HANDBOOK

VOLCANBOX PLATFORM:
A SYSTEMATIC METHODOLOGY FOR VOLCANIC HAZARD ASSESSMENT, RISK MANAGEMENT, AND EARLY WARNING SYSTEM

by
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VOLCANBOX is a muliplatform system developed as part of the projects EC ECHO funded projects: **Development and Implementation of e-TOOLS for Volcanic Hazard Assessment and Risk management (VeTOOLS)** (Grant SI2.695524) (www.vetools.eu), and **European Volcano Early Warning Systems (EVE)** (Grant 826292) financed by European Commission, Directorate-General Humanitarian Aid and Civil Protection - ECHO, A.5 Civil Protection Policy Unit, and integrated into the prevention and preparedness projects in the framework of the Union Civil Protection Mechanism of 2015 and 2018.

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Presentation

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. Volcanic eruptions are considered extreme events that due to their relatively low frequency are sometimes regarded as less important than other natural hazards that impact more frequently, such as the meteorology derived hazards or even earthquakes. However, the high destructive potential of volcanic eruptions and the wide distribution of their potential impacts on people and the environment, strongly recommend to do not left behind our duties concerning risk reduction related to volcanoes. Volcanoes directly threaten large population centres in many areas around the World and have an important influence on the socio-economic development of these regions; as well, they can have serious environmental and economic impacts at global level in the form of climate change and/or the disruption of global air traffic.

Volcanic hazards present a particularly acute threat to Europe. With several volcanic active systems in Europe, and numerous others in member states' overseas territories (e.g. Guadeloupe, Martinique, Réunion, Montserrat and the Macaronesian islands), predicting, preparing for and recovering from volcanic disasters is a pressing concern. Crucially, as the 2010 eruption of Eyjafjallajökull demonstrated, even comparatively small volcanic eruptions do not respect national boundaries and can have a global economic impact. Volcanic hazards are inherently complex, difficult to predict, rarely present a single hazardous threat, and often result in cascading risks.

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, amongst 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

Deaths	**Volcano**	**Location**	**Year**	**Major Cause of Death**
92,000	Tambora	Indonesia	1815	Starvation
36,417	Krakatau	Indonesia	1883	Tsunami
29,025	Mt. Pelee	Martinique	1902	PDCs
25,000	Nevado del Ruiz	Colombia	1985	Lahars
14,300	Unzen	Japan	1792	Volcano collapse, tsunami
9,350	Laki	Iceland	1783	Starvation
5,110	Kelut	Indonesia	1919	Lahars
4,011	Galunggung	Indonesia	1882	Lahars
3,500	Vesuvius	Italy	1631	Lahars, lava flows

Table 1: Summary of losses of most deadly eruptions (from Siebert et al., 2010)

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. However, despite these crucial advances, the evaluation and management of volcanic risk still has some important shortcomings, as it is 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.

In order to help mitigate these problems and to help scientists and Civil Protections to collaborate and work together, the VeTOOLS project was aimed at defining a precise methodology and to develop the corresponding tools to conduct volcanic hazard assessment and risk management in a systematic and comprehensive way. For this reason, the project developed the set of tools required to conduct volcanic hazard assessment in a systematic way. All these tools have been integrated into a multi-platform, named VOLCANBOX (www.VOLCANBOX.eu), which facilitate the interaction and cooperation between scientists and Civil Protection Agencies in order to share, unify, and exchange procedures, methodologies and technologies to effectively reduce the impacts of volcanic disasters by improving assessment and management of volcanic risk (Martí et al., in prep a; Martínez-Sepúlveda et al, in prep a). The EVE project has gone a step forward implementing new tools for hazard and risk analysis into the VOLCANBOX platform and also a new module that corresponds to the first European Volcano Early Warning System (VEWS). This VEWS has the objective to help European Civil Protections and Volcano Observatories, to anticipate as early as possible to new volcanic eruptions, thus contributing to enhance their prevention and preparedness to reduce the impact of such hazards (Martí et al in prep b).

This handbook presents a general description of the concepts and methodologies that are behind VOLCANBOX and explains the different tools that it contains offering some examples on their use and on the limits of its applicability. The handbook is written in an easy and simple way that should allow potential readers and users to understand it as an effective guideline to help in conducting volcanic hazard assessment and risk management. The idea of VOLCANBOX is to grow up as new tools will be incorporated into it, so this handbook is limited, for what concerns the description of tools, to those now included in the system. However, the concepts exposed reflect the the common understanding shared by the members of the VeTOOLS and EVE projects on how volcanic risk reduction should be accomplished.

Barcelona, February 28, 2022

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PART 1: GENERAL CONCEPTS

1.1. Hazard vs. 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 socio-economic 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, i.e. 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 x value x vulnerability (Fournier d'Albe, 1979). Hazard is the physical event having an impact on a particular area within a specific timeframe and so contains implicit spatial (i.e. the probability that the effects of the event will extend over a certain distance or surface area) and 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:

$$\text{Risk} = \frac{\text{Hazard x Vulnerability x Value}}{\text{Mitigation measures}}$$

The enormous human and economic losses caused by unexpected volcanic events can unfortunately be easily illustrated by numerous historical examples (see 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 programmes is always preferable to merely reacting once disasters have struck.

An overall risk reduction plan should include several essential programmes that work in harmony: 1) a scientific programme aimed at improving knowledge of the process and its potential impacts (i.e. hazard assessment); 2) a monitoring programme for determining the current state of activity of the process; 3) an educational programme,, to educate the population about the potential hazards and risks that threaten them; and 4) a management programme for designing emergency plans and resilience strategies (Fig. 1). Each of these programmes should include a corresponding public communication and outreach sections in order to add transparency to the scientific process and to build support, trust, and understanding on the part of the public. These programmes 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.

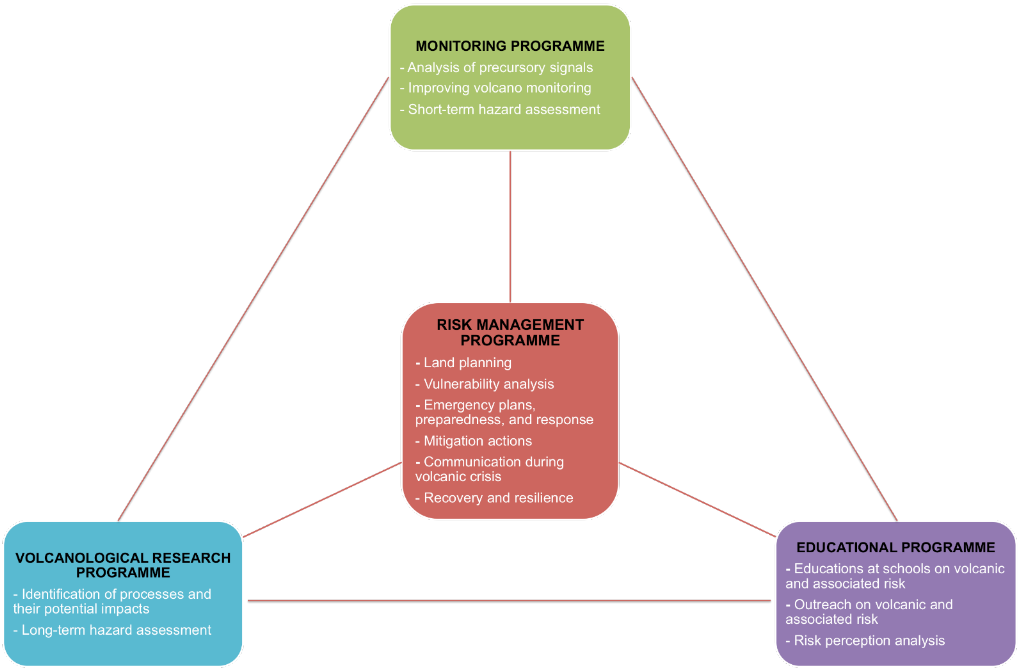


Figure 1. Volcanic risk reduction tetrahedron, showing the essential programmes to be conducted and the main tasks included in each of them (after Martí 2017).

Therefore, hazard assessment is one of the first steps in estimating risk and in 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 categorise 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 programmes and dissemination actions focused on explaining to the local population the volcanic hazards they are exposed to. Finally, hazard assessment is a pre-requisite for conducting vulnerability analyses and estimating the potential impact and the economic losses to societies and the environment in the event of a fresh eruption.

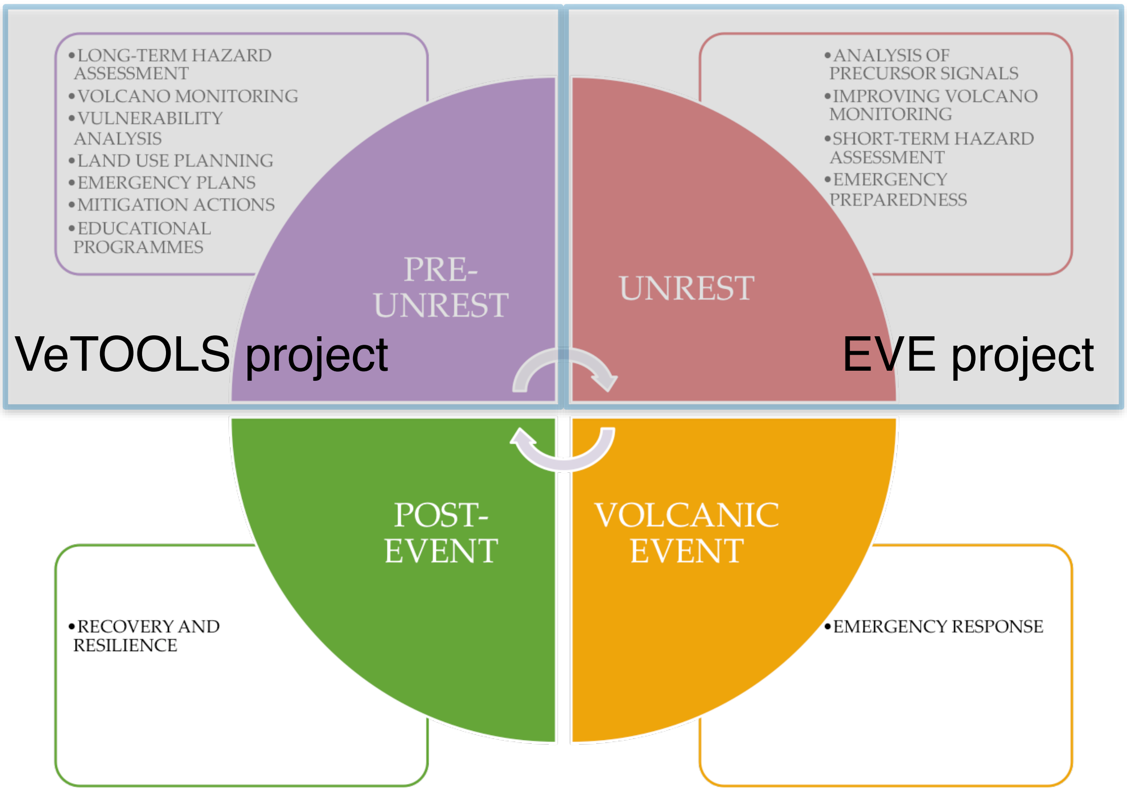


Figure. 2. Phases of the volcanic risk management cycle and main tasks to be conducted in each of them (after Martí 2017), and indication of the work done in the VeTOOLS and EVE EC ECHO projects, respectively

1.2. Active vs. 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 behaviour 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 and 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, i.e. 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.

1.3. Polygenetic vs. monogenetic volcanism

Volcanoes are characterised 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 behaviour 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 behaviour such as effusive, explosive, Strombolian, Plinian, Vulcanian and Pelean that were assumed to characterise certain types of volcano may on occasions be misleading since a volcano may exhibit explosive and effusive, and/or Strombolian, Plinian or Vulcanian, behaviour during different eruptions or even during the same eruption.

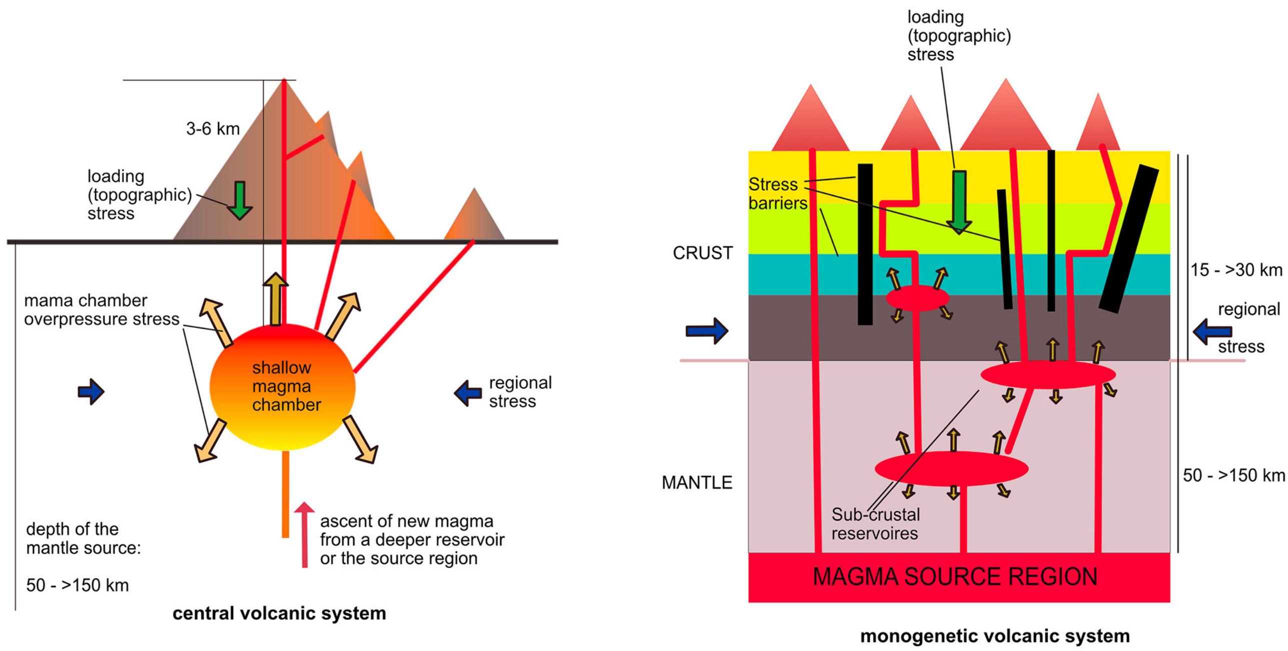


Figure 3. Sketch illustrating the main differences between polygenetic (central) and monogenetic volcanisms and the main stress components in each of them (see text for more explanation) (After Martí et al., 2016)

When analysing 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 (i) are active for hundreds of thousands or even millions of years, (ii) always produce eruptions from the same central vent or vent system and thus construct large volcanic edifices composed of lavas and volcaniclastic products, and (iii) 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 shield volcanoes (Mauna Kea and Mauna Loa in Hawaii, Nyamuragira in the Congo, and Fernandina in the Galapagos) that are generally characterised by either (i) broad, low-relief volcanic edifices mostly constructed out of lavas and pyroclasts of mafic composition

(Walker, 2000) or (ii) composite or central volcanoes or stratovolcanoes (e.g. El Teide in Tenerife, Vesuvius in Italy, Mt St Helens in USA, 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 Marti, 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., 2003; 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, and so forth).

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 (Michocan-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 characterise 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., 2009) 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 otherwise of a shallow magma chamber and the resulting stress fields that characterise 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 kilometres 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 normal to the minimum and parallel to the maximum compressive stresses). An over-pressurised 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). 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 so 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 analogue 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.

1.4. Volcanic unrest

A volcanic eruption typically requires a batch of magma to ascent to the earth surface. Magma may come from shallow or deep reservoirs (or chambers) where it has accumulated and differentiated, or from deeper source regions. To reach the earth's surface, magma needs to deform the surrounding rock displacing it apart and opening new fractures to create the necessary space and pathways to cross from deeper to shallower levels. This will produce a series of changes in the vicinity of the magma that may be translated into surface deformation, seismicity, or other changes of potential fields that should be detected by ground based and remote geophysical monitoring systems (Scarpa and Tilling, 1996; Sparks, 2003; Sandri et al., 2004; Cañon-Tapia, 2014). When magma approaches to the surface and pressure around it decreases, the dissolved gases may exsolve and separate from the liquid phase, thus giving rise to appearance of geochemical indicators of magma ascent.

Therefore, when the state of a volcano changes as magma increases in pressure and migrates inside the system, the volcano experiences an increase in the activity that is being monitored, changing the values of the measured geochemical and geophysical parameters. However, a volcano may also change its state due to external factors not related to the magma itself, such as changes in regional tectonics or in the conditions of the associated geothermal systems, which will also result in a variation of the monitored parameters. Whether o not the observed activity at a given volcano and at a given time is caused by changes in the magmatic system or to changes of the regional stresses or the volcano geothermal system, and whether or not the unrest phase will end with an eruption, is the challenging question that needs to be answered with a proper interpretation of monitoring data and good knowledge of the volcano's past behaviour.

