will depend on aspects related to the data acquisition and processing methods. The precise reliability weight for each dataset should be based on the accuracy of the dataset according to the criteria of the expert(s) who have collected/computed the data. This is particularly important in geophysical datasets generated by the application of inversion techniques, whose precision will vary in terms of the numerical procedure used.

Assuming a linear combination of the contribution of each dataset, weighted with the two aforementioned parameters, we can obtain a final probabilistic distribution for vent opening in the area considered by assigning to each point (pixel) a specific value that is proportional to the total probability for the area for the time considered (Fig. 7). Each dataset must be remapped onto its corresponding probabilistic density function. The remapping method will depend on the relationship between the dataset and the distribution of the vents in the volcanic system, which can have a statistical or deterministic basis, depending on the knowledge of the physical processes that link the data and the spatial distribution of vents, and on the characteristics of the dataset. One of the most common methods for estimating the spatial probability for the opening of future vents is the kernel technique (Martí and Felpeto, 2010). A kernel function is used to obtain the probability of hosting a new vent at a particular sampling point, calculated as a function of the distance to nearby vents and a smoothing factor \( h \) or bandwidth, which represents the degree of randomness in the distribution of past vents. The most commonly used kernel functions are the Gaussian and Cauchy kernels.

The huge development in Geographic Information Systems (GIS) in recent decades has significantly contributed to the systematisation of natural hazard analysis by facilitating new computational and visualization methods (Leidig and Teeuw, 2015). In the case of volcanic susceptibility, different GIS-based methods have been developed in recent years that make similar assumptions and use comparable calculation methods (Martin et al., 2004; Martí and Felpeto, 2010; Cappello et al., 2012; Selva et al., 2012; Becerril et al., 2013). As a more practical approach, Bartolini et al. (2013) have developed QVAST, a free tool designed to generate user-friendly quantitative assessments of volcanic susceptibility. If different input data sets (structural elements) are available for the area, QVAST computes the total susceptibility map by assigning different weights to each of the corresponding probabilistic density functions, which are then combined via a weighted sum and modelled in a nonhomogeneous Poisson process. Examples of the application of this tool can be found in Becerril et al. (2014) and Bartolini et al. (2014 a, b) (Fig. 7).
When monitoring data generated during an unrest phase are available, the QVAST e-tool can also be used to update susceptibility maps. In fact, seismicity and surface deformation are good indicators of magma movement. As unrest evolves, these precursory signals help to fix with greater accuracy the probable vent location by inferring the position of magma below the surface.

Simulation Models and Eruption Scenarios

The next step in long-term hazard assessment is to use the stratigraphic record to identify all the volcanological scenarios a volcanic system may generate. As explained, the reconstruction of the eruptive record of a volcanic system enables us to identify the products of each different eruption and intereruptive episodes, as well as the spatial and temporal relationships between them (Groppelli and Martí, 2013). Volcanic eruptions are complex and multiphase, and involve different direct and indirect products and hazards (Cashman and Sparks, 2013). Understanding the detailed nature and the sequence of possible phases in past eruptions, together with the timing of volcanic and associated products, is axiomatic in hazard and risk assessments because it explains how a volcanic system may behave in the future. This will provide valuable information on the duration, extent, and intensity of past eruption phases, which will be crucial for identifying potential danger zones and in land planning and development of emergency plans. In addition, if the volcanic system has been active in recent years and direct observation and instrument monitoring of eruptions have been possible, we can associate possible precursory/premonitory activity to particular eruption types and products.

When all possible past volcanic scenarios in a particular system have been identified, we can create a simulation based on current topographic, demographic, and environmental conditions. Essentially, we are interested in simulating the volcanic and associated processes that might constitute a hazard. Volcanic scenarios are normally simulated by assuming a specific vent location, to anticipate what might happen in the event of an eruption of a certain type originating at that particular point (e.g., Mastrolorenzo and Pappalardo, 2010; Martí et al., 2012; Gehl et al., 2013) (Fig. 8). However, it is also possible to create scenarios in a zone with distributions of volcanic susceptibility values, for instance when we construct partial or total hazard maps (see “Hazard Maps”). The results
of these simulations will depend on the locations of the vent(s), the hazards considered, topographic constraints and the type and quality of the simulation models used.

Currently, the modelling of volcanic processes based on physical disciplines such as thermodynamics, and solid and fluid mechanics is a well-developed field of research (Martí and Folch, 2005; Parfitt and Wilson, 2008; Fagents et al., 2013; Neri et al., 2014). Models have been developed to describe phenomena related to volcanic activity that range from lava flows to ash fallout, and from magma chamber dynamics to pyroclastic flow propagation. After several years of progress, model development and application is now regarded as an accepted methodology in volcanological studies (Martí and Folch, 2005; Fagents et al., 2013). However, different models depend on different assumptions, are characterized by varying degrees of accuracy and precision, and imply varying levels of approximation to natural processes. Modelling results must therefore be treated with caution, and it is vital to take into account all the possible interpretations of the outputs, which will depend on the assumptions and simplifications employed in the modelling process. When physical models are used for practical goals such as hazard evaluation, particular attention must be paid to model selection, uncertainty treatment, and result evaluation (Martí and Folch, 2005).

Depending on the availability of data and computational resources, we can create either stochastic (probabilistic) or deterministic models. Given that they use very few variables and the large number of unknowns, stochastic models (e.g., Felpeto et al., 2007) can provide probabilistic outcomes—that is, the probability that a certain area will be affected by an eruptive process—that thus reflect the degree of uncertainty in the simulation. These models do not require great computational effort. On the other hand, deterministic mod-
Assessing Volcanic Hazard: A Review

els (e.g., Esposti-Ongaro et al., 2002, Neri et al., 2014) use a large number of parameters and provide more realistic results (i.e., the maximum extension area affected by an eruptive episode) but require considerable computational time and effort. In general, probabilistic models are more often used in volcanic hazard assessment due to several important issues (Felpeto et al., 2007): the lack of precise knowledge of the physical processes governing the dynamics of most volcanic hazards, the difficulties in getting complete parameterization sets for each phenomena, the great time and computational costs implied in deterministic models, and the acceptable results that probabilistic models provide. The results of simulation models are normally represented using a GIS that can manage all the geographic (digital elevation model [DEM], etc.) and cartographic data required for high-quality analysis, and can generate graphical representations of eruption scenarios and hazard maps (see Fig. 8).

Volcanological literature contains abundant examples of the application of simulation models to types of hazards such as lava flows (e.g., Felpeto et al., 2001; Favalli et al., 2005), fallout (e.g., Macedonio et al, 2005), PDCs (e.g., Sheridan and Malin, 1983; Toyos et al., 2007), lahars (e.g., Schilling, 1998; Patra et al. 2005), debris avalanches (e.g., Dondin et al., 2011), or volcanic tsunamis (e.g., Choi et al., 2003). Some of these models are freely available for download and are appropriate for expert users working on volcanic hazard assessment. This is the case of VORIS 2.0.1, a GIS-based tool developed by Felpeto et al. (2007) that allows users to simulate lava flows, fallout, and pyroclastic density current scenarios. HAZMAP is a free program for simulating the sedimentation of volcanic particles at discrete point sources that predicts corresponding ground deposits (deposit mode) (Macedonio et al. 2005). LAHARZ is a semiempirical code for creating hazard-zonation maps that depict estimates of the location and extent of areas inundated by lahars (Schilling 1998). TITAN2D is a computer program model developed by the University at Buffalo (Patra et al. 2005) that simulates granular flows over digital elevation models based on a “thin layer model.” The outputs from this program (represented dynamically) are flow, depth, and momentum, which yield the deposit limit, runout path, average flow velocity, inferred deposit thickness, and travel time.

Simulating eruption scenarios using the results of susceptibility analyses and simulation models of different hazards is the first step toward producing qualitative and quantitative hazard maps in long-term assessments. Simulating eruption scenarios is also crucial in short-term assessments during a volcanic crisis, as it helps determine potential impacts and identify possible evacuation routes, thereby aiding decision making. The simulation of eruption scenarios is also necessary in vulnerability analysis, to identify which elements may be affected by volcanic processes and how. Finally, the simulation of eruption scenarios is very useful when explaining volcanic hazards to local populations, as they provide a realistic and easy-to-understand way of clarifying the degree of hazard people may be exposed to, assuming that extensive communication and outreach have been done well before the crisis stage of a volcanic episode (Haynes et al., 2007).
Hazard Maps

The construction of hazard maps is another important step in hazard assessment that must be carried out before the onset of a volcanic crisis (see Fig. 2) (Tilling, 1989; Sparks et al., 2013). Hazard maps are required for land planning and for preparing and then executing emergency plans during a volcanic crisis. They are also the basis used to conduct risk analysis and identify communities exposed to the greatest risks. Today, a hazard map is a dynamic concept that differs from the classical static maps drawn under the assumption that no changes will occur over long periods of time. A hazard map may change as new information becomes available, as the accuracy of simulation models improves, with revisions of cartographic and geographic data, or as fresh eruptions occur. Thus, the methodologies and concepts used to construct hazard maps must bear in mind the fact that a map is a temporal and open product that is continuously evolving (Felpeto et al., 2007).

Hazard maps are usually probabilistic (spatial probabilities) and may be constructed for just a single hazard, for groups of hazards, or for all the hazards forecasted for a particular area; they may be qualitative or quantitative, or may cover certain restricted areas or a whole volcanic field (Felpeto et al., 2007; Haynes et al., 2007; Sparks et al., 2013; Calder et al., 2015). Previously, hazards maps were constructed using information pertaining to past events, so the resulting map was basically a lithostratigraphic cartography of the products of past eruptions in which the emphasis was placed on their superficial extent (Fig. 9). However, modern hazard maps are constructed using GIS and computational facilities, and represent what could happen if similar eruptions to those occurring in the past take place again (Felpeto et al., 2007; Calder et al., 2015). They thus describe areas that could be affected by each hazard, the degree of affectation or impact, and the potential risk. Hazard maps constitute the main tool for illustrating and visualizing how a territory can be classified according to the degree of hazard to which it is exposed, and are thus very relevant tools in territorial management. However, they are also highly useful for illustrating and communicating to the population in general and decision makers the reality of their territory and what could happen in the event of an eruption (Haynes et al., 2007).
The construction of a hazard map requires a considerable computational effort, as it combines mathematically all the information obtained in the steps of the hazard assessment process (i.e., volcanic susceptibility and eruption scenarios). While a simple scenario usually represents just what could occur in case of an eruption from a particular vent, the construction of a hazard map implies the computation of the same scenario(s) for all points (pixels) of the map where the probability of hosting a new vent is not zero. The results obtained from these simulations are merged into a single map showing a normalized distribution of the probabilities resulting from combining, recalculating, and normalizing all the results obtained from each individual simulation.

An important question to be considered when creating hazard maps is how to communicate them to their potential final users (local population, civil protection, decision makers, media, etc.). Not all have the same educational background, a handicap if all are to receive and understand the same message. The generation of a hazard map is complex, but it is not always necessary to incorporate all this complexity into the final map. Maps containing an excess of information are hard to understand and may fail to inform. On some occasions people do not understand maps and do not know how to read them. The
Assessing Volcanic Hazard: A Review

most usual and simplest (in terms of visualization) hazard maps are those that depict a zonation, in which the area around the volcano is divided into zones of decreasing hazardousness (Tilling, 2005; Sparks et al., 2013) (Fig. 10). Alternatively, hazard maps may show the hazard level (probability) in a qualitative or quantitative way throughout the whole study area, thereby highlighting the zones that may be affected by specific hazards or all by the hazards associated with the volcanic system (Fig. 10). Recently, Preppernau and Bernhard (2015) have reported that volcanic hazard maps created to inform the public of the nature and extent of the hazards that threaten them are not always well understood by those who are not trained in map use or geology. These authors also compare the effectiveness of conventional 2D maps and 3D perspective maps for relief representation (Fig. 11): A 3D representation in which people can easily recognise familiar topographic features in their area is a much better option for communicating hazard information than classical 2D maps. The combination of digital hazard maps with 3D reliefs obtained through freely accessible and easy-to-use tools such as Google Earth offers a potentially important way of visualizing hazard maps.