This change of activity (seismicity, ground deformation, gas emissions.) compared with a previous background level is what is generally known as volcanic unrest. To reduce the potential impacts of volcanic eruptions, it is crucial to be able to anticipate them well in advance. These signals may be recorded by various monitoring instruments, in many cases, also felt by the populations leaving close to the volcano.

Every volcano has its own physical and chemical characteristics (internal structure, rock rheology, magma composition, etc.) and thus pre-eruptive unrests may show a significant range in values or thresholds for the monitored geophysical and geochemical parameters. A given volcano may show some level of commonality on a given parameter (e.g. RSAM) for eruption of similar size and character (e.g. Merapi; Ratdomopurbo, 2013) but it may also show unrest periods that differ from the patterns that occurred in 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 times. We have no record of monitoring data to use as a background, and the detailed knowledge about previous eruptions may also be lacking (e.g., Sinabung 2010).

Establishing potential patterns in the evolution of volcanic unrest that could help identifying the outcome within a limited degree of uncertainty requires the analysis of as many unrest episodes as possible. The importance of having large datasets to use probabilistic analysis in eruption forecasting stresses the need of a database of observational data freely available for being consulted. This is what pretends the WOVOdat project (www.wovodat.org), a database initially designed by Venezky and Newhall (2007) and now being maintained and implemented at the Earth Observatory of Singapore, which shows time series of monitoring data that can be analysed and compared for different eruptions and volcanoes. WOVOdat will certainly be of invaluable will help to identify possible behaviour patterns when the amount of data stored will be universally representative for all types of volcanism and volcanic eruptions. However, the use of WOVOdat and other databases (e.g.: Siebert et al., 2010; Phillipson et al., 2013; Potter et al., 2015), including the data sets stored in each volcanic observatory around the world, requires that some definitions and concepts are generally accepted and in practice to facilitate the interpretation of existing data and, more importantly, their comparison among eruptions and volcanoes. Data need to be reported and interpreted in the same way (i.e., using same formats and time scales) to be able to identify common or different behaviour patterns among all volcano types and, thus, to establish effective methods to forecast volcanic eruptions.

Eruption forecasting cannot be only based on the analysis of volcanic unrest, as it also requires to identify which outcomes from such unrest (e.g.: no eruption, phreatic explosion, magmatic eruption) have the highest probabilities of occurrence and how are they associated to a given unrest pattern. This is necessary to correctly implement the emergency plans according to the most probable outcome. Therefore, eruption forecast also requires a hazard assessment that needs to be combined with the unrest analysis, in order to get a precise short-term hazard analysis that could identify how, when and where the next eruption will be, rather than only knowing whether the eruption will occur or not. Otherwise, it may result in failed volcano forecasts (e.g.: La Sufriere Guadeloupe, 1976; Tungurahua, Ecuador , 1999).

The background level of activity above which we may consider that volcanic unrest is occurring needs to be defined for each volcano by experts who know how is currently behaving and it has done in the past. Establishing a background level of activity should be mainly based on volcano monitoring data but also considering other volcanological aspects such as the past history of the volcano. For example, it is well-known that caldera volcanoes may go through many more major episodes of unrest than stratovolcanoes before they erupt. Comparison with other volcanoes may sometimes help, but volcanoes are complex natural systems, subjected to a large number of non-linear processes that make them easily departing from pre-assumed patterns. Even if eruptions of similar characteristics may occur at different volcanoes it is not necessarily true that unrest episodes preceding them have to be also similar. However, we may assume that volcanic unrest will normally imply an increase in seismicity, ground deformation and gas emissions (Scarpa and Tilling, 1996; Sparks, 2003; Cañon-Tapia, 2014), but the range of variation of each parameter, as well as the time scales for these variations, may differ significantly from one volcano to another (Fig. 4). Also, the fact that volcanic unrest can be triggered by the movement of fresh magma but also by changes in the geothermal system (e.g. overpressurisation due to self sealing, e.g.: Gaetta et al 1996; Chiodini et al., 2002), or in regional tectonics (variation in magnitude of differential stresses, e.g.: Hill et al., 2002), illustrates that depending on the cause of unrest, the monitoring parameters and their possible combination may be different among volcanoes or even in the same volcano (Sobradelo and Martí, 2015).

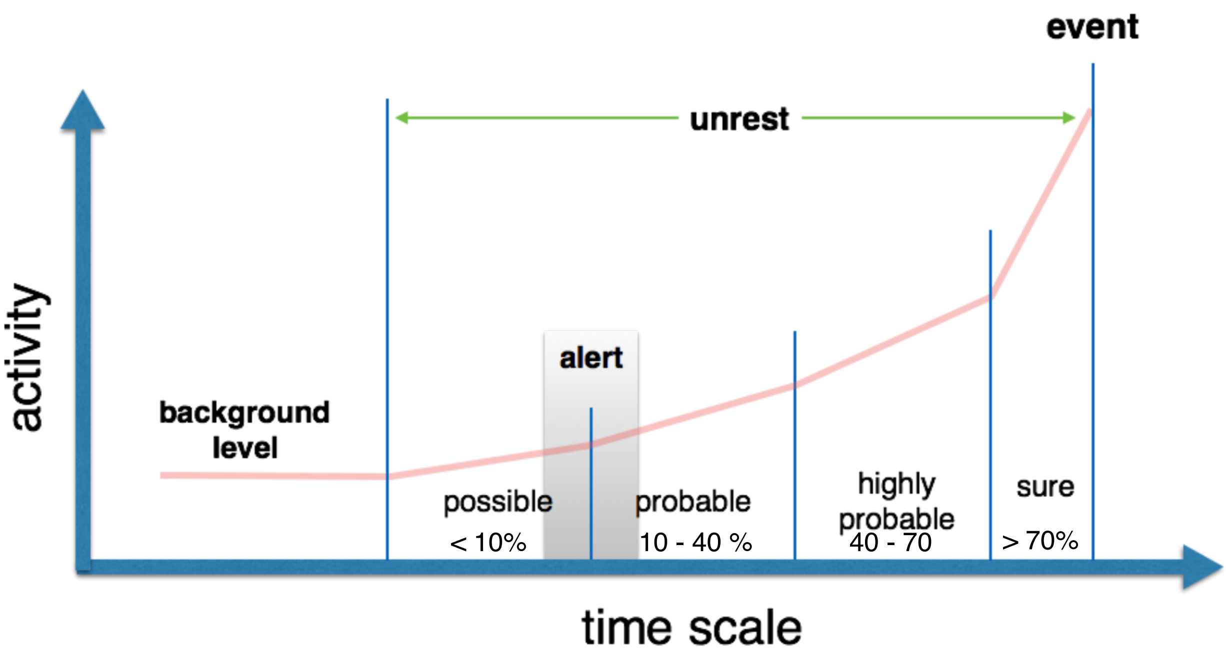


Figure 4. Time evolution of volcanic activity during an unrest episode (not to scale). Volcanic unrest starts when there is an increase of activity (i.e., increase in the values of the monitored parametres) in the volcanic system with respect to a previous background level. In most cases (e.g.: www.WOVOdat.org) volcanic activity will increase progressively, with a clear acceleration at the last moment, until an event occurs (eruption or no eruption). The occurrence of an event marks the end (the outcome) of that particular unrest, even if volcanic activity increases again (new unrest episode). We also indicate the relative stages in the evolution of the unrest in terms of probabilistic forecasting of the unrest outcome, as well as the time window in which normally an alert is declared. Despite the shape of the curve represented here is similar in most volcanic unrests, the exact level of activity and duration of the unrest may be significantly different between volcanoes and between eruptions of the same volcano. Values indicating probabilities of occurrence have been fixed arbitrarily

The analysis of an unrest episode requires defining its time limits (when it starts and when it finishes) (Fig. 4). This is not an easy task as not all volcanoes present the same background level of activity, and not all unrest episodes have the same level or intensity of activity. In other cases, the background level of activity may be not known because of lack of monitoring or the short time in which it has been operating. In others, we may observe fluctuations (i.e. increases and decreases of activity; e.g. calderas) that may not help to define a clear tendency in the evolution of the unrest. Also, we can have volcanic systems in permanent unrest since monitoring was implemented, so there is no confidence to establish a reference background level. Moreover, in retrospective analysis we may want to consider time scales much longer than the monitoring period, or the unrest phenomena described in historical chronicles. Or, we may face the dilemma of whether or not significant increases of activity not ending with an eruption can be considered as unrest. To avoid these problems, we assume that an unrest episode is any variation with respect to the background level or, in other words, any change in the state or dynamics of the volcanic system, recorded by monitoring networks and/or perceived by the nearby populations, which correlates with a volcanic event (outcome in the terms of hazard), being this an eruption or no eruption. Any unrest episode will have different stages and forecasting of the outcome should be more reliable as time passes and more information is gathered (Fig. 4). In the case that the unrest does not end up with an eruption, the return of the geophysical and geochemical indicators to a background level will coincide with the end of the unrest episode. With this definition we assume that any unrest represents a change in the conditions of the volcanic system and allows to analyse the time variation of such changes along the recorded (historical and monitored) history of the volcano (Fig. 5).

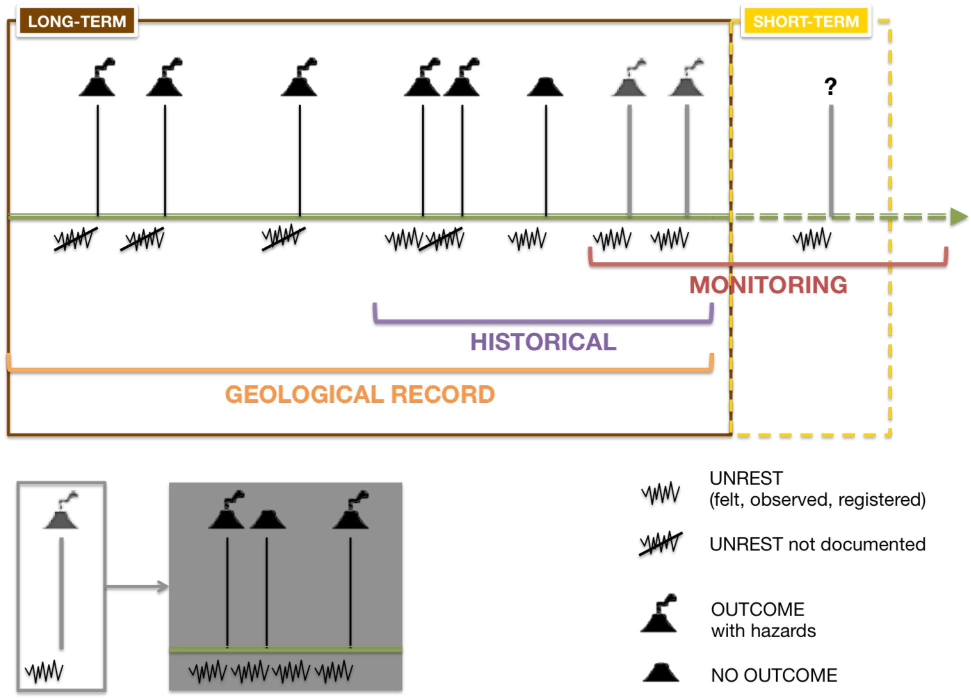


Figure 5. Time scale evolution of long- and short-term hazard analyses and variation of the degree of detail, considered in eruption forecast. Long-term hazard assessment: Long-term assessment is based on historical and geological data, as well as on simulation models of possible hazards, and refers to the available time window before an unrest episode occurs in a volcanic system that currently shows no signs of unrest. Short-term hazard assessment: refers to 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 and to forecast a possible eruption. Unrest: any variation with respect to the background level or, in other words, any change in the state or dynamics of the volcanic system, recorded by monitoring networks and/or perceived by the nearby populations, which correlates with a volcanic event (outcome in the terms of hazard), being this an eruption or no eruption. In the case that the unrest does not end up with an eruption, the return of the geophysical and geochemical indicators to a background level will coincide with the end of the unrest episode. Outcome: end of the unrest associated with a hazard occurrence. No outcome: end of unrest without associated hazard. Historical: time period that goes from the appearance of written records to present. Monitoring: time period that covers the registered instrumentally volcanic activity. Geological record: time period that covers all geological registers from a specific volcano or volcanic system.

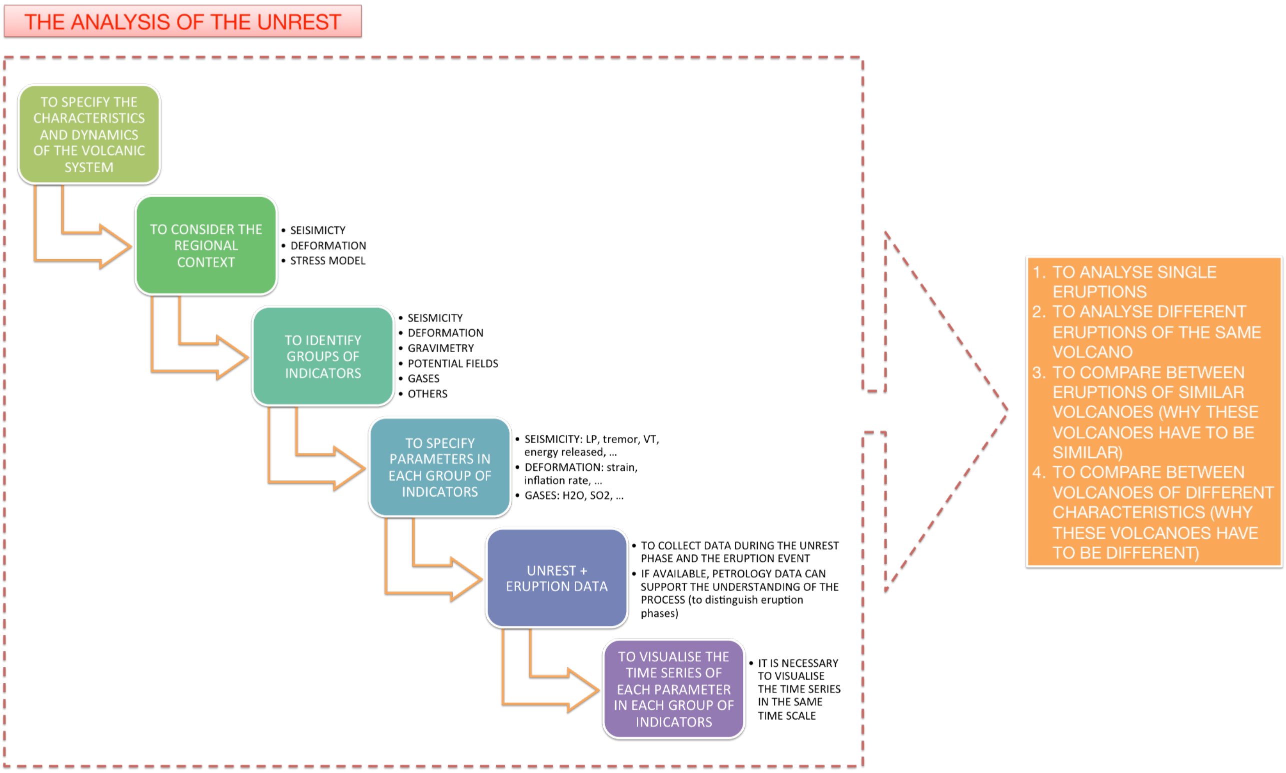


Figure 6. Schematic representation of the stages included in the volcanic unrest analysis, indicating the different aspects or parameters to be considered, and the possible uses of such analysis (see text for more explanation).

Figure 6 shows a flow chart-type diagram detailing the sequential way in which we could approach the different steps of a volcanic unrest analysis. We suggest that to understand volcanic unrest it is first necessary to characterise the volcano or volcanic systems in terms of eruption dynamics, eruption frequency, and magma composition. This will provide the basic parameters that, in case of initiating a volcanic unrest, will offer the clues on the intensity of the unrest and on how it may evolve. In addition, we need to gather information on the geodynamic setting and degree of deformation (seismicity, strain, …) that the volcano may be currently experiencing at a regional level. This allows discriminating between local deformation that may be attributed to the volcano from that related to the activity of plate boundaries or mantle instabilities (e.g mantle plume upwelling). Another important step is to identify groups of unrest indicators that will better describe the evolution of unrest in our volcano. These will surely include seismicity, surface deformation, potential fields, gases and may be other that we could consider in each particular case and depending on monitoring facilities available. For example, in open vent volcanoes degassing and seismicity seem to be better indicators of unrest than deformation, whereas currently the dome complex of Laguna del Maule is experiencing a huge deformation and significant seismicity, although limited or no degassing. The next step is to specify which particular parameters we will consider (e.g.: for seismicity: seismic energy released, total number of VT events, presence of LP events,…..; for gases: total gas flux, presence of SO2, …..), and which ranges of variation may be assumed to consider a change in activity significant or representative of the evolution of the volcanic unrest. Some directions towards such systematisation of unrest have already been done (e.g. Potter et al 2015).