Figure 10  Examples of zonation hazard maps. A. Map showing volcanic hazard zones on the island of Hawaii first prepared in 1974 by Donal Mullineaux and Donald Peterson of the U.S. Geological Survey and revised in 1987. The current map divides the island into zones that are ranked from 1 through 9, based on the probability of coverage by lava flows. (source: 2008 Rainbow Properties http://www.rainbowproperties.com/Volcano_Info/page_2145864.html, and http://hvo.wr.usgs.gov/volcanowatch/archive/1994/). B. Definition Of Boundary Limits and Volcanic Risk Map for Soufriere Hills Volcano from September 1997, which defines three main zones: Exclusion Zone: No admittance except for scientific monitoring and National Security Matters. Central Zone: Residential area only, all residents on heightened state of alert. All residents to have rapid means of exit 24 hours per day. Hard hat area; all residents to have hard hats and dust masks. Northern Zone: Area with significantly lower risk, suitable for residential and commercial occupation (source: Montserrat Volcano Observatory http://www.geo.mtu.edu/volcanoes/west.indies/soufriere/govt/miscdocs/rskzone.html)
Another question raised in the scientific literature is whether or not hazard maps should be qualitative or quantitative (Marzocchi et al., 2012a). Hazard maps essentially show probabilities but, unfortunately, probability is a concept that is not always well understood. Hazard maps showing the qualitative hazard distribution (i.e., high, medium, low, or very low) of a volcanic area (Fig. 11) may be sufficient for land planning and preparing emergency plans. However, Marzocchi et al. (2012a) have argued that the use of qualitative maps may be inappropriate for managing situations where the volcanic risk is high—for instance, volcanoes close to highly urbanized areas, nuclear repositories or nuclear power plants, or, more generally, critical infrastructures—because of the potential cost of any mitigation action. In these cases, a quantitative evaluation of hazard (or risk) would seem to be more appropriate for evaluating which actions should be taken in order to reduce risk. Selva et al. (2014) remark that, “the adoption of a systematic and rational decision-support procedure based on quantitative assessment has the advantage of providing a transparent audit trail, which reduces the degree of subjective opinion in volcanological communication to civil authorities.” Despite the accuracy of this statement, a detailed and precise quantification of hazard is not always possible, as it depends on the quality and degree of knowledge of the volcanological record. Occasionally, this may not be complete or not sufficiently enlightening, and the resulting hazard assessment will have a significant degree of uncertainty. Applying simulation models when the input data are scarce or of poor quality may lead to overestimates or underestimates of the hazard, and so may provide an erroneous basis for a risk analysis or for correct decision making. Although it is theoretically desirable to obtain quantitative hazard maps, it is not always possible. Thus, we should evaluate in each case the potential limitations that exist and provide the best result in terms of the available information (Fig. 12).
Temporal Analysis

According to the definition of hazard given in earlier sections of this review, once the spatial analysis has been performed, we need to conduct a temporal analysis to complete the computation of the hazard assessment for the volcanic system in question (Sobradelo et al., 2013). Temporal analysis refers to the eruption frequency or eruption recurrence of a volcanic system and is calculated using stratigraphic, geochronological, and historical data. Unfortunately, volcanic eruption datasets are usually small and the eruptive recurrence is usually much longer than in other natural phenomena such as earthquakes or tsunamis, so the possibility of obtaining precise recurrence estimates will depend on how well known our volcanic system is.

Each volcanic system has a characteristic eruption recurrence that may range from several eruptions per year or few years in highly active volcanoes (e.g., Piton de La Fournaise in La Reunion) to once in hundreds to thousands of years (e.g., El Teide in Tenerife) in low eruption-frequency volcanoes, or even once in tens of thousands of years in some monogenetic volcanic fields (Simkin and Siebert, 2000); nevertheless, when eruptions do occur in less active areas, they tend to be clustered in both time and space. The recurrence time of each volcano depends on the magma supply rate from the source region to the volcanic system, which in turn depends on the deformation and magma production rates in each geodynamic setting. Seemingly, geodynamic contexts with higher magma production rates have greater rates of volcanism (Sigurðsson, 2000). However, when we look at a particular volcano or volcanic system, or when we try to compare volcanoes, variations in eruption frequency often diverge from this general or global tendency. For example, if we compare Hawaii and the Canary Islands, two volcanic regions located in similar geodynamic settings, we see that their respective eruption frequencies are dissimilar (Carracedo, 1999; Tilling et al., 2010). In the large volcanoes in the Andes, a highly active geodynamic setting with a relatively high magma production rate, eruption frequencies are very low, occurring once in hundreds to thousands of years (Francis, 1993). A comparison between Indonesia, the Caribbean, and Japan, three volcanic island arcs, reveals that the eruption frequencies of individual volcanoes vary in all these volcanic areas (Siebert et al., 2010).
The question remains: What else controls eruption frequencies in individual volcanoes? A consensus exists that, in addition to the rate of magma supply, the mechanical properties of the crust and magma and the tectonic regime also play major roles in controlling the eruption frequency (Jellinek and De Paolo, 2003). It is clear that in volcanoes producing large eruptions, the eruption frequency is low (once in hundreds to thousands of years) and in direct proportion to the large volume of magma needed to trigger an eruption. However, in volcanoes or in monogenetic systems that generally produce small volume eruptions, eruption frequencies tend to be much shorter, which suggests an inverse relation at a global level between the volume of eruptions and the eruption frequency (Mason et al., 2004; Deligne et al., 2010). Apparently, less magma implies less capacity (e.g., less overpressure) for magma to reach the surface. The exact mechanisms controlling eruption frequencies are still not well known and require more study if we are to determine and predict in a more quantitative fashion the eruption frequency of each volcanic system. Nonetheless, the relative eruption frequency established from the past eruptive record of a volcano should be sufficient for undertaking long-term hazard assessments.

When trying to establish the eruption frequency of a particular volcanic system, we must take into account the time perspective needed to carry out such a task. Individual volcanic eruptions may vary in duration from minutes to centuries and, as indicated, each eruption may have several phases and pulses during its active life, be they short or long, which may also include episodes of quiescence. This is the case of volcanoes such as La Soufrière on Montserrat or Stromboli, which experience long ongoing eruptions. If we look at these volcanoes from a current time perspective, we can identify individual eruptions instead of just different phases of the same eruption. However, if we could look at these volcanoes from a geological perspective, for example a period of several tens of thousands of years, would we be able to distinguish quite so many “different” eruptions? Or should we group all the products together as originating from different phases of the same eruption? In this latter case, we would have to look at the deposits generated by the volcanic activity, as we would not have witnessed the eruptions and therefore the distinction between different eruptions would not be so clear, particularly if no evident time breaks marked by paleosoils or erosion surfaces are present between the deposits. Therefore, how do we establish a distinction between eruptions if we only examine the geological record? This is a problem we have to face when working with volcanoes that have not erupted or have not erupted quite so frequently in historical time. In these cases, we have to rely on volcanic stratigraphy and, in the best of cases, detailed geochronology to establish the eruption frequency. The main problem is that the preservation of the volcanological record is not always complete and that geochronological dating is not precise enough to determine exact ages or to separate the ages of deposits that were produced over relatively short time intervals. Consequently, any time series we obtain may not be complete or sufficiently precise to quantify eruption recurrence. Another problem arises when dealing with volcanoes that have been active in historical times, that is, since written documents have existed for a particular area. These periods may be too short and available records may be incomplete; in these cases it is essential to complement historical infor-
mation with data from the geological record but without losing sight of the fact that the precision of both sets of data will not be the same.

Another issue is how long a time period needs to be before it can be used to estimate eruption frequency. Obviously, this will depend on the periodicity shown by eruptions. In general, for currently active volcanoes, the Holocene period (i.e., the last 10,000 years) should cover the necessary time window (Siebert et al., 2010). In volcanoes with very high eruptivity (e.g., Colima in Mexico, Piton de La Fournaise in La Reunion), historical time alone may be sufficient. However, if we aim to obtain an as accurate as possible mathematical quantification of a volcanic hazard from small datasets, we need to search for methods that will allow us to work with databases that are small and sometimes incomplete (i.e., the statistical methods derived from “extreme value theory”) (Davison and Smith, 1990; Coles, 2001; Beguería, 2005). Examples of the application of extreme value theory for establishing eruption recurrences using incomplete time series can be found in Coles and Sparks (2006), Mendoza Rosas and De la Cruz Reina (2008, 2010), and Sobradelo et al (2011).

Probabilistic Event Trees

The ultimate aim of volcanic hazard assessment is to quantify volcanic hazard, that is, to estimate the probabilities of occurrence of all possible eruptive scenarios in time and space by combining the spatial and temporal analysis explained in previous sections. Once this has been accomplished, we then require a straightforward method of assessing the relative likelihoods of the different ways in which a volcanic system may evolve in the future or—more urgently—when a new eruptive process will take place. When a volcanic crisis starts, we need to highlight all relevant possible outcomes of volcanic unrest in progressively greater detail and assess the hazard in each scenario by estimating the probability of occurrence within a future time interval. In addition, we need a simple way of passing this information in its entirety on to the corresponding decision makers. Although previous experience has shown that probabilities are not always well understood by decision makers (or even by scientists), the forecasting and prediction of the complex and random behavior of volcanic systems, as well as the quantification and communication of underlying uncertainties, are all necessary disciplines. Additionally, during volcanic crises statistical methodologies serve as a tool for drawing up cost/benefit analyses that will influence the decisions taken by the authorities (i.e., emergency plans and evacuation) (Marzocchi and Woo, 2007; Sobradelo et al., 2015). Methodologies should help decision makers understand the complexities of problems and enable them to envisage the potential consequences of making poorly informed decisions.

The complexity of any volcanic system and its associated eruptive processes, in combination with the lack of data that characterize many active areas and, in particular, those with long recurrence periods, ensure that volcanic hazard quantification is a great challenge, above all because there is often not enough observational data to build a robust statistical model. Since we rely on geological and geophysical data, aleatoric (stochastic),
and epistemic (data or limited knowledge), uncertainties are significant and must be mini-
mized. Aleatoric uncertainty is a consequence of the intrinsic complexity of a system that
limits our ability to predict the evolution of the system in a deterministic way. This type of
uncertainty introduces a component of randomness into the outcomes, regardless of the
extent of our physical knowledge of the system. Epistemic uncertainty, on the other hand,
is directly related to our knowledge of the system and the quality and quantity of data we
have gathered: The more data we have, the better we know the system and the less the
epistemic uncertainty (Woo, 1999).

In most cases, a logic tree of volcanic events and impacts can be constructed on the basis
of volcanological scenarios defined using existing geological and historical volcanological
records (Newhall and Hoblitt, 2002; Marzocchi et al., 2004; 2008; Neri et al., 2008; Sob-
bradelo and Martí, 2010). An event tree is a graphic representation of events in the form
of nodes and branches (Fig. 13) that was first introduced into volcanology by Newhall and
Hoblitt (2002) as a tool for volcanic hazard assessment. Each node represents a step with
a set of possible onward branches (outcomes for that particular category). Nodes are al-
ternative steps taken from a general prior event, state, or condition leading to increasing-
ly specific subsequent events that reach final outcomes. The aim is to depict all relevant
possible outcomes of volcanic activity in progressively greater detail, and to assess the
probability of occurrence of each hazard scenario within a specified future time interval.
Probability weights for the various logic-tree branches are assigned through statistical
analysis of data or the formal elicitation of expert volcanological judgement (Aspinall and
Woo, 1994; Aspinall, 2006).