Here we have emphasised monitoring data before the eruption, but it is also necessary to collect monitoring data during the eruption, in order to observe possible variations of monitoring parameters related to variations in eruption dynamics, which could indicate variations in the plumbing system. This analysis needs to be complemented with the petrological and rheological characterisation of erupted products, as variations in composition and physical properties of magmas may be related to changes in the plumbing systems and eruption dynamics (Saunders et al 2012; Martí et al 2013; Tárraga et al 2014).

Finally, it is convenient to carry out a retrospective analysis of all time series in order to make them comparable at the same time scale, as this will allow us to identify possible changes in the evolution of the volcanic unrest and during the eruption, which could be used as precursors in next events, thus helping to improve volcano forecasting. We believe with such systematisation of unrest indicators and combination with other geological data we should be able better forecast and understand the physical meaning of various levels of unrest

1.5. 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 (Fig. 7). 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 which direct and indirect hazards can derive from a volcanic eruption and which interrelations they may show.

Volcanic eruptions exhibit a large variety of different dynamics and engender (i) direct hazards (i.e. those directly derived from the volcanic activity) dependent on factors such as magma composition, rheology and availability, and rock permeability and strength, and (ii) indirect hazards (i.e. those triggered by the action of the direct hazards) that will unfold as the eruption interacts with the surrounding area. Eruptions may last from just a few hours to several years – or even longer in the case of the flood basalt eruptions – and may involve volumes ranging from a few millions of cubic meters to several thousands of cubic kilometres. A volcanic eruption may evolve from effusive to explosive and/or vice versa, which is why today it is more usual to distinguish between phases and pulses (e.g. Strombolian, violent Strombolian, Plinian, dome growth, dome collapse, lava fountaining, etc.) within a particular eruption rather than to classify eruptions, as in the past, as simply corresponding to one or another eruptive style (e.g. Pelean, Strombolian, Vulcanian, lava flow, etc.). Each phase and pulse of volcanic eruption may generate a variety of products, which will have different dynamics and emplacement modes and so will generate different potential hazards.

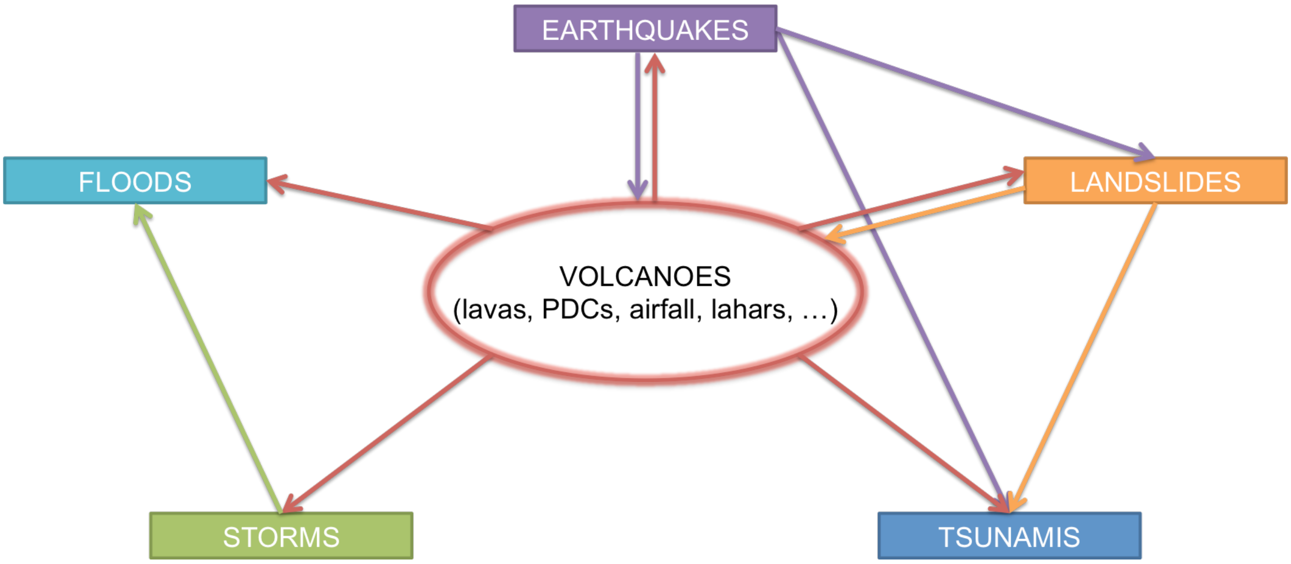


Figure 7. Causes/effects relationships between the main direct and indirect volcanic hazards (see Table 2) (after Martí, 2017)

In general terms, we distinguish between effusive and explosive eruptive activity depending on whether or not the magma is fragmented (i.e. it generates pyroclasts) by the expansion of the dissolved gases as the magma decompresses. Although more primitive (or mafic) magmas tend to be poorer in volatiles (gases) than more evolved (or felsic) magmas, both types of eruptive activities are common in all magmatic compositions. Additionally, depending on the effectiveness of the pre-eruption degassing, which will essentially depend on the permeability of the host rock, the amount of gas retained in the magma may decrease significantly, thereby transforming what could have been a potentially explosive eruption into a non-explosive one. Conversely, when magma interacts with meteoric water in a lake or an aquifer or with seawater, a weak or non-explosive eruptive episode may be transformed into a highly explosive one. However, the aim of this review is not to enter into eruption dynamics in great detail and readers should consult the abundant volcanological bibliography on the subject if necessary (e.g.: Francis, 1993; Sigurdsson, 2000; Dobran, 2001; Martí and Ernst, 2005; Parfitt and Wilson, 2008).

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.

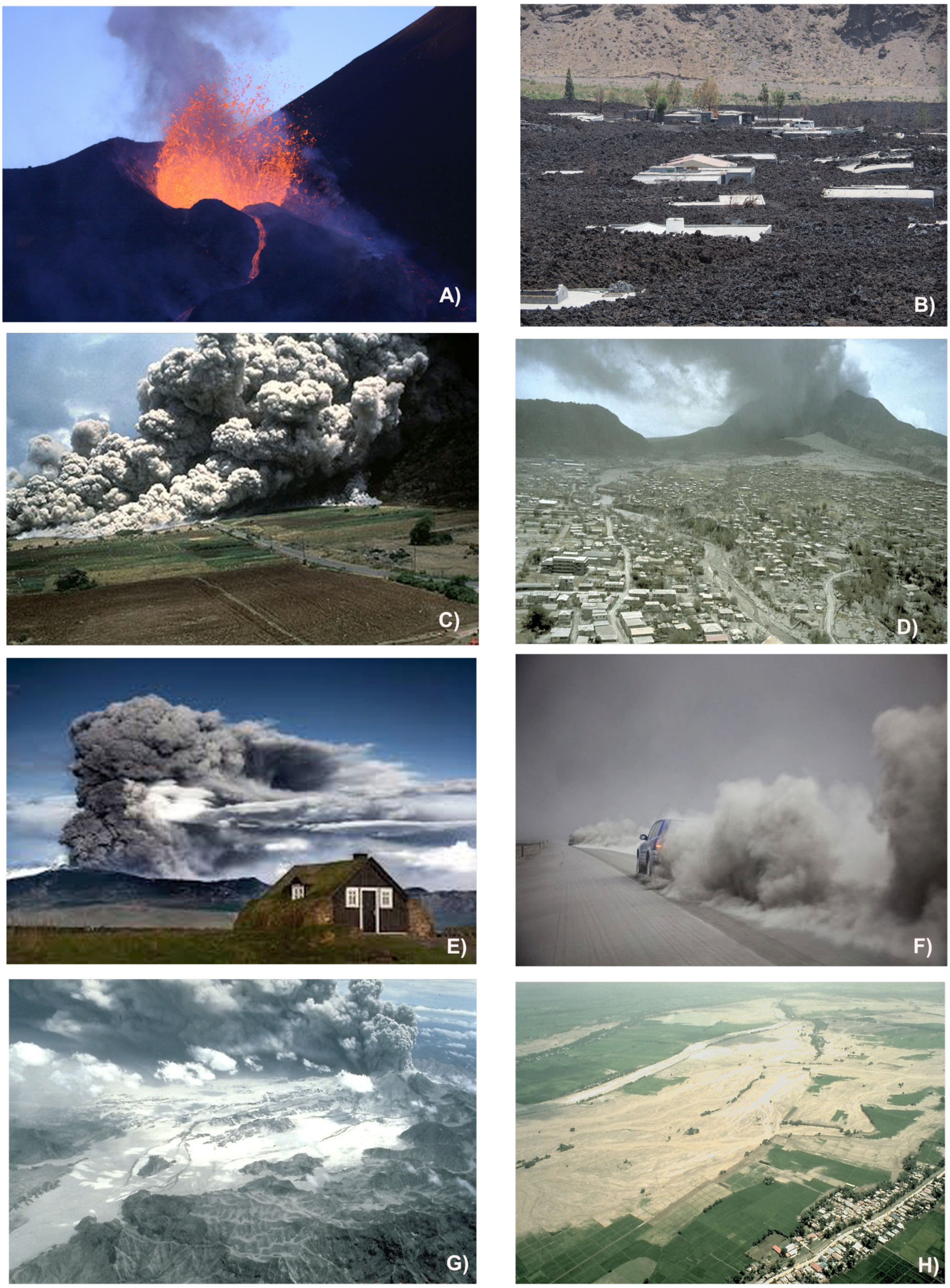


Figure. 8. Examples of volcanic hazards and their impacts (photos). A) Lava fountain and during Fogo (Cape Verde) eruption of 2014 (Photo: Ricardo Ramalho). B) Bangaeira Town (Fogo) partially buried by the 2014 lavas (Photo: Joan Marti). C) Example of La Sufriere (Montserrat) pyroclastic density current (PDC) (Photo: internet). D) Plymouth town partially buried by the La Sufriere PDCs desposits in 1995 (Photo: https://en.wikipedia.org/wiki/Montserrat). E) Eruption column during the Eyjafjallajokull 2010 eruption (Photo: www.eventbrewer.com). F) Road covered by ash fallout during the Eyjafjallajokull 2010 eruption (Photo: http://

phys.org/news/2010-04-ash-fall-iceland-contaminate-experts.html). G) Lahars forming from Pinatubo eruption 1991 (Photo: internet, www.geo.auth.gr). H) Distal areas inundated by the Pinatubo lahars (Photo: Internet, www.geo.auth.gr)

Type of hazard	Hazard	Nature and main characteristics	Main physical controls
Direct hazards	Lava flows	Non-fragmented magma, continuous non-newtonian flow	Gravity, topography, temperature, viscosity, eruption rate
	Ballistics	Particles ejecta directly from the vent during explosive phases, ballistic emplacement	Gravity, density, air friction, explosion intensity, ejecta angle
	Fallout	Magma and rock fragments transported into the atmosphere by eruption clouds, deposited as individual particules	Gravity, density, particle size and shape, air friction, atmosphere structure (density and viscosity), diffusivity, wind velocity
	PDCs (dilute)	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 lateraly directed blast explosions	Gravity, grain-size distribution, momentum, temperature, particle/gas ratio, juvenile pyroclasts/lithics ratio, topography, flow regime, total mass
	PDCs (dense)	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	Gravity, grain-size distribution, temperature, momentum, particle/gas ratio, juvenile pyroclasts/lithics ratio, topography, flow regime, total mass
	Lahards	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	Gravity, topography, solid/water ratio, grain-size distribution, yield strength
	Debris avalanches	rockfalls, rockslides, and debris avalanches, which can move rapidly downslope and which are originate immediately before, during, or immediately after an eruption	Gravity, topography, bulk density
	Floods	low density normal stream flows primarily that may originate from lahars when they reduce particle concentration of from syn-eruptive heavy rainfall	Gravity, topography, grain size, water content, yield strength, bulk density
	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
	Earthquakes	Ground shaking and movements caused by seismic shocks of magnitudes usually of ≤ 5, associate to magma movement and readjustment of the volcanic systems during eruptions	Hypocentral location, structure and stratigraphy of volcanic system, local effects, rupture dynamics.

Indirect hazards	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 which energy is transferred from the impact (volcanic explosion,edifice collapse, earthquake, …) to the water column.
	Secondaris debris flows	Slurry of pyroclasts, rock debris and water that originates on the slopes of volcanoes after a volcanic eruption	Gravity, topography, solid/ water ratio, grain-size distribution, yield strength
	Post-eruption erosion and sedimentation	In mass remobilisation of volcanic material by heavy rainfall and other post-eruption causes	Gravity, topography, grain size, water content, yield strength, bulk density
	Atmospheric effects	Local changes of atmospheric dynamics (rainfall, shock waves, lighting) caused by the entrance of ask particles and gases into the atmosphere surrounding the erupting volcano	Eruption cloud characteristics, atmosphere charactestics
	Climatic effects	Regional to global effects on climate caused by the formation of aerosols by the injection of volcanic gases and ash particles in the high atmosfere	Size of the eruption, columns height, gases composition, total mass injected, winds strength and direction
	Famine and desease	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.	Size of the eruption, columns height, gases composition, total mass injected, atmosphere structure and dynamics, winds strength and direction
	aircraft ecounters with volcani 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.	Engines characteristics, grain size, composition and shape of ash particles, concentration of ask in atmospheric air

Table 2: Principal types and characteristics of volcanic hazards (adapted and expanded from Blong, 1984 and Tilling, 2005).

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 (Fig. 8).

Lava flows constitute the commonest volcano hazard resulting from a non-explosive 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 and so 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 kilometres and cover hundreds of square kilometres at velocities of up to several kilometres per hour (Tilling, 2005). In some extreme cases, such as the Columbia River Basalts in the USA, the flow discharge rate has been estimated at $1x10^6$ m^3/sec and the resulting lava flows cover tens of thousands of square kilometres (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 sub-rounded) 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 and so 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 kilometres. 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 kilometres 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). 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 1000s 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 kilometres, 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 centimetres 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 occasions 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 pyroclastic density currents (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 one hundred kilometres. 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 post-eruption (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 vapour 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 kilometres in distance (Lavigne et al., 2000; Vallance, 2000).

Another important direct volcanic hazard are 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 18 May 1980 on Mount St Helens in the USA (Voight et al., 1981). Due to the steep slopes that characterise many large volcanoes, such avalanches are often highly mobile and can run for several tens of kilometres (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 relationship 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).

1.6. Size and duration of volcanic eruptions

An intrinsic concept that is usually taken for granted by experts and non-experts 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 section.

VEI	Ejecta Volume (bulk)	Classification	Description	Plume height	Frequency	Troposphere injection	Ionosphere injection	Examples
0	< 10,000 m³	Hawaiian	Effusive	100 m	constant	negligible	none	Kīlauea, Piton de la Fournaise, Erebus
1	> 10,000 m³.	Hawaiian / Strombolian	Gentle	100 m - 1 km	daily	minor	none	Nyiragongo (2002), Raoul Island (2006), Stromboli Island - (continuous since Roman times to present)
2	>100,000 m³	Strombolian / vulcanian/ Hawaiian	Explosive	1-5 km	weekly	moderate	none	Unzen (1792), Cumbre Vieja (1949), Galeras (1993), Sinabung (2010)
3	> 10,000,000 m³	Vulcanian / Peléan/Sub-	Catastrophic	3–15 km	few months	substantial	possible	Nevado del Ruiz (1985), Soufrière Hills (1995), Nabro (2011)
4	> 0.1 km³	Peléan / Plinian/Sub-plinian	Cataclysmic	> 10 km (Plinian or sub-Plinian	≥ 1 yr	substantial	definite	Mayon (1814), Pelée (1902), Galunggung (1982), Eyjafjallajokull (2010)
5	> 1 km³	Peléan/Plinian	Paroxysmic	> 10 km (Plinian)	≥ 10 yrs	substantial	significant	Vesuvius (79), Fuji (1707). Tarawera (1886), St. Helens (1980), Puyehue (2011)
6	> 10 km³	Plinian / Ultra-Plinian/ Ignimbrite	Colossal	> 20 km	≥ 100 yrs	substantial	substantial	Veniaminof (c.1750 BC), Huaynaputina (1600), Krakatoa (1883), Novarupta (1912), Pinatubo (1991)
7	> 100 km³	Ultra-Plinian/ Plinian/ Ignimbrite	Super-colosal	> 20 km	≥ 1,000 yrs	substantial	substantial	Mazama (c. 5600 BC), Thera (c. 1620 BC), Mount Rinjani (1257), Tambora (1815)
8	> 1,000 km³	Ignimbrite/ Plinian/Ultra-Plinian	Mega-colosal	> 20 km	≥ 10,000 yrs	vast	vast	La Garita caldera (26.3Ma), Yellowstone (640,000 BC), Toba (74,000 BC), Taupo (24,500 BC)

Table 3: Volcano Explosively Index (VEI) (adapted from Newhall and Self, 1982, Siebert et al., 2010, and VEI, 2015)

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 (DRE), 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) have 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.