Probability event trees are useful in both long- and short-term hazard assessments, as
they offer, respectively, a rapid view of the probabilities of occurrence of all possible sce-
narios of a particular volcanic system during a quiescence period or an updated distribu-
tion of probabilities during a crisis. The construction of a probability event tree for esti-

---

**Figure 13** Event tree structure developed by Sobradelo and Martí (2010) and used as the basis for HASSET (see Sobradelo et al., 2013). Clone indicated repetition of the same tree structure.
Assessing Volcanic Hazard: A Review

Evaluating volcanic hazard is based on accurate volcanological records that allow for the precise reconstruction of the volcano’s past history (Newhall and Hoblitt, 2002). This enables eruption scenarios to be determined that can quantitatively define the future eruptive behavior and potential impact of the volcano. However, problems arise if knowledge of the volcanological history is poor, geochronological data are scarce, and/or historical activity has not occurred or has never been chronically. Some recent eruptions such as those on Montserrat or in Pinatubo have encountered this problem (Newhall and Punongbayan, 1996; Aspinall et al., 2003). In these cases, the lack of knowledge of previous unrest and, more crucially, of the precursors of previous eruptive events precludes the use of repetitive patterns to anticipate new eruptions (see Sandri et al., 2004).

In recent years, probabilistic event trees have been developed as part of long-term hazard assessments of certain volcanoes (Marzocchi et al., 2004; Neri et al., 2008; Queiroz et al., 2008; Sobradelo and Martí, 2010), which can also be used as the basis for short-term hazard assessments in the event of renewed volcanic activity. The ultimate aim of a volcanic hazard event tree is to assign probabilities to the different eruption possibilities or scenarios that can be envisaged, given the eruption history of the volcano and our knowledge of other analogous volcanoes. There are two basic ways to assign probabilities to the different nodes and branches of an event tree: Expert Judgment Elicitation and Bayesian Inference. Expert Judgement Elicitation and, in particular, the so-called Classical Model (Cooke, 1991), uses performance-weighting schemes to derive uncertainty distributions over model parameters using expert judgement (see Aspinall and Cooke, 2013). This approach provides a basis for a weighted averaging of subjective opinions. The weights are derived from experts’ calibration and information performances, measured by the so-called “seed” variables (Aspinall, 2006). The classical model is unique in that it embodies a performance-based expert scoring scheme whereby weights are ascribed to individual experts on the basis of empirically determined calibration and informativeness scores. In practice, when assigning probabilities to an event tree using Expert Judgement Elicitation, all the scientists that participate in the elicitation process provide their individual opinions as to the relative likelihoods of occurrence of the ways in which a volcanic unrest episode and/or an eruption may unfold. These opinions are pooled using the weights obtained from a calibration procedure in which the expert’s assessments are treated as statistical hypotheses, and the probability that these hypotheses are rejected is used to provide a score for calibration (under the assumption that the calibration variables are independent realizations of the experts’ distributions) (see Aspinall, 2006 and Aspinall and Cooke, 2013, for more details). The outcomes of this process are recorded as numerical probability values on the event tree. On each branch, the results are given as three numbers: the median probability (i.e., 50th percentile value for the distribution of opinions provided by the group) and the corresponding 90% credible interval bounds (i.e., the approximate 5th percentile and 95th percentile distributional values). This way of representing the collective scientific uncertainty associated with forecasting volcanic hazards is very different to that of other approaches and gives formal, quantitative expression to all the uncertainties involved, essential for any comprehensive probabilistic risk assessment.
The other common way of assigning probabilities to an event tree is to use a Bayesian Inference. In Bayesian statistics, probability has a subjective interpretation. Bayesians scientists use probability to make statements about the available partial knowledge of an underlying process or “state of nature” (unobservable or as yet unobserved) in a systematic way. The fundamental principle of Bayesian statistics is that what is known about anything that is incompletely or imperfectly known can be described by a probability or probability distribution (Rice, 2007; Sobradelo and Martí, 2010; Sobradelo et al., 2013). Bayesians regard both observed data and unknown parameters as random variables. Posterior inference about unknown parameters is then conditional on the particular realization of data actually observed. If, for example, we have both observed data and unknowns, we may posit a model that specifies the likelihood. From a Bayesian point of view, an unknown parameter should have a probability distribution that reflects our uncertainty and, given that the observed data are known, it should be conditional on the unknown parameter. Therefore, our knowledge of the unknown parameter is expressed through a posterior distribution, that is, the posterior distribution is approximately equal to the product of the prior distribution and the likelihood; the prior distribution expresses our uncertainty about the unknown parameter before seeing the observed data, while the posterior distribution expresses our uncertainty about the unknown parameter after seeing the data.

Despite the differences between these methods, Expert Elicitation and Bayesian Inference complement each other and can be used simultaneously in both long- and short-term hazard assessments. Although the Bayesian approach provides a quick way of automatically updating final probabilities, the lack of information in the geological record or lack of precursors and triggers for each branch sometimes make it impossible to automatically compute probabilities. Nonetheless, the use of Bayesian methodology tends to remove the additional bias that the human decision component adds to results using the elicitation method, and also controls epistemic and aleatoric uncertainties (Sobradelo and Martí, 2010). This methodology also allows the level of segmentation and complexity of the event tree structure to be as complete and extensive as needed, the only requirements being mutually exclusive and exhaustive events at each node. It also allows probabilities to be automatically updated when new data arrive or, in the case of short-term hazard assessment, if the system becomes active and monitoring data on precursors exists. The eliciting method, on the other hand, requires a group of experts to meet each time new data are obtained, to update the probability calculations. Nevertheless, during a volcanic crisis both Elicitation and Bayesian models are needed and the elicitation team can provide input and interpretation of the probabilities of the updated Bayesian model.