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, non-explosive eruptions may continue for several weeks or even months or years.

1.7. Long-term vs. 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 (Marzochi 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.

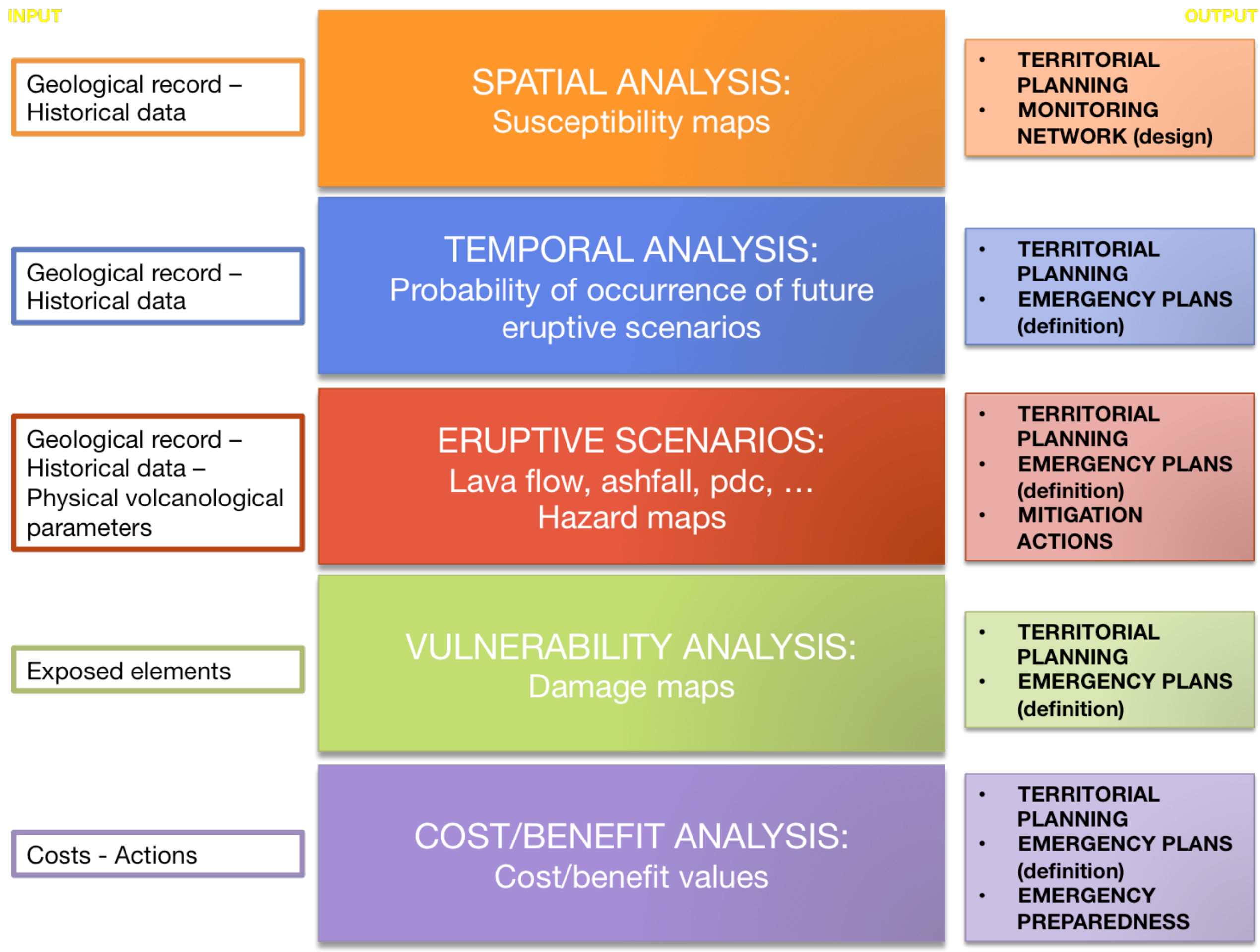


Figure 9. Schematic representation of the sequential steps included in long-term hazard assessment, indicating the input parameters, possible outputs of each phase of such analysis, and the corresponding actions (see text for more explanation).

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 (Fig. 9). 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 (Fig. 10). 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.

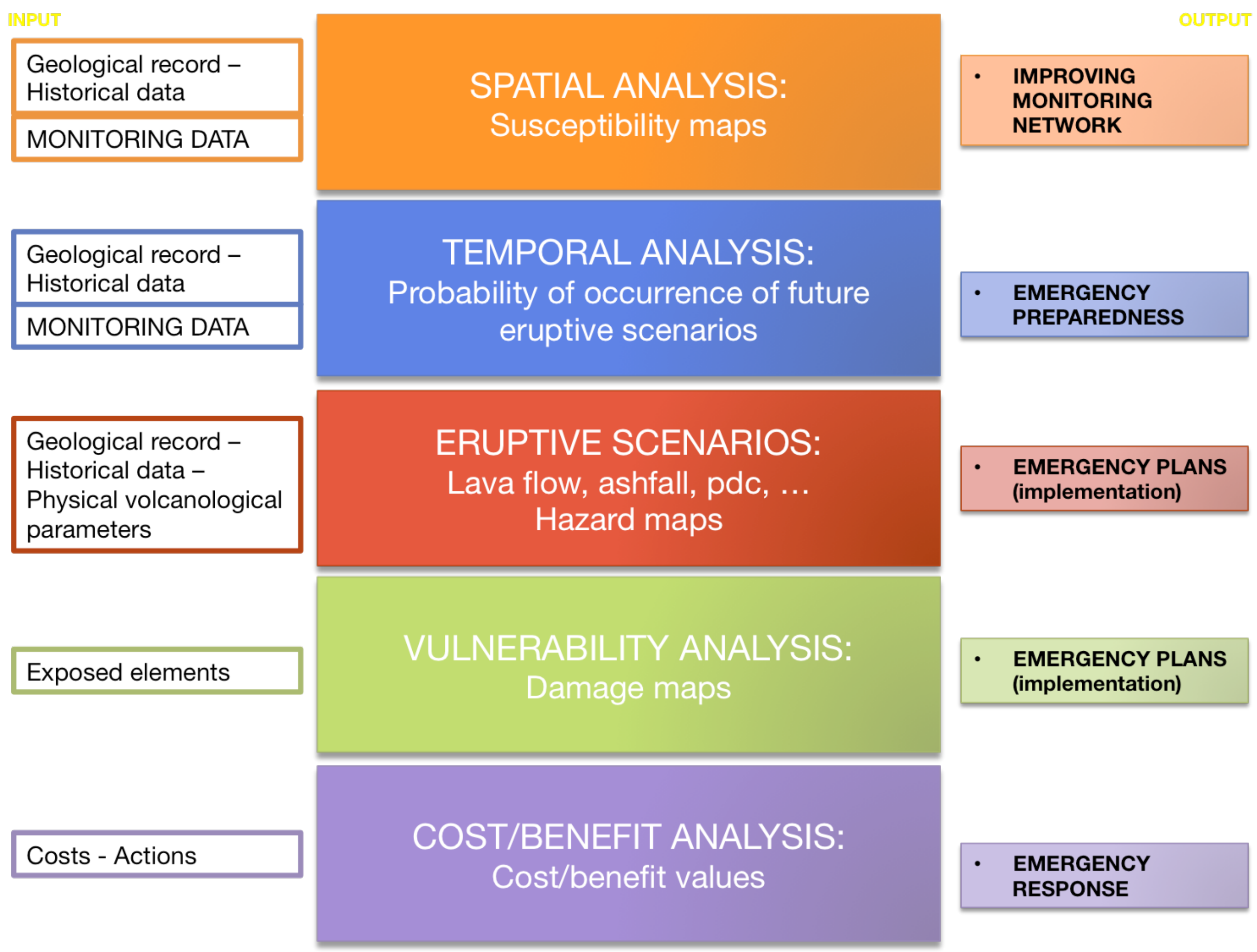


Figure 10. Schematic representation of the sequential steps included in short-term hazard assessment and how it combines with the long-term analysis, indicating the input parameters and possible outputs of each phase of such analysis, and the corresponding actions (see text for more explanation).

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.

1.8. Spatial and temporal analyses

As indicated above, 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 behaviour 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, characterise the succession of volcanic deposits represented in each eruption, and reconstruct the sequence of eruptive and depositional events that formed them (Cas and Write, 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 products. 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 will 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 (eg: Pinatubo 1991 eruption, Philippines, Newhall and Punungbayan, 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 non-volcanic processes (Cas and Write, 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 characterise 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 centres, 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 behaviour (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 post-eruptive processes may remove or transform the primary deposits, and products from other eruptions can become incorporated into the stratigraphic sequence (Cas and Write, 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 Write, 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 (Marti and Geyer, 2009; Martí and Felpeto, 2010; Menand, 2011; Gundmundsson, 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 behaviour of the volatile components) should provide valuable information on the eruptive behaviour 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 behaviour 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, i.e. sampling must be conducted on all the eruptive units that erupted during a pre-defined time interval.

1.8.1. 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 determine 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 analysed 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 characterised 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 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 centres 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 is 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 (Marzochi et al., 2008; Sobradelo and Martí, 2013; 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, 2013; Bartolini et al., 2016). Nevertheless, depending on the characteristics of the volcanic system, significant uncertainty will still be associated with forecasts.

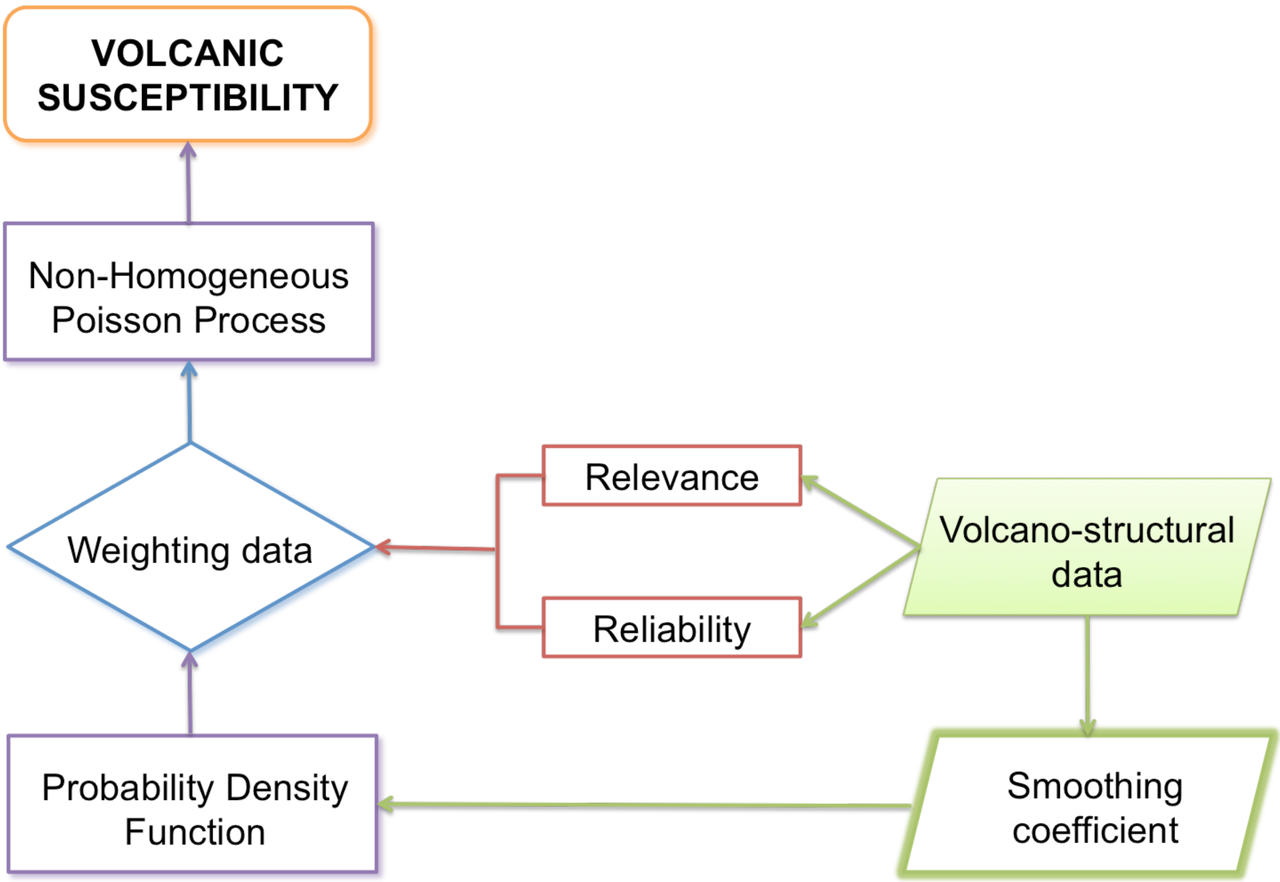


Figure. 11 Flow chart describing how volcanic susceptibility is evaluated (see text for more explanation)

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 centres is clearly not random as vents tend to cluster. In these cases, a non-homogeneous 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. 11). 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 of the data considered in the evaluation of the volcanic susceptibility. As explained above, the structural elements used to calculate volcanic susceptibility are stress indicators; nevertheless, some are better then 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; Bevilaqua 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 its 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 theoretical 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 above-mentioned 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. 12). 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.

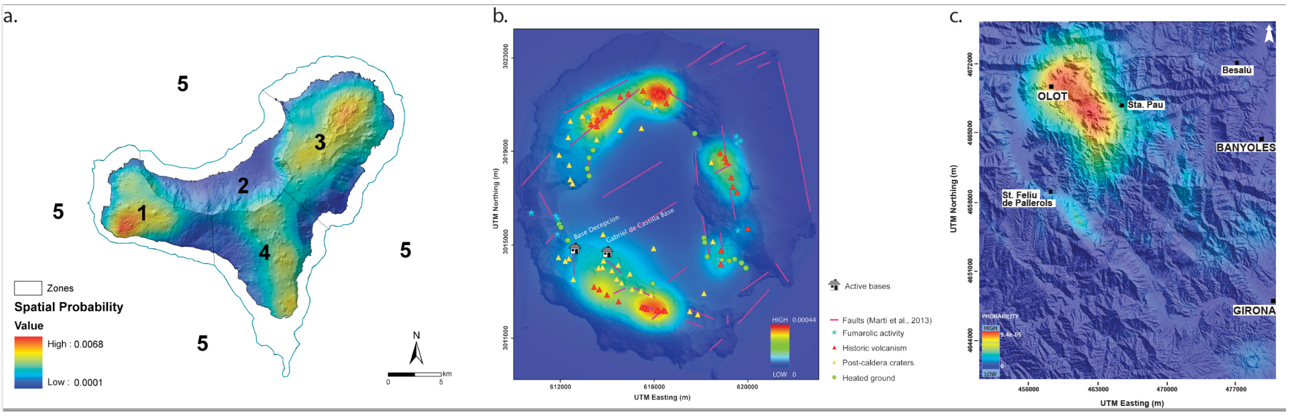


Figure. 12. Examples of susceptibility maps. a) El Hierro Island, Canary Islands (Becerril et al., 2014); b) Deception Island, Antarctica (Bartolini et al., 2014a); c) La Garrotxa Volcanic Field, NE of Spain (Bartolini et al., 2014b)

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 visualisation 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; Capello 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 non-homogeneous 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. 12).

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.

1.8.2. 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 above, the reconstruction of the eruptive record of a volcanic system enables us to identify the products of each different eruption and inter-eruptive 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 since 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 the development of emergency plans. In addition, if the volcanic system has been active in recent years and direct observation and instrument monitoring of eruptions has been possible, we can associate possible precursory/ premonitory activity to particular eruption types and products.