In recent years, several probabilistic tools based on Bayesian methodology have been developed for long- and short-term hazard assessment and eruption forecasting (Marzocchi et al., 2008, 2010; Sobradelo et al., 2013) that have been successfully applied to different volcanic systems (Selva et al., 2012; Sandri et al., 2012, 2014; Bartolini et al., 2014a, 2014b; Becerril et al., 2014). These tools assist decision makers to assess the required mitigation actions associated with each scenario and estimate the corresponding potential risk. BET_EF and BET_VH, developed by Marzocchi et al. (2008, 2010), and HASSET,
developed by Sobradelo et al. (2013), are two similar probability tools, freely available on the Internet (http://vhub.org/resurces/betv; http://gvbcsic.wordpress.com/hassseth; www.volcanbox.es), built on an event tree structure, that use Bayesian inference to estimate the probability of occurrence of a future volcanic scenario (Fig. 14). They also evaluate the most relevant sources of uncertainty in the corresponding volcanic system. Each node of the event tree represents a step and contains a set of possible branches (the outcomes for that particular category). The nodes are alternative steps from a general prior event, state, or condition that move toward increasingly specific subsequent events and a final outcome. Compared with BET, HASSET accounts for the possibility of (1) flank eruptions (as opposed to only central eruptions) and monogenetic volcanism, (2) geothermal or tectonic unrest (as opposed to only magmatic unrest), and (3) felsic or mafic lava composition (or the absence of composition data), as well as (4) certain volcanic hazards as possible outcomes of an eruption, and (5) the extent of each hazard.

**Figure 14** Input data (upper part) and outputs (lower part) of the HASSET tool for long-term probabilistic analysis of volcanic hazard (see Sobradelo et al. 2013).

### Analyzing Potential Impacts

Although not an intrinsic part of hazard assessment, also relevant to this review is a mention of some important aspects of vulnerability analysis and the potential impacts of volcanic hazards. This is essential when undertaking risk analysis based on hazard assessment, and needs to be conducted by specialists in the field of vulnerability analysis (e.g., engineers, architects, physicians, psychologists, social scientists, economists). Vulnerability analysis should define inventories of elements at risk from volcanic eruptions, determine appropriate vulnerabilities to principal volcanic hazards (both to property and people), and carry out impact assessments based on given eruption scenarios (e.g., Gehl et al., 2013).
Therefore, once the hazard assessment has been conducted, the next step is to add population, infrastructure, and land-use data to evaluate the vulnerability associated with the impact of particular hazards. The data required for generating vulnerability maps are very complex and varied, and depend on the observation scale. Vulnerability is directly dependent on the type of phenomena and the socioeconomic characteristics of the area in question. The exposure analysis identifies the elements at risk to the potential hazard and focuses on the relevant assets of the study area (population distribution, social and economic conditions, and productive activities and their role in the regional economy). The inventory of exposed elements in any area threatened by volcanic eruptions should include all elements that could be damaged in the case of volcanic impacts (people, infrastructures, soil, animals, etc.), which should constitute the input for developing vulnerability functions and expected impacts on elements at risk. Examples of volcanic vulnerability and impact analysis can be found in Spence et al. (2004) and Zuccaro and De Gregorio (2013) for a hypothetical eruption of Vesuvius, Martí et al. (2008) and Scaini et al. (2014) regarding potential fallout hazard associated with Teide, Gehl et al. (2013) for Mount Cameroon, and Jenkins et al. (2014) in a more general approach.

The vulnerability analysis defines a physical vulnerability indicator (i.e., the vulnerability function) for all exposed elements, as well as a corresponding qualitative vulnerability index. Systemic vulnerability considers the possible relevance of all elements in the system and their interdependencies by taking into account all exposed and nonexposed elements (people, buildings, transportation network, urban services, and productive activities). Systemic vulnerability maps can be obtained by multiplying each element by the corresponding coefficient, so for each phenomenon the specific vulnerability maps overlap the maps of the modelling results (e.g., Zuccaro and De Gregorio, 2013; Scaini et al., 2014). In addition, we should assess physical, economic, and environmental impacts—the cumulative damage to exposed elements produced by possible sequences of hazards—by integrating hazard, inventory and vulnerability data into a dynamic impact modelling framework. According to time and space combinations in the volcanic hazard event trees, it is necessary to define a procedure able to assess at every stage of the eruptive process the accumulated damage to exposed elements and their distribution throughout the territory. The final impact/damage scenario can be examined by parameterizing the cumulative damage that each element experiences in the possible sequence of events. Using the hazard analysis, cascading impacts involving direct and indirect volcanic hazards and their effects should be used to identify impact/damage scenarios in possible hazardous event chains and their probability of occurrence. Finally, damage assessment can be performed by associating a qualitative damage rating to each combination of hazard and vulnerability, although it is important to bear in mind their specific contexts and roles in the system. The way one element can be damaged—and thus lose its functionality—depends on the type of hazardous event and the characteristics of the element. The end products are damage maps with levels of detail according to user preferences (e.g., Scaini et al., 2014) that are useful for territorial planning and risk management in active volcanic areas.
Communicating Volcanic Hazard

As mentioned in the previous sections of this review, scientific communication is an essential part of hazard assessment. Data originating directly from the scientific community has a special influence on risk perception and on the confidence that people have in scientific information. Scientists responsible for conducting hazard assessment should ensure, in collaboration with local authorities, that communication on volcanic hazards and risks reaches all levels of society, from the general public to the decision makers, in order to guaranty that all citizens are aware of the risks that volcanic activity may impose on their lives and properties. This will facilitate understanding of scientific communication during volcanic crisis, thus making the threatened population less vulnerable. Therefore, scientific communication has to be conducted both during quiescence periods and in times of emergency, and always in an accurate and transparent way.

Information coming directly from the scientific community has a special influence on risk perception and on the confidence that people have in scientific information (Johnston et al., 1999). This is why scientists working in active volcanic areas should make the effort to contribute to educating the local populations on volcanic hazards and risks, so they are aware of where they live and possible threats on them. Conducting communication activities and outreach at schools and for the general public and potential visitors during quiescence periods, in which volcanoes do not show signs of alarm, is highly recommendable if we don’t want to catch people by surprise in the case of a crisis. It should not be a major problem living with volcanoes if we know about them and about the mitigation measures and emergency plans that have been designed to preserve our security.