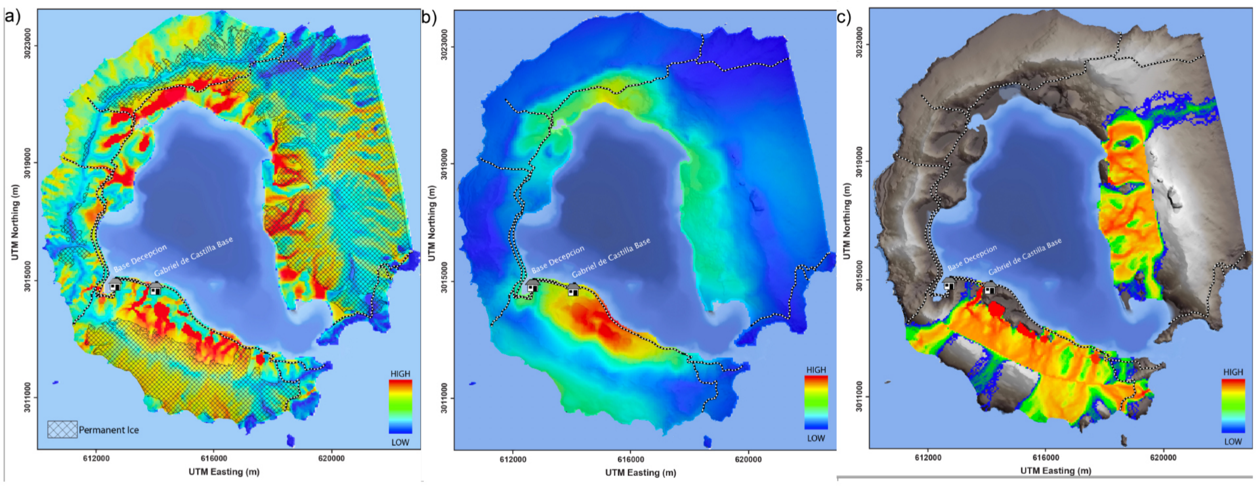


Figure. 13 Examples of eruptive scenarios at Deception Island: a) lava flows, b) PDCs, c) Lahars (see Bartolini et al 2014a)

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. 13). 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 below). 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, solid and fluid mechanics is a well-developed field of research (Martí and Folch, 2005; Parffit 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 (Marti and Folch, 2005; Fagents et al., 2013). However, different models depend on different assumptions, are characterised 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 models (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 a 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 parameterisation 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 system that can manage all the geographic (DEM, etc.) and cartographic data required for high-quality analysis and can generate graphical representations of eruption scenarios and hazard maps (Fig. 13).

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 Maling, 1983; Toyos et al., 2007), lahars (e.g. Schilling, 1998; Patra et al. 2005), debris avalanches (eg: 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 semi-empirical 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.

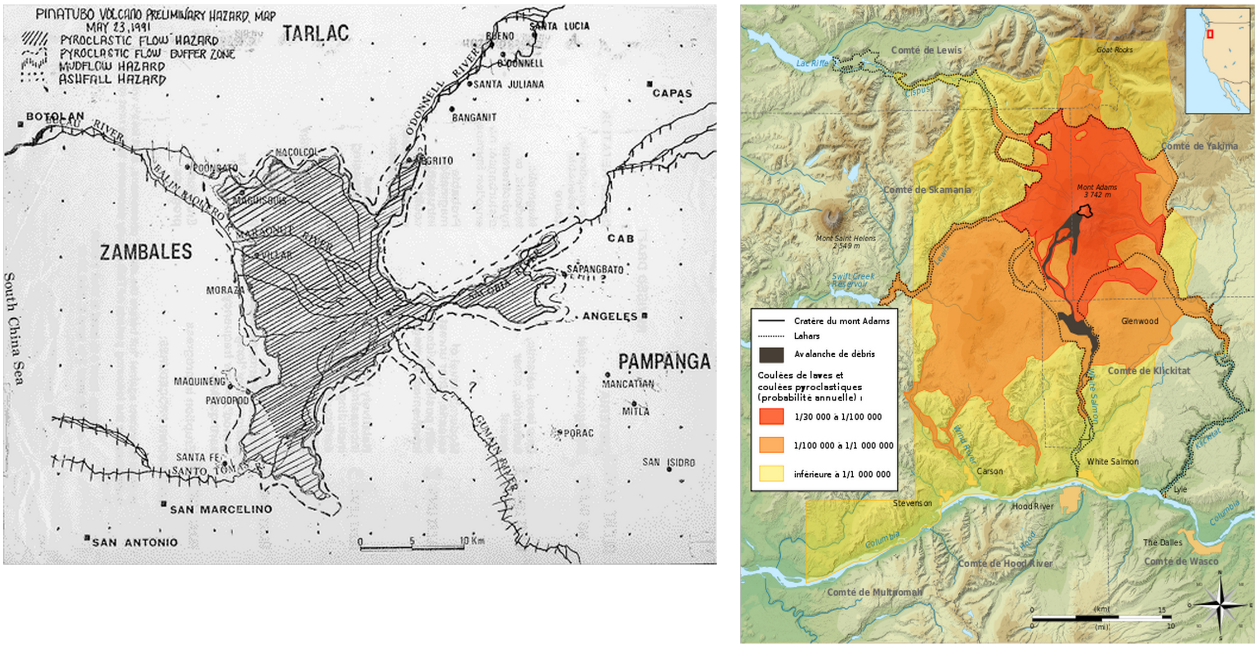
Simulating eruption scenarios using the results of susceptibility analyses and simulation models of different hazards is the first step towards producing qualitative and quantitative hazard maps in long-term assessments. Simulating eruption scenarios is also crucial in short-term assessments during a volcanic crisis as it helps determine potential impacts and to 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).

1.8.3. 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 (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 identity 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).

Hazards 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 and 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. 14). 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 visualising 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., 2013).

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 normalised distribution of the probabilities resulting from combining, recalculating and normalising all the results obtained from each individual simulation.



a) b)

Figure 14 Examples of field based hazard maps. a) Hazard map of Pinatubo volcano made in May 1991 (source: http://pubs.usgs.gov/pinatubo/punong2/fig5.gif). b) Topographic map in French of Mount Adams region, with volcanic hazards(1).

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 most usual and simplest (in terms of visualisation!!) 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. 15). 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. 15). 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. 16): 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 us Google Earth offers a potentially important way of visualising hazard maps.

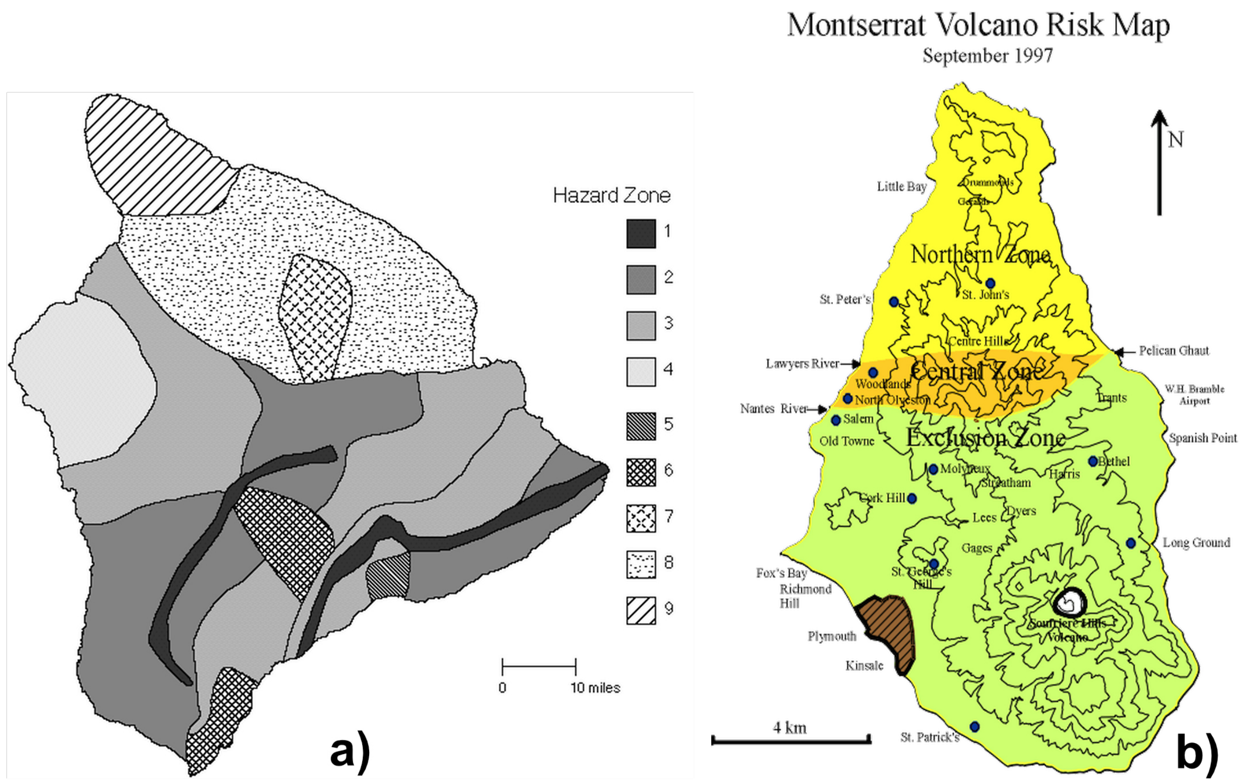


Figure. 15 Examples of zonation hazard maps. a) Map showing volcanic hazard zones on the island of Hawaii first prepared in 1974 by Donal Mullineaux and Donald Peterson of the U.S. Geological Survey and revised in 1987. The current map divides the island into zones that are ranked from 1 through 9 based 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. very high, high, medium or low) of a volcanic area (Fig. 15) 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 urbanised 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 so 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. 17).

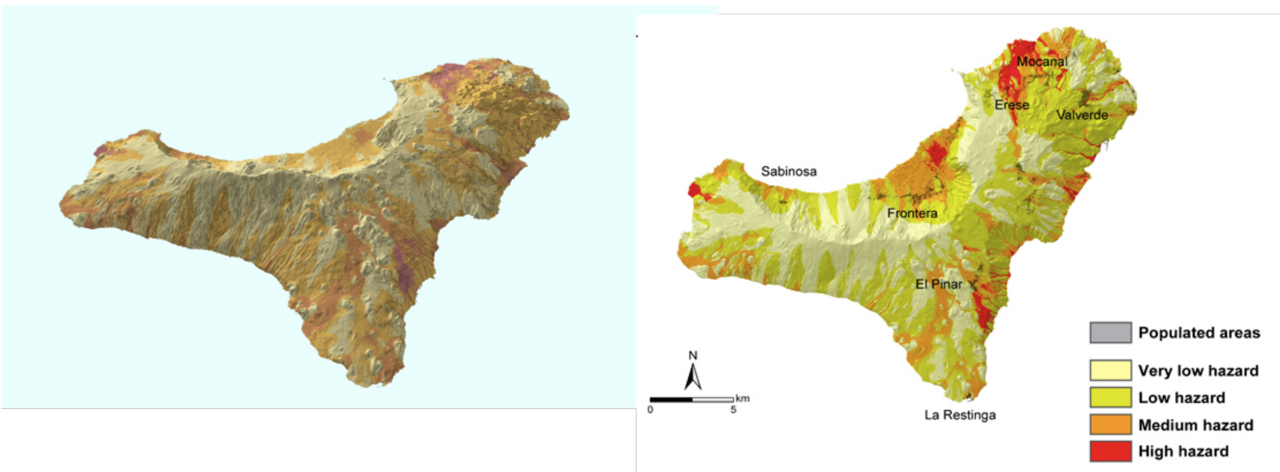


Fig. 16. Two examples of the same hazard map (qualitative volcanic hazard of El Hierro, Becerril et al 2014) plotted on different 3D topographic relief representations: Left side: On a Google Earth relief (© 2015 Google Earth); right side: on a shaded relief obtained from the light detection and ranging (LIDAR) technology based on the digital elevation model (DEM) of El Hierro Island with a cell size of 10m generated by the Spanish National Geographic Institute (IGN).

1.8.4. 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, geochonological 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 and so the possibility of obtaining precise recurrence estimates will depend on how well known our volcanic system is.

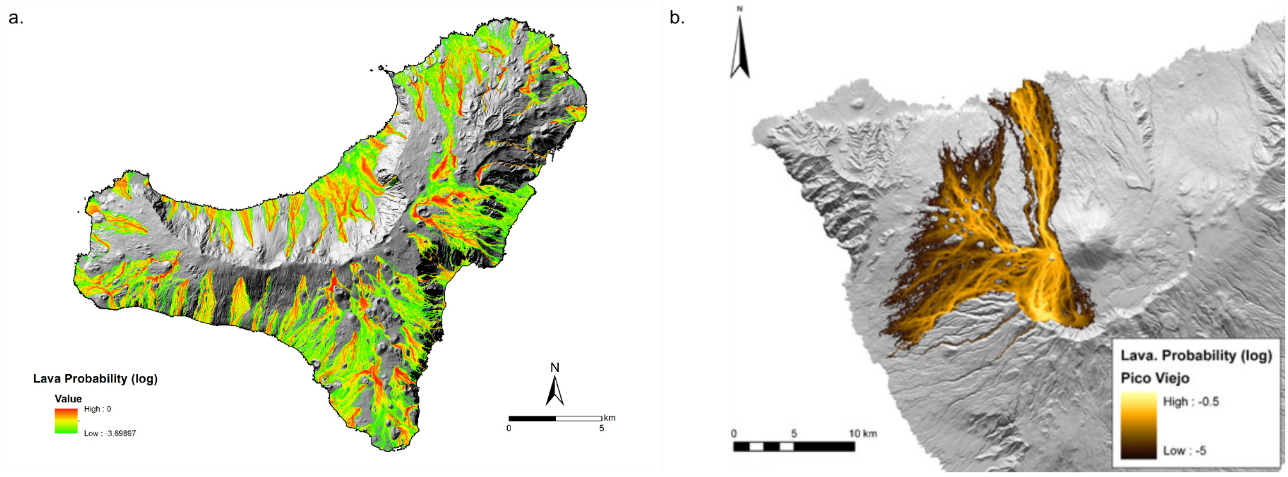


Figure. 17. Examples of quantitative hazard map and scenario. a) Quantitative hazard map for lava flow invasion at El Hierro (Becerril et al 2014). b) Quantitative scenario for lava flow invasion at Teide volcano (Martí et al., 2012)

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 every hundreds to thousands of years (e.g. El Teide in Tenerife) in low eruption frequency volcanoes, or even to every 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 (Sigurdsson, 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 only every hundreds to thousands of years (Francis, 1993). A comparison between Indonesia, Caribbean and Japan, three volcanic island arcs, reveals that the eruption frequencies of individual volcanoes vary in all these volcanic areas (Sibert 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 (every 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 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 above, 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 Soufriere on Montserrat or Stromboli that experience long on-going 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 so 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 and so in these cases it is essential to complement historical information 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 et al. (2008, 2010) and Sobradelo et al (2011).

1.9. 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 to 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 behaviour 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 taking poorly informed decisions.

The complexity of any volcanic system and its associated eruptive processes, in combination with the lack of data that characterise many active areas and, in particular, those with long recurrence periods, ensure that volcanic hazard quantification is a great challenge, above all as 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 so must be minimised. 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; Sobradelo 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 alternative steps taken from a general prior event, state or condition leading to increasingly 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).

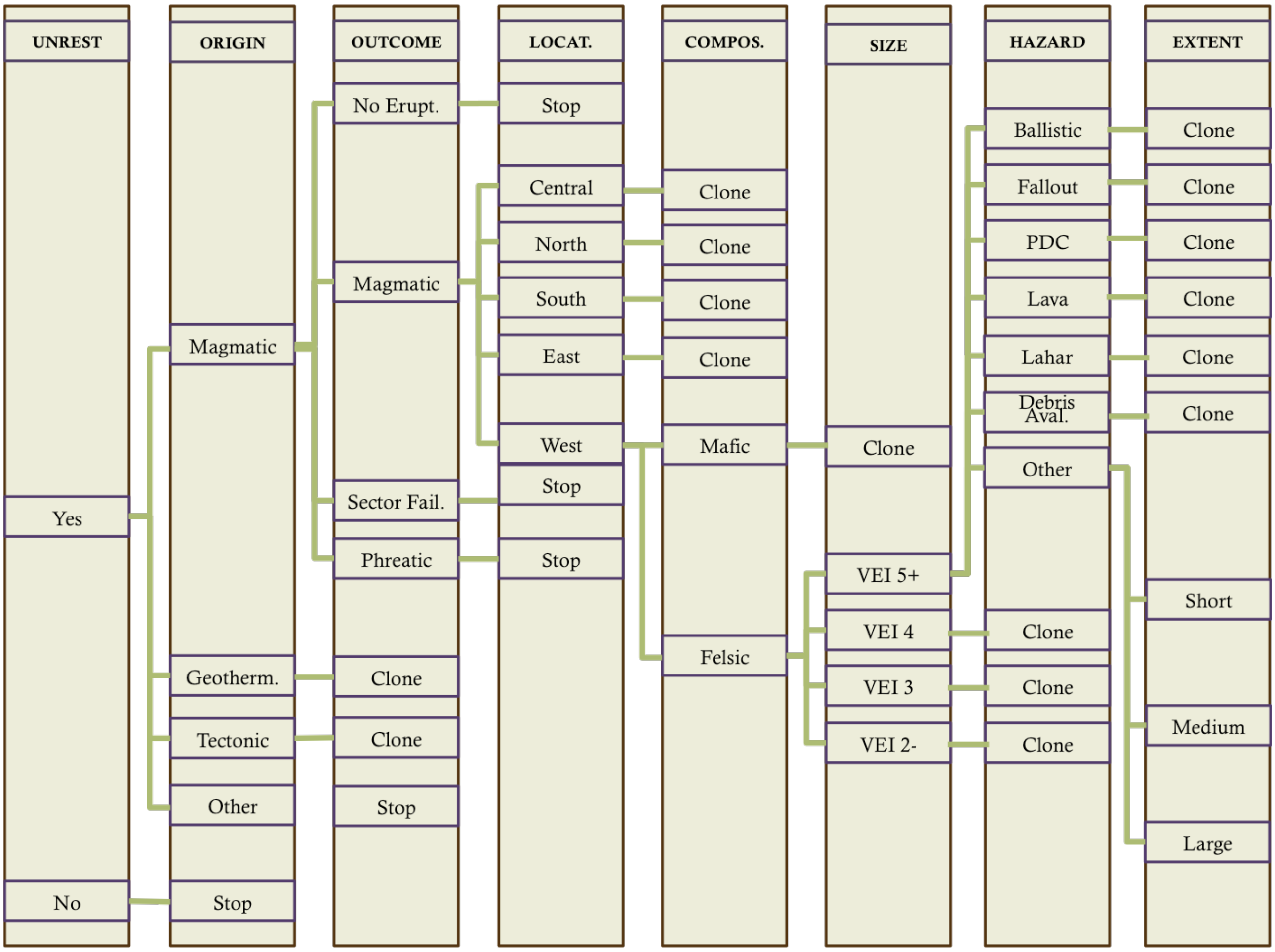


Figure. 18 Even tree structure developed by Sobradelo and Martí (2010) and used as the basis for HASSET (Sobradelo et al., 2014). Clone indicates repetition of the same tree structure.

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 scenarios of a particular volcanic system during a quiescence period or an updated distribution of probabilities during a crisis (Fig. 18). The construction of a probability event tree for estimating 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 behaviour 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 chronicled. 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 et al., 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 realisations 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. 50%ile value for the distribution of opinions provided by the group) and the corresponding 90% credible interval bounds (i.e. the approximate 5%ile and 95%ile 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 realisation 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 is known, it should be conditional on the unknown parameter. Therefore, our knowledge of the unknown parameter is expressed through a posterior distribution, i.e., 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 uncertainly about the unknown parameter after seeing the data.

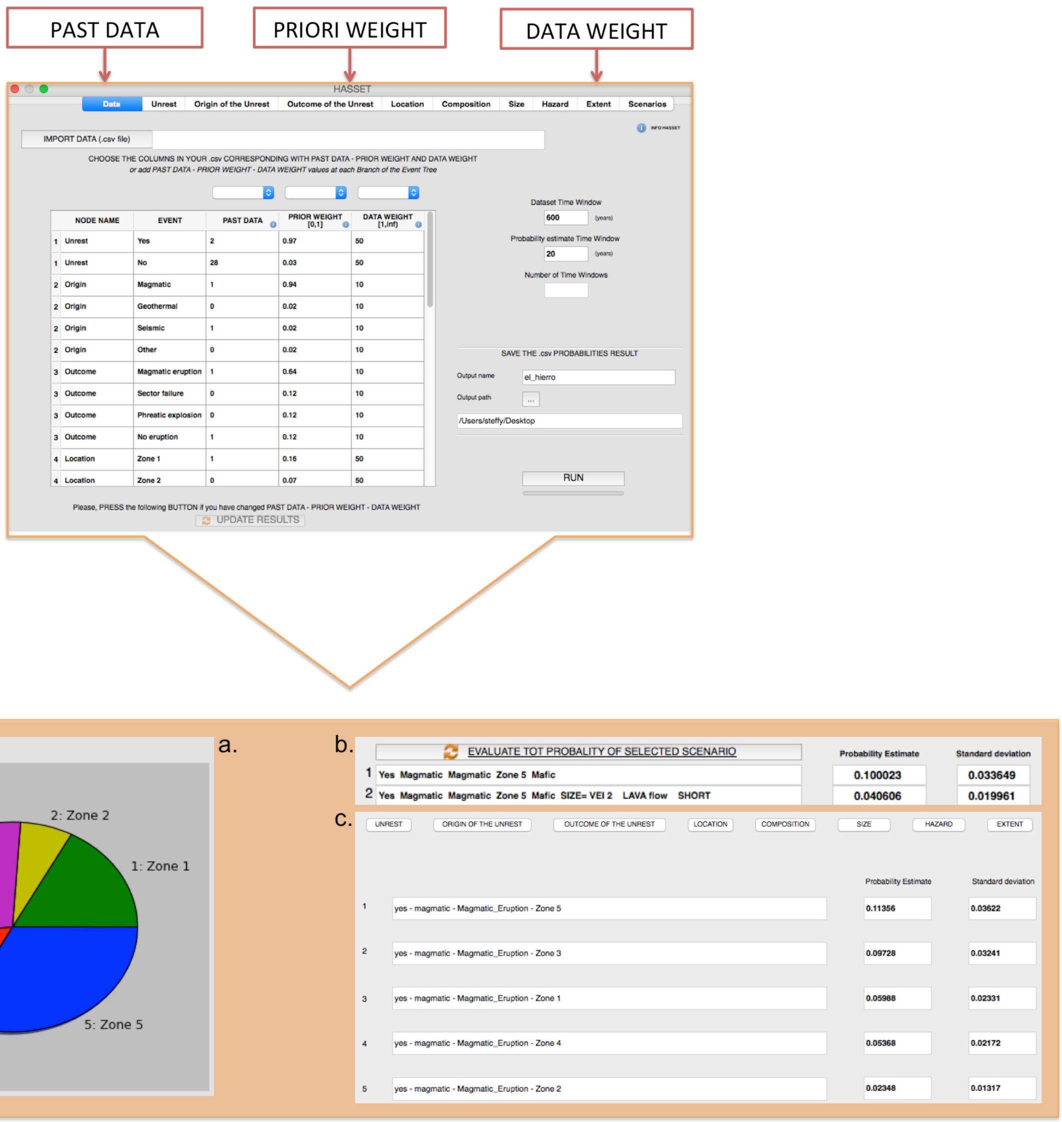


Figure 19. Input data (upper part) and outputs (lower part) of the HASSET tool for long-term probabilistic analysis of volcanic hazard (Sobradelo et al 2014).

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., 2007, 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., 2014 a, 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 (Fig. 19), developed by Sobradelo et al. (2013), are two similar probability tools, freely available on the Internet (http://bet.bo.ingv.it; http://www.gvb-csic.es/software-y-database/HASSET-hazard-assessment.html), built on an event tree structure, that use Bayesian inference to estimate the probability of occurrence of a future volcanic scenario (Fig. 18). 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 towards increasingly specific subsequent events and a final outcome. Compared to BET, HASSET accounts for the possibility of (i) flank eruptions (as opposed to only central eruptions) and monogenetic volcanism, (ii) geothermal or tectonic unrest (as opposed to only magmatic unrest), and (iii) felsic or mafic lava composition (or the absence composition data), as well as (iv) certain volcanic hazards as possible outcomes of an eruption, and (v) the extent of each hazard.

1.10. Analysing 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, etc.). 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 (eg: 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 socio-economic 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, Gelh et al (2013) for Mount Cameroon, and Jenkins et al. (2014) in a more general approach.

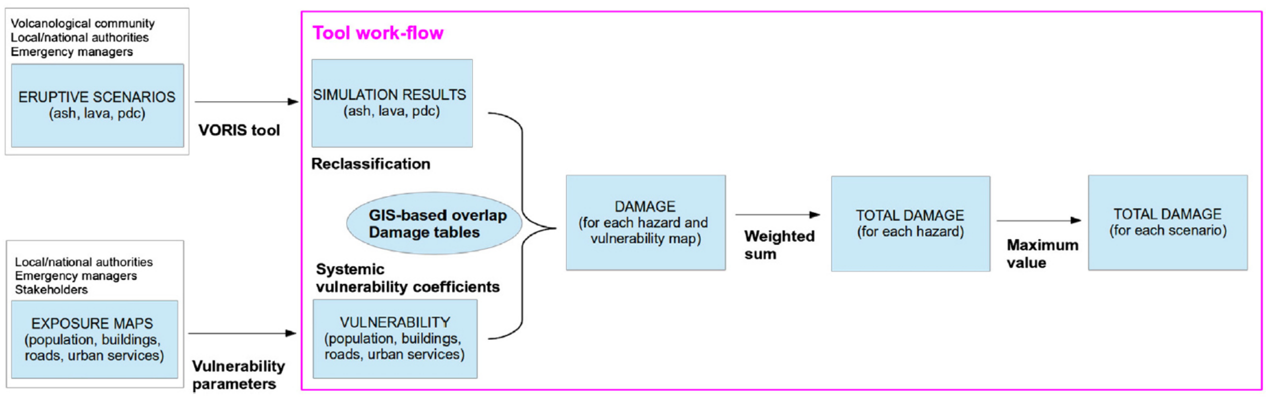


Figure 20. Sketch of the methodology proposed by Scaini et al (2014) to estimate volcanic vulnerability, underlining the role of main operations performed before and during the tool work-flow. The first operations are performed out of the work-flow (simulation of eruptive scenarios, exposure analysis and production physical vulnerability maps). Then, the tool produces reclassified maps for each hazardous scenario, systemic vulnerability and, through a GIS-based overlap, thematic damage maps. Finally, damage maps are combined in order to produce systemic damage maps for each hazardous phenomenon, and a final map for each eruptive scenario.

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 non-exposed elements (people, buildings, transportation network, urban services and productive activities). Systemic vulnerability maps can be obtained by multiplying each element by the corresponding coefficient and so for each phenomenon the specific vulnerability maps overlap the maps of the modelling results (eg: Zuccaro and De Gregorio, 2013; Scaini et al., 2014) (Fig. 20). 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 parameterising 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.

1.11. 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 the 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 has in scientific information. This is why scientists working in active volcanic areas should make the effort to contribute to educate 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 do 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 with 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 last years considerable efforts have been made to analyse 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; Gaillart, 2008; Solana et al., 2008, McGuire et al., 2009; Barclay et al., 2011; Marzocchi et al., 2012; 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 is 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. However, 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 on 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, 2017). 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 policy-makers, 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. The main goal of hazard assessment is to respond to the desire to know how, where and when an eruption will occur. As explained above, to answer these questions probabilities should be used to characterise associated uncertainties (Donovan et al., 2012b; Doyle et al., 2014; Sobradelo and Martí, 2017). However, communicating probabilities and, in particular, uncertainty, is not an easy task and may require different approaches according to the receptor 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 to meteorologists, who have much more available data and observations, volcanologists have to deal with higher degrees 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 and so no universal model for understanding the behaviour 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 be not 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 programme rather than just sporadic communication actions (even if the latter are also always welcome) (Gregg et al., 2004; Gaillant, 2008; Patton et al., 2008; Haynes et al., 2008b).

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 (i.e. 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 programmes and outreach activities will vary from country to country in terms of cultural and socio-economic 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 programmes 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 (eg.: IAVCEI, 1999; McGuire et al., 2009; Aspinall, 2010; Donovan et al., 2012 a, b; Marzocchi et al., 2012; Doyle et al., 2014; Martí, 2015; Sobradelo and Martí, 2017) insist on the need to explain the uncertainty that accompanies any forecast regarding the future behaviour 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 behaviour of volcanoes as natural systems (aleatory uncertainties) and from our lack of knowledge of the behaviour 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 characterised 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 behaviour and all eruption forecasting in case of reactivation will be (short-term hazard assessment).

1.12. Cost/benefit analysis

Understanding the potential evolution of a volcanic crisis is crucial for designing effective mitigation strategies. This is especially the case for volcanoes close to densely populated regions, where inappropriate decisions may trigger widespread loss of life, economic disruption, and public distress. An outstanding goal for improving the management of volcanic crises, therefore, is to develop objective, real-time methodologies for evaluating how an emergency will develop and how scientists communicate with decision-makers (see Sobradelo et al., 2014).

An effective method for improving how decisions are made is to prepare scenarios that describe the potential impact of an eruption. Recent procedures have focussed on scenarios for the possible eruptive behaviour of a volcano and on probabilistic criteria for evacuating populations at risk. In the first case, the Bayesian methodology proposed by Newhall and Hoblitt (2002) has been used to develop computer-assisted procedures for transforming field data into probabilities that an eruption scenario will take place (Marzocchi et al. 2008, 2010; Sobradelo et al. 2014). In the second, Woo (2008) followed the method of Katz and Murphy (1997) to develop a probabilistic criteria for evacuation decision-making within a cost-benefit analysis framework and showed how this may be quantitatively expressed in terms of the proportion of the evacuees owing their lives to the evacuation call.

The two approaches together provide a framework for assisting decision-makers during an emergency (Marzocchi and Woo 2007; Marzocchi et al. 2012). However, their evaluation of social impact has been restricted to the economic consequences of lives lost and of an evacuation. More comprehensive analyses are needed to take account also of the potential cost from injuries to people, from the loss of property and livelihoods, and from the consequences of mitigating actions beyond an evacuation. For example, even before a crisis develops, mitigating actions can be implemented that involve vulnerable infrastructure, economic and environmental interests, and the establishment of no-construction zones. Each of these actions will have an associated potential loss that will depend on a number of parameters that, in addition to the population at risk, include the vulnerability of a district and the value of its exposed economic and physical infrastructure.

The availability and consequences of a mitigating action may vary as a crisis develops and so influence the final decision. Analyses must therefore be structured in a systematic, quantitative manner, so that actions already taken can be re-evaluated as necessary during an emergency. As part of Operations Research, Bayesian decision theory provides the tools to combine the philosophy, theory, methodology, and professional practice necessary to address complex decision-making problems in a formal manner. It uses procedures, methods, and tools for identifying, clearly representing, and formally assessing important aspects of a decision, for prescribing a recommended course of action, and for translating the formal representation of a decision and its corresponding recommendation into insight for the decision-maker and other stakeholders (Rice 2007; Berger 2010).

Sobradelo et al (2014) developed a new Bayesian Decision Model (BADEMO) that applies a general and flexible, probabilistic approach to managing volcanic crises. The model combines the hazard and risk factors that decision-makers need for a holistic analysis of a volcanic crisis. These factors include eruption scenarios and their probabilities of occurrence, the vulnerability of populations and their activities, and the costs of false alarms and failed forecasts. The model can be implemented before an emergency, to identify actions for reducing the vulnerability of a district; during an emergency, to identify the optimum mitigating actions and how these may change as new information is obtained; and after an emergency, to assess the effectiveness of a mitigating response and, from the results, to improve strategies before another crisis occurs. Moreover, BADEMO can account for changes in the values of controlling parameters during an emergency and so enables recommended actions to be re-evaluated and modified as circumstances evolve.