During an unrest episode or volcanic crisis, scientific communication becomes an element of major importance to conduct its management in a successful way. In these situations, contacts between scientists and the media and the general public are expected. Poor communication strategies may have serious consequences during emergencies. Scientists must find the correct way to communicate their information ensuring transparency of the scientific process during the crisis. During recent years, considerable efforts have been made to analyze scientific communication during volcanic crisis and to investigate the best ways to transmit scientific knowledge to the different receivers (e.g., IAVCEI, 1999; Gregg et al., 2004; Haynes et al., 2007; 2008a, b; Gaillard, 2008; Solana et al., 2008, McGuire et al., 2009; Barclay et al., 2011; Marzocchi et al., 2012a; Donovan et al., 2012a, b, c; Doyle et al., 2014; Dohaney et al., 2015; Martí, 2015; Bird, et al., in press).

Volcanology is by nature an inexact science, and increasing quantities of hazard information are being calculated and conveyed using probabilistic methods (e.g., Newhall and Hoblitt, 2002; Marzocchi et al., 2004; 2008; Neri et al., 2008; Sobradelo and Martí, 2010; Sobradelo et al., 2013). Appropriate scientific communication should provide information not only on the volcanic activity itself, but also on the uncertainties that always accompany any estimate or prediction (Sobradelo and Martí, in press). This may be relatively straightforward in areas in which volcanoes erupt frequently, where both the local population and decision makers are aware of the existence of volcanic hazard and risk. Howev-
er, this may be more of a challenge in volcanic areas with long eruptive recurrence intervals and in those without any historical record of volcanic activity. A lack of information—or the use of incorrect information—regarding a hazard and the potential risk derived from the existence of that hazard may lead to bad land planning and create a society that is poorly equipped to face such a hazard, which will have dramatic consequences in the event of an eruption. Unfortunately, scientific communication on volcanic hazards can be challenging, and there is no general agreement as to how such communication should be conducted, not only among scientists but also between scientists and other stakeholders (e.g., decision makers, media, and the local population) (Doyle et al., 2014; Sobradelo and Martí, in press). The critical questions here, as in the case of other natural hazards, are how to quantify the uncertainty that accompanies any scientific analysis and forecast and how to communicate this understanding to policymakers, the media, and the general public.

Communicating volcanic hazards implies the translation of the scientific understanding of volcanic activity into a series of clearly explained scenarios that are easily understandable by decision-making authorities and the population in general (Martí, 2015). The main goal of hazard assessment is to respond to the desire to know how, where, and when an eruption will occur. As explained, to answer these questions, probabilities should be used to characterize associated uncertainties (Donovan et al., 2012b; Doyle et al., 2014; Sobradelo and Martí, in press). However, communicating probabilities and, in particular, uncertainty, is not an easy task and may require different approaches according to the receiver of the information. Forecasting future volcanic activity essentially follows the same approach as in other natural hazards (e.g., storms, landslides, earthquakes, or tsunamis). However, this approach does not necessarily require the same level of understanding in the population and decision makers. Compared with meteorologists, who have much more available data and observations, volcanologists have to deal with a higher degree of uncertainty, which is mainly derived from the lack of observational data (Martí, 2015). It is also important to remember that all volcanoes behave in different ways, therefore no universal model for understanding the behavior of volcanoes can ever exist. Each volcano has its own particular features depending on, for example, the magma composition and physics, rock rheology, stress fields, geodynamic environment, and local geology, which make them all unique—what is indicative in one volcano may not be relevant in another. All this ensures that the communication of volcanic hazards and risks is a great challenge, and it is very difficult to communicate this high degree of uncertainty to the population in general and decision makers.

At this point, it is important to differentiate between the level of communication needed during a quiescence period (when long-term hazard assessment is supposed to be carried out) and that needed during an emergency. It is obvious that, to guarantee effective scientific communication during a volcanic emergency, sufficient time and energy must be spent to inform people of the reality of the area they live in, of the potential hazards that may threaten them, and how to react in the event of an emergency. This requires an educational program rather than just sporadic communication actions (even if the latter are
Effective hazard mitigation can be achieved if the people directly threatened by the hazard in question are actively involved in the hazard mitigation measures. Such active participation requires both awareness (i.e., knowledge and acceptance of existing hazards) and the willingness to undertake individual actions that will effectively reduce risk. There is a broad debate in the international literature about what actions should be taken to achieve these two objectives (e.g., Stein and Stein, 2014). However, a general consensus exists regarding the importance of education and outreach activities, which have the double function of disseminating scientific information and of creating a positive bond between the local population and the scientific community based, on mutual trust and transparency.

Educational programs and outreach activities will vary from country to country in terms of cultural and socioeconomic factors and the actual subject in question. They should directly involve schools and local communities. Unfortunately, in many cases these activities have never been part of a rational framework addressed to reduce risk, in which specific goals should be clearly defined and the appropriate scientific, social, and educational skills should be available. Education and scientific communication during quiescence periods should focus on the results of long-term hazard assessments. It should explain the type of hazards that may affect the area, when they may occur, the monitoring actions that are currently being undertaken to control and warn of volcanic activity, the emergency programs that the authorities have set up in the event of a crisis, the mitigation measures implemented to reduce risk, and the benefits provided by volcanoes that help sustain local economies. This information can equip a society to face a volcanic threat and also—and more importantly—help demonstrate that we can live with volcanoes if we understand them. Hazard maps and probabilistic event trees need to be shown and explained during quiescence periods, and scientists must be sure that they are transparent and well understood.

In the case of an emergency, scientific communication on volcanic hazards will be much easier, fluent, and comprehensible if background efforts have been made. Studies on communication during volcanic emergencies (e.g., IAVCEI, 1999; McGuire et al., 2009; Aspinall, 2010; Donovan et al., 2012 a, b; Marzocchi et al., 2012b; Doyle et al., 2014; Martí, 2015; Sobradelo and Martí, in press) insist on the need to explain the uncertainty that accompanies any forecast regarding the future behavior of a natural system, which can be done through the use of probabilities. The uncertainty that accompanies the identification and interpretation of eruption precursors derives from the unpredictable behavior of volcanoes as natural systems (aleatory uncertainties) and from our lack of knowledge of the behavior of those systems (epistemic uncertainties). These uncertainties can be redefined as superficial or deep (Cox, 2012; Stein and Stein, 2013), depending on the eruption frequency of the volcano. Highly active volcanoes with high eruption frequencies can be more easily forecast (i.e., they are reasonably well known) than those characterized by low eruption frequencies. Therefore, the better we know the past eruptive history and the
more we view the volcanic system as part of a long-term hazard assessment, the better our prediction of its future behavior and all eruption forecasting in case of reactivation will be (short-term hazard assessment).