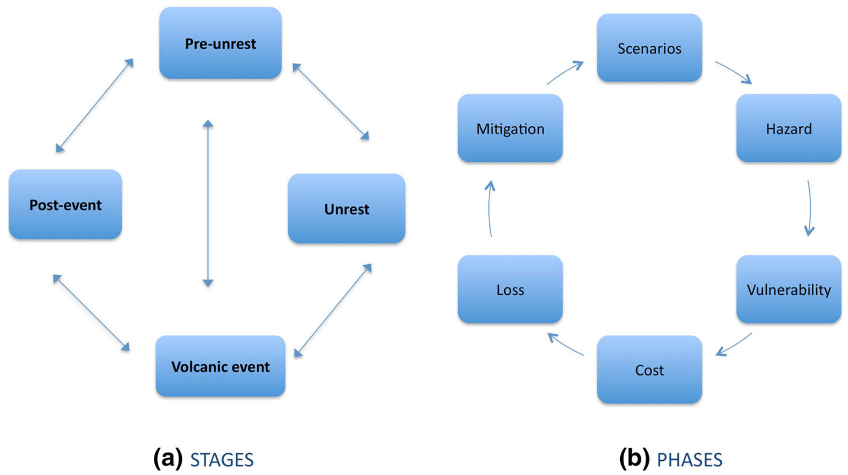


Figure 21. a) Volcanic crisis management is part of a longer cycle that also includes pre-unrest and post-event stages, which are crucial for determining the level of preparedness and resilience. A different degree of preparedness and reaction is required in each stage of this cycle, in order to be as effective as possible when facing a volcanic threat. b) Six phases in each stage conform to a cyclic process in the decision-making problem (see Sobradelo et al., 2014 for explanations)

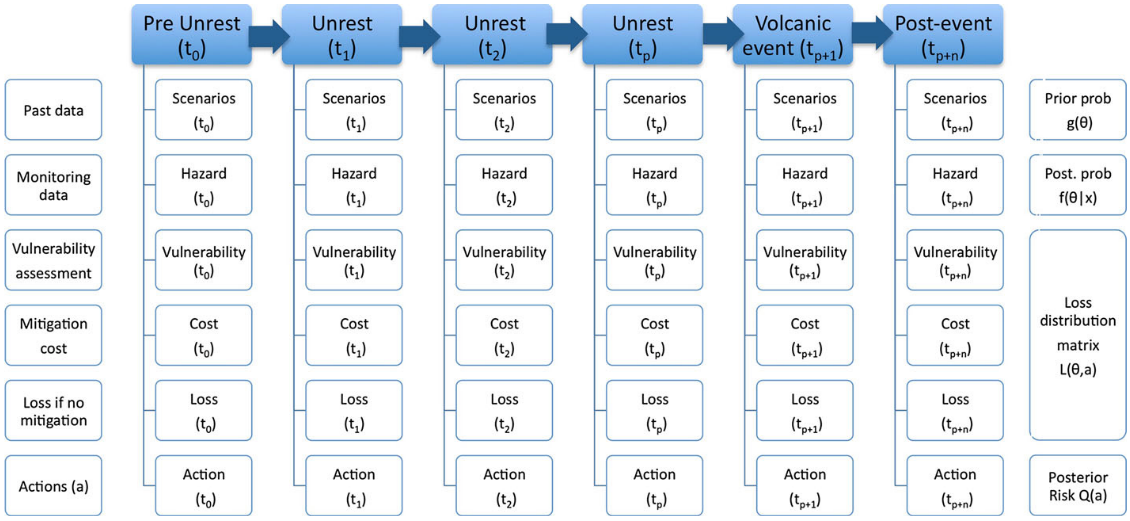


Figure 22.
Decision model structure of Sobradelo et al (2014). General form of the decision problem as a hierarchical event tree structure made of four stages (nodes), pre-unrest, unrest, volcanic event, and post-event and six phases (branches) per stage, scenarios, hazard, vulnerability, cost, loss and mitigation

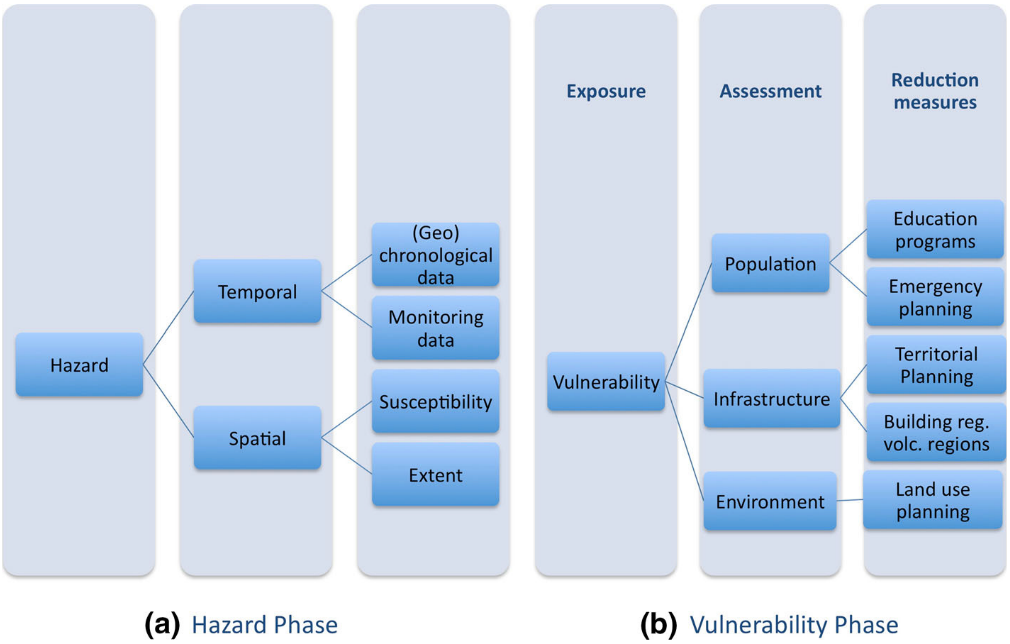


Figure 23. a) The information required in the hazard phase is (geo)chronological and/or monitoring data for the temporal assessment, and susceptibility and extent for the spatial hazard. b) Educational programs, emergency, territorial and land use planning, as well as building regulations, will all play a vital role in the volcanic crisis management and will determine the resilience of a community to face a volcanic event

PART 2: VOLCANBOX:

description, tools, and applications

Presentation

One of the most important tasks of modern volcanology is to minimise the risk of volcanic eruptions. Their impact can affect considerably human life and the environment. It is clear that a volcanic eruption, although it can be at the same time fascinating and impressive, presents similar or even more problems than more frequent natural events. It is possible to live near a volcanic area if we consider the benefits that volcanoes can gives us, but it is important to be aware of the existing threat and to know how to minimise the risk. Understanding the potential evolution of a volcanic crisis is crucial for designing effective mitigation strategies. VOLCANBOX is an integrated software multi-platform (Windows, Mac, Linux) specially designed to assess and manage volcanic hazard and risk. This new platform contains user-friendly free e-tools sequentially structured following the methodology explained Part 1 of this handbook. VOLCANBOX is designed to be used with personal computers and is specifically addressed to long- and short-term hazard assessment, vulnerability analysis, decision-making, and volcanic risk management. The e-tools included have been freely provided by different authors and integrated into a proper GIS platform. VOLCANBOX is designed to be implemented before an emergency, to identify optimum mitigating actions, and adapt more adequate scenarios to the current situation as new information is obtained. Furthermore, e-tools contained in the VOLCANBOX allow to identify the most appropriate probabilistic and statistical techniques for volcanological data analysis and treatment in the context of quantitative hazard and risk assessment.

Forecasting volcanic eruptions and predicting the most probable scenarios are subjected to a high degree of uncertainty, which needs to be quantified and clearly explained when transmitting scientific information to decision makers. VOLCANBOX, using the systematic methodology described in Part 1 of this handbook, offers a simple and easy way to visualise the degree of uncertainty in long and short term hazard assessment and, consequently, in the scientific information used to manage a volcanic crisis.

In the following sections, we describe the structure of the VOLCANBOX platform, provide a brief introduction to its use, explain each of the e-tools included, and present a series of examples that illustrate the results that can be obtained. However, what follows is not a manual's user. This will be provided latter with the installation guide of VOLCANBOX.

2.1. Data, data management, and databases: why?

Before starting with the description of the VOLCANBOX interface and its main operability, it is necessary to explain the nature of data that will be use, how they will be stored and classified, and used in each application.

We live in an age where data as well as the information generated from it is growing at an overwhelming rate. No less rapidly, the number and heterogeneity of sources that generate them is growing, and the technologies responsible for supporting their life cycle are born, updated, and die. This scenario has caused the inability to govern this vast ocean of data - and therefore to be able to extract information from it - to become an endemic evil of the 21st century. The lack of agreed protocols for: extracting, organising, transforming and storing data, make the current scenario of Volcanology a clear paradigm of this problem. In this context, it is difficult to take advantage of cutting-edge technologies to create tools that are able to extract information automatically. On the other hand, the lack of defined content structure implies that many valuable resources, in terms of knowledge, are at best forgotten on a hard drive, whether due to human or technological barriers.

It is therefore necessary to create a series of standard protocols and tools to address this issue, which affects both pre-existing resources and those that have not yet been generated.

2.2. Database Architecture

When working on a scientific product in the area of volcanology, the team generates a series of files that in many cases depend on third-party tools for their interpretation. Generally, once the experiment is completed, these documents are stored following - at best - certain protocols. The problem in part is that these are not agreed between the different teams. In addition, they tend to evolve and do not create tools to adapt old work to change.

In the long run, what usually prevails are the reports resulting from the experiment. The inability to reproduce them - due to the obsolescence of the tools and formats used, as well as the lack of consensus on where and how they should be stored -generates a bottleneck when it comes to making the most of it.

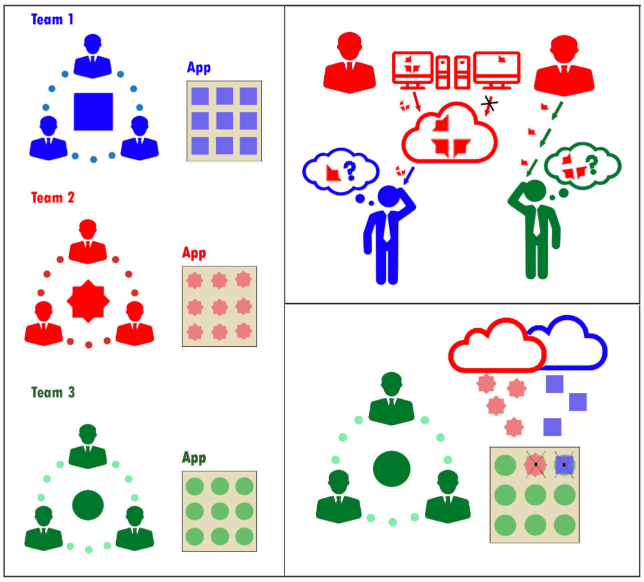


Figure 24 a). Three teams perform similar assessments, but use different formats. b) Team 2 did not follow a specific protocol for storing data associated with a particular experiment. Team 1 accesses team 2's cloud to get them, Team 3, on the other hand, has requested them directly from a member of Team 2. Team 1 and Team 2 are unable to reproduce the experiment for lack of data. c) Team 3 accesses Team 1 and Team 2 clouds, but can't use data on them due to compatibility issues

On the other hand, creating protocols that standardise these processes involves defining protocols and structures that adapt to the data and content you are working with. In such a heterogeneous context, modelling all content using a single scheme is by no means trivial, which is why it seems like a good strategy to take a multilingual persistence-based approach.

This philosophy, instead of adapting all the information to fit it into a single technology or structure, prefers to divide the system into a set of subsystems - each of them chosen taking into account both the type of data to be hosted, as expected of them - that they communicate with each other. This communication is essential, as it allows you to resolve requests as if they were a single system.

By adopting this approach, if, for example, in the future we need to store content that is difficult to fit into our system, we could add an extra piece to it - tailor-made to carry this responsibility - without having to make major modifications to the system.

Given this problem, an infrastructure has been designed, which has been implemented during the development of the EVE project. It consists of two distinct parts:

- A tool called *VOLCANBOX* that will offer:

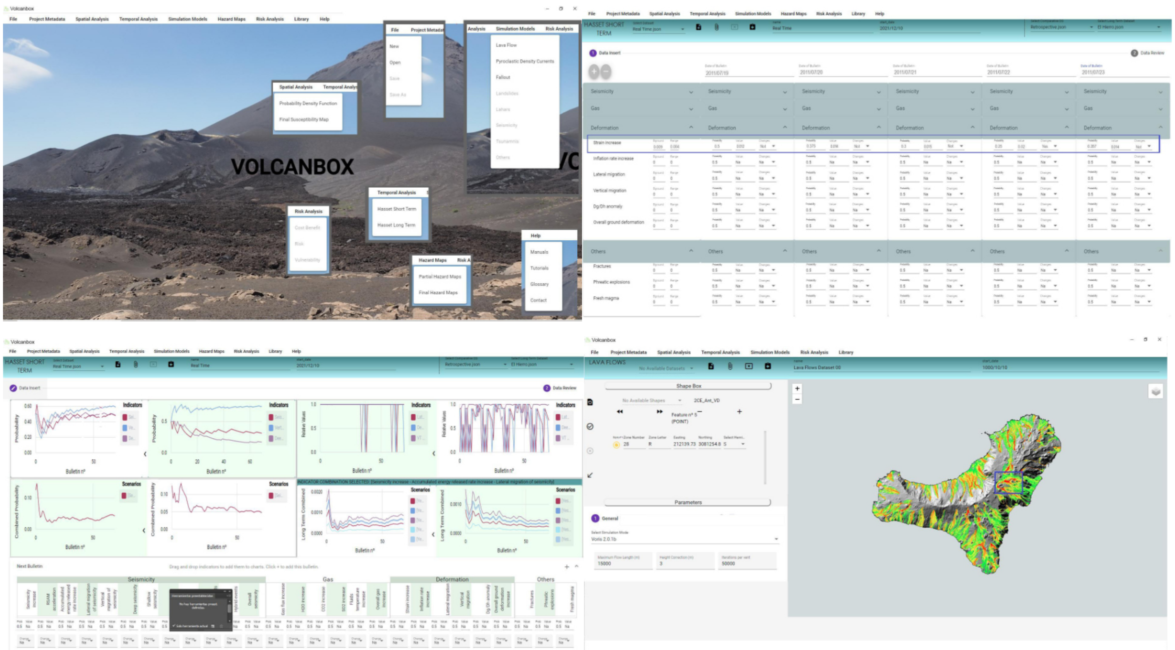


Figure 25. Details of the VOLCANBOX interface

  - GIS toolkit capable of:
    - Extract georeferenced data from encoded files in most formats on the market.
    - Import, modify, or generate user-friendly vector files by typing coordinates or clicking on specific points on the map.
    - Perform - in a manner that is transparent to the user - the operations necessary to be able to cross-encode data on more than 11,000 compatible reference systems.
  - *Long and Short Term* statistical analysis.
  - Elaboration of *Probability Density Functions* with different methods of estimating bandwidth.

- Elaboration of *Susceptibility Maps* from a weighted set of probability density functions
- Suite of sections for the assessment of the following volcanic hazards:
  - Lava Flows.
  - Pyroclastic Density Currents
  - Fallout
  - Landslides
  - Lahars
  - Seismicity
  - Tsunamis
  - Others
- Partial and total hazard maps.
- Library that acts as a database, to organise and offer information, in the same application, that is, by "GIS" tools of third parties.
- Tools for viewing and extracting information from data uploaded to the application.
- Online functions to publish information and facilitate collaboration between teams.
- Generation of new data from the Crossover of different experiments in order to search for new information.

- A data storage system focused on polyglot persistence. This will be structured in *Volcanic Zones* that will contain the following elements:

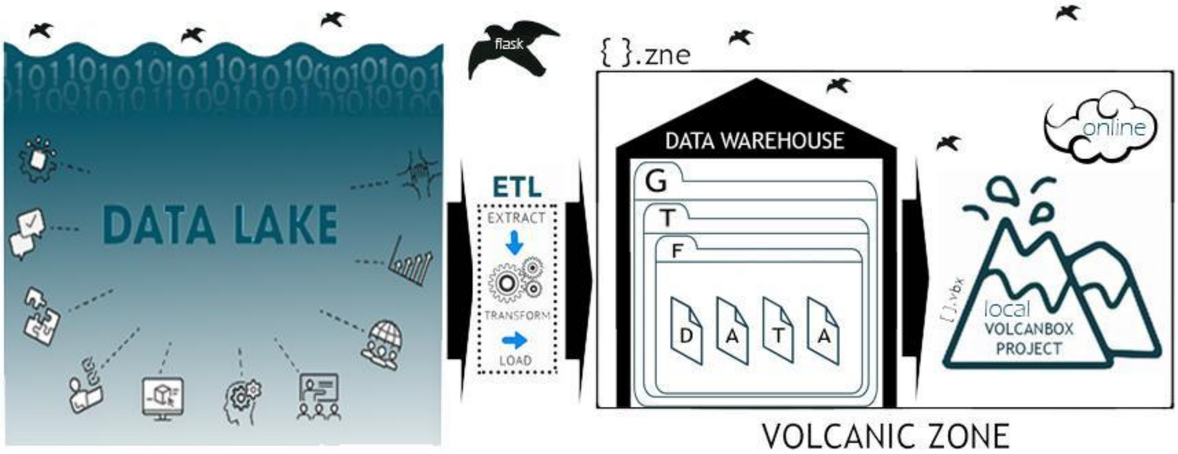


Figure 26. Sketch illustrating the the internal structure of the data storage system

- **Data Lake** : A storage repository that contains raw acquired data. Each item is assigned a unique identifier and a set of tags. These allow you to relate them to each other, without the need for a closed data structure and relationships.
- **Flask Microservices** : A set of services capable of storing, managing, and delivering data stored on the system.

- **ETL** : are the acronyms for Extraction, Transformation and Loading, and refer to a set of techniques, tools and technologies that aim to extract data from various sources and transform them to be able to load them into other systems.
- **Volcanic Zone:** A set of subsystems that resolve data relating to a given geographical area. Includes:
  - **Data Warehouse** : A series of guidelines and good practices for storing data extracted from the Data Lake component. Their purpose is to provide a standard structure that facilitates their subsequent recovery, as well as ensuring compatibility with *VOLCANBOX*.
  - **Local VOLCANBOX Project** : A directory and file structure resulting from a Volcanic Risk Assessment generated using the *VOLCANBOX* application, as well as all input data that has been used to perform it.
  - **VOLCANBOX Online Project** : Database architecture designed to serve the online features of the *VOLCANBOX* application.

The purpose is that this whole set of subsystems can work as a whole in a way that is transparent to the user. To accomplish this task, an ecosystem of microservices implemented through the *Python Flask Library* is proposed. This structure will allow, among others:

- Preserve and recover the sources in their original format and contents.
- Standardise the way data is organised, maximising its usefulness when it is exchanged between computers.
- Compatible data from different sources so that it can be cross-referenced.
- Generate new data from existing data.
- Easily reproduce any previous experiments.
- Automate early warning delivery using the VEWS Volcano Early Warning System* platform.
- Prepare the terrain for the application of machine learning algorithms.