Final Remarks

Volcanoes represent complex systems capable of generating a number of dangerous phenomena including lava flows, pyroclastic fallout, pyroclastic flows, landslides, gas emissions, earthquakes, lahars, outburst floods, mudflows, and tsunamis. Furthermore, many volcanoes have the potential to generate several or all of these dangerous phenomena simultaneously, even if the frequency, intensity, and scale of each phenomenon is specific to each volcanic system. Despite a broad consensus that every volcano has its own behavior and “personality,” volcanologists do not agree on the extent to which this concept holds true. The eruptive behavior of a volcano can only be assessed by combining a number of information sources such as stratigraphic, sedimentological, petrologic, and structural studies, and geological mapping.

Stratigraphic studies are the main tool for reconstructing a volcano’s activity over time periods that go back beyond the historical record. In volcanic hazard-oriented studies, the use of volcanic stratigraphy has the potential to permit the identification of all past significant eruptive events (eruptions), to assess the age of individual eruptive events and the eruption frequency of the volcanic system, and to reconstruct eruptive sequences (the succession of eruptive acts that occur during a single eruption). Field studies specifically aimed at systematically reconstructing past volcanic activity should reach the standard and precision required in hazard assessment. This information should also constrain theoretical models that pretend to forecast potential scenarios for future eruptions. Models of volcanic and associated processes that do not relay on known geology may end up being too speculative and not reliable for volcano forecasting. So, we should not forget that geological work is essential in long-term and short-term hazard assessment, and that it should constitute the basis on which to build any eruption forecasting model.

This review has presented a systematic approach to the different steps that constitute a volcanic hazard assessment process and paid special attention to the reconstruction of the eruptive history of volcanic systems. It has discussed the most commonly used concepts and methods in both long- and short-term hazard assessments and how they contribute to the reduction of volcanic risk. The main purpose of the review, however, is to promote unified and consistent assessments of volcanic hazard and thus help mitigate the serious social, economic, and political consequences derived from the occurrence (and nonoccurrence in some crisis alerts) of volcanic eruptions and related phenomena. A key aspect of this review’s philosophy is that procedures, methodologies, and technologies should be unified and communicated clearly, consistently, and frequently to social communities via the development of integral approaches to hazard assessment.
Assessing Volcanic Hazard: A Review

Long-term hazard assessment is the first task that a society threatened by volcanoes needs to undertake if it aims to live with volcanoes and take advantage of what they offer (nice landscapes, productive soils, mineral and energy resources, etc). Volcanic hazard assessment is crucial in active zones as a means of improving the quality of life, health, and safety of millions of people worldwide. This is evident if we bear in mind that the continuous threats posed by volcanoes militate against and can dramatically invalidate any serious long-term territorial planning. The impact of disasters caused by eruptions significantly increases when societies are not prepared to cope with volcanic threats or simply ignore them. Erroneous land planning, a lack of emergency plans, and poor knowledge of volcanic hazards and risk—not only among the general population, but also among decision makers and even scientists—may convert a natural event into a disaster.

We must take advantage of new technologies and social media (e.g., Facebook, Twitter) when conducting hazard assessments and presenting the results to society, as they will revolutionise how hazard and risk information is disseminated in the future. For example, the use of information systems in both the long and short terms in hazard assessment and risk management during a real volcanic crisis (and false alarms) will help improve citizens’ safety in the face of natural hazards by making the flow of information in user organizations more efficient (“smart” organisations), fomenting the development of policy tools, and improving the education of citizens. However, discussing modern ways of undertaking hazard assessments and disseminating their results in a much deeper way would require a much longer review and is beyond the purpose of this one, but certainly these aspects deserve attention in further studies.

In conclusion, from a scientific point of view it is necessary to unify methodologies and protocols to facilitate long- and short-term hazard assessments in active volcanic systems, and to design strategies for defining effective educational and communication programs that will minimize volcanic risk. It is also vital to promote the development of fast, ready-to-use, geologically based hazard assessment models that can be used in effective land planning and rational emergency plan design, and also in the management of volcanic crises, thereby contributing to the improvements in risk management and reduction. Scientists in charge of conducting hazard assessments should consider how they can work with governments and civil protection agencies in a logically structured way. From a technological point of view, innovations include the development of integral and easy-to-use GIS-based software with prototype libraries devoted to assessing and managing risk, their links with databases, and the use of network technologies to create virtual agoras as future reference resources, as well as the use of social media as an effective way to disseminate information on hazard and risk. Finally, the analysis of the role that emerging Internet technologies will have in issues such as “interactive knowledge acquisition,” “knowledge representation and reasoning,” “digital library technology,” and “GRID computing technology” will help to establish the foundations for future collaborations in volcanic analysis.
Acknowledgements

This review is the result of several years of work dedicated to exploring ways of improving methods and protocols in volcanic hazard assessment. This is a task that I would not have been able to accomplish without the inestimable collaboration of my colleagues Rosa Sobradelo and Stefania Bartolini. Part of the research conducted to obtain the necessary information was funded by the European Commission (FP7 Theme: ENV 2011.1.3.3-1; Grant 282759: VUELCO; and EC ECHO Grant SI2.695524 (VeTOOLS)). I also thank an anonymous reviewer who provided a constructive and thorough review to the original manuscript. The English text was corrected by Michael Lockwood.

References


http://www.appliedvolc.com/content/2/1/2
Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Assessing Volcanic Hazard: A Review


Joan Martí Molist
Department of Geophysics and Geology, Instituto de Ciencias de la Tierra "Jaume Almera"