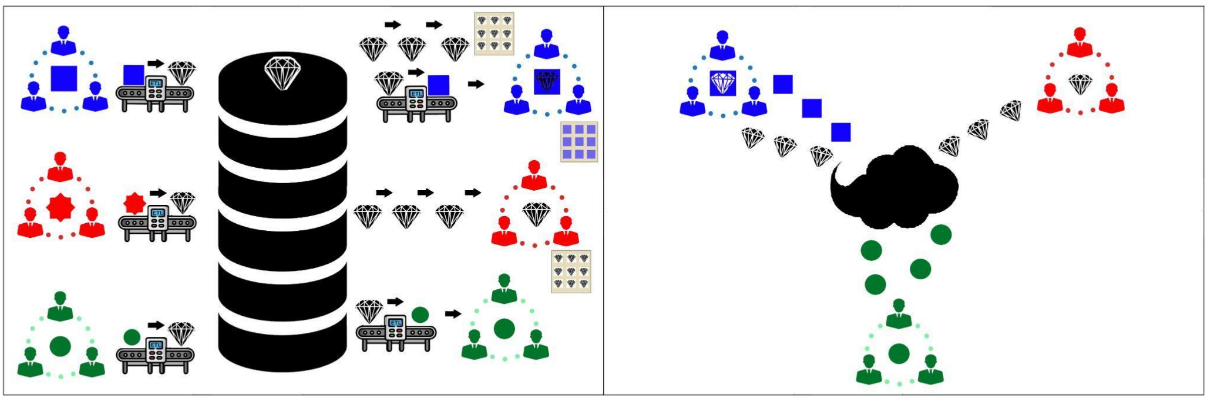


Figure 27. a) Teams send data for storage, and ETLs transform data into suggested formats. The red team has adopted the VOLCANBOX platform, so it can use the data without the ETLs having to transform it. In the blue team some members have decided to adapt the proposed formats, otherwise there are members who have not yet made the leap; however, thanks to ETL transformations all members can receive the data in the desired format. The green team still uses its usual formats, thanks to the

ETLs they can now get the data that the blue and red teams have saved. b) The complexity of the platform is transparent to the user, they see the system as a black box that accepts the desired formats.

** VEWS is a platform that through a set of web tools aims to facilitate interaction and cooperation between scientists and Civil Protection Agencies to anticipate volcanic disasters in a timely manner. The VOLCANBOX application will be able to connect to the VEWS to generate or update new alarms and include in them all the results achieved that it deems appropriate.*

2.2.1. Data Lake

One of the challenges associated with the problem that this document seeks to resolve is to ensure the availability of all relevant content in terms of volcanic risk assessment. The disparity - in terms of format, structure, nature, purpose, etc. - make it very difficult to store them using a closed scheme. This is a very common issue in the so-called big data environments, for this reason the concept of Data Lake -very present in these environments- has been taken as inspiration.

A Data Lake is a large set of raw data, which does not yet have a definite purpose - unlike for example a Data Warehouse where data has already been structured, filtered and processed by for a specific purpose.

Figure 28.- Sketch illustrating the contents (in different format and files) that can be found into the data lake

When content is in Data Lake, it can be normalised and enriched. This may include metadata extraction, format conversion, augmentation, entity extraction, cross-linking, aggregation, denormalisation, or indexing.

This type of implementation has been chosen so that users can include as much heterogeneous content as possible, otherwise it will also allow the creation of a database to, in the near future, combine and process this data using mass data techniques, and so on to be able to carry out searches and analyses that would otherwise have been impossible.

2.2.1.1. Label system

As mentioned above, the Data Lake component does not have a defined structure. But how does Data Lake then be able to provide us with information when we want to retrieve it?

Unlike other systems where data is stored following certain formats and / or a certain hierarchy of directories, files, tables, relationship tables, etc. our Data Lake component assigns each item a unique identifier, and a series of tags.

These tags can be either a manual assignment - that is, made by the same user - or automated - that is, made by the same system using, for example, artificial intelligence techniques. In fact, in the latter case, as the Data Lake grows, the system will be able to learn and discover new similarities between the different stored content, and thus enrich the data by assigning new tags automatically. For example, it may be the case that a user stores content without being clear about the correct tag and that the system itself finds one or more suitable ones. It is worth noting that for time limitations, only the first option has been implemented, however, the system is fully compatible with the second.

In order to label the contents, the work carried out by Bartolini et al. 2014*, who proposes a database structure called VERDI which aims at data storage for the assessment of volcanic hazard and risk.

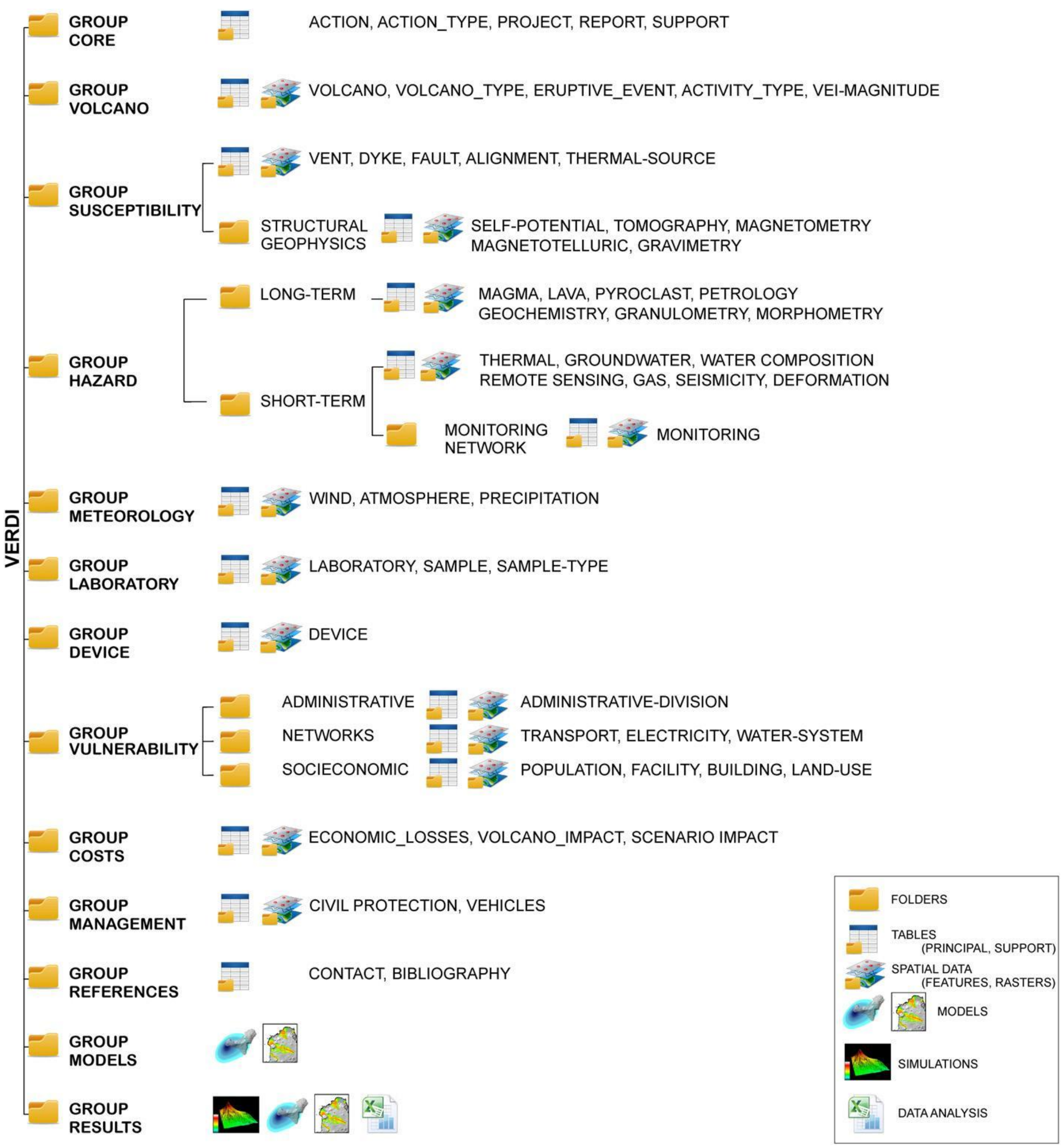


Figure 29.- Image of the groups included in the VERDI data base

* Despite taking advantage of the work done in the VERDI data architecture, the concept of a label should not be confused with a specific storage structure. On the contrary, the only thing that is advised to the user is that, if he uses, for example, the tag, shape, also use the top tags, this way you can filter the information as if it existed in a real hierarchy - in terms of implementation - without it really being that way.

One detail to keep in mind is that, by its nature, this component is not designed to provide real-time data. This is where the concept of polyglot persistence makes sense, so to solve requests in real time, we already have other more suitable components in our system.

On the other hand, sources can often contain information that is considered confidential, fortunately, the data lake is equipped with tools to ensure control of access to information.

2.2.1.2. Obtaining Contents

Regarding the process of obtaining the contents in order to include it in our *Data Lake*, we can also make a simile with the *Silo* concept of massive data environments.

In our case, *Silos* can be the hard disks of research groups, databases such as WOVOdat, web pages and databases of volcanological laboratories (e.g. Volcanological Observatory of Piton de la Fournaise, INGV Osservatorio Etneo) or the website of the National Geographic Institute (IGN).

Data Silos occur when there is no centralized system to store all the data on a computer. A silo, therefore, makes it more difficult to discover new data, as each is controlled by an independent department, with different policies and even technologies.

You may feel that *Data Silos* are needed to allow more flexibility for computers, iterate faster, and adjust policies to needs in a simple way. However, from a global point of view, it is very difficult to extract value from the data and discover new ideas.

One of the main reasons for adopting a Data Lake is usually to avoid Data Silos, which often occur due to rapid and uncontrolled growth.

As for the **EVE** project, the task of compiling data has had to be mostly manual and has required the collaboration of the different partners of the project. Each workgroup has its own databases, and its own storage systems, but the vast majority of these do not have an extraction system for external users, which makes it difficult to extract the data without their collaboration. In order to obtain the necessary data to be able to perform the *Long Term and Short term analysis*, the partners were provided with two templates in *'.ods'* format in order to gather the data of the volcanoes and eruptions selected for study.

The template that aims to collect the eruptive history of a given volcano is what we have called *Long Term Template* and is as follows:

Initiation date	duration in days	ORIGIN OF THE UNREST	OUTCOME OF THE UNREST	LOCATION	SIZE (VEI)	COMPOSITION	HAZARD	EXTENT	observations
		magmatic, or hydrothermal, or tectonic, or other	magmatic eruption, or phreatic explosion, or sector failure, or no eruption	central, or northern flank, or southern flank, or eastern flank, or wester flank,	from 0 to 8	mafic or felsic	lava flows	small	the extend needs to be defined for each hazards and for each volcano, based on the geological record
								medium	
								large	
							pdc	small	
								medium	
								large	
							fallout	small	
								medium	
								large	
							ballistic	small	
								medium	
								large	
							lahars	small	
								medium	
								large	
							landslides	small	
								medium	
								large	
							others	small	
								medium	
								large	

Figure 30.- Long Term Template used in VOLCANBOX (see text for more explanation)

In this table, the information of the different identified episodes of unrest of a certain volcano has been collected. Each row in the table corresponds to an episode of a rest, and for each of these episodes the following data has been entered in the different columns:

- Initiation date
- Duration in days
- Origin of the unrest
    - Magmatic, hydrothermal, tectonic or other
- Outcome of the unrest
    - Magmatic eruption, phreatic explosion, sector failure, or no eruption
- Location
    - Central, northern flank, southern flank, eastern flank or western flank
- Size (VEI)
    - Form 0 to 8
- Composition
    - Mafic or felsic
- Hazard
    - Lava flows
    - PDC
    - Fallout
    - Ballistic
    - Lahars
    - Landslides
    - Others
- Extent
    - Small, medium or large

With this information entered, each unrest episode will be characterised, and with the whole set of unrest episodes, we will have collected the eruptive history of the volcano, through the time-lapse selected. These data are necessary to be able to make calculations of eruption probability and the most probable scenarios by using the tools developed in this project.

In order to obtain the data needed to perform the Short Term analysis of selected eruptions, the template we have called *Short Term Template* was developed and is as follows:

UNREST_INDICATORS	BACKGROUND LEVEL	VARIATION RANGE: significant variation with respect to the previous value or based on previous observations in other unrest	BULLETIN 1		BULLETIN 2		BULLETIN 3	
			Y/N/not available	Value	Y/N/not available	Value	Y/N/not available	Value
Seismic events (total number) increase								
RSAM acceleration								
Accumulated energy released rate increase								
Lateral migration of seismicity								
Vertical migration of seismicity								
Deep seismicity								
Shallow seismicity								
VT events increase								
LP events increase								
Tremor events increase								
Hybrid events increase								
Other								
Other								
Other								
Overall seismicity increase (direct observation)								
Gas flux increase								
H2O increase								
CO2 increase								
SO2 increase								
Others								
Fluids temperature increase								
Other								
Other								
Other								
Overall gas increase (visual observation)								
Strain increase								
Inflation rate increase								
Lateral migration								
Vertical migration								
Dg/Dh anomaly								
Other								
Other								
Other								
Overall ground deformation increase (visual observation)								
Fractures								
Phreatic explosions								
Fresh magma								
Other								
Other								
Other								

Figure 31.- Short Term Template used in VOLCANBOX (see text for more explanation)

The aim of this template was to collect the data obtained through the monitoring networks of the different volcanological observatories and of different episodes of unrest. The most widely used unrest indicators used by the experts were chosen and which include seismic, gas, deformation and other observations such as the presence of fractures, groundwater explosions or the presence of fresh magma. The different parameters are in the rows of the table. In the first column, we must enter the "Background level" of the parameter whose data we are entering. This value will mark the moment when, in the case of having higher parameter values, the volcano will have entered a state of unrest. In the second column we will introduce the “Variation range”, a value from which we will consider that there has been a change with respect to the previous bulletin. The ideal scenario is that these values are introduced by experts from different volcanological observatories. The column below is that of the newsletter. Here we will enter the date, and the value of the parameter that has undergone a change in the "value" column. In the event that we do not have obsolete values but relative ones, in the “Y / N / Not available” column, we will include “Y” in the event that the parameter has changed with respect to the previous bulletin, “N” in the case that has not changed, and "Not available" when we do not have information.

The data obtained have been extended by searching to:

- WOVOdat database (https://wovodat.org/)
- Global Volcanism Program, Smithsonian Institution web page (https://volcano.si.edu/)

- Catalogues and bulletins published on the websites of the various observatories, the main ones consulted were:
    - National Geographic Institute (IGN) (https://www.ign.es/web/ign/portal/vlc-area-volcanologia)
    - Volcanological Observatory of Piton de la Fournaise (https://www.ipgp.fr/fr/dernieres-actualites/344)
    - National Institute of Geophysics and Volcanology (INGV) Ethno Observatory. Catania Section (https://www.ct.ingv.it/index.php)

- Publications in scientific journals
- Master's thesis and Doctoral Thesis

Unfortunately, although in order to carry out the objectives of this proposal it is not desirable to have to adopt this mostly artisanal methodology, ours is a paradigmatic case. However, in order to find solutions to this problem, this first approach was strictly necessary, as we needed to know in depth the characteristics of the domain in which we are working.

This issue highlights the need for a proposal like ours and, more specifically, the development of tools to automate the maximum number of processes surrounding the data life cycle. These tools should be comfortable, secure, and accessible to all types of users involved, and should be minimally intrusive and most compatible with pre-existing systems. This is where flask microservices come into play.

2.2.1.3. Microservices Flask

Python Flask microservices, among others, can assume the responsibility of "translator" between technologies, offering a unique method and language of consultation to communicate with the different subsystems. Imagine for example that we have different subsystems each with a completely different query language, a Microservice is able to link a particular query and create a new one adapted to the needs of a subsystem. In this way you can offer the user the feeling of being working on a single system source.

As I will see later, there are cases where the data requires intermediate processes to extraction and storage. In these cases, the power of *Python* can be harnessed to carry them out. In fact, processes can communicate with each other, providing a gateway to the adoption of external tools in case using *Python Scripts* is not the best option. Thus, we can create a whole ecosystem of specialized Microservices with the aim of obtaining maximum efficiency.

It will therefore be necessary to adopt and elaborate tools for extracting, transforming and loading information.

2.2.1.4 ETL

The tools of information extraction, transformation and loading are very important in architectures composed of different subsystems -as is the case of ours-, as they have the responsibility to act as a link between the different technologies that are involved.

The ultimate goal is to make these tasks automated and linked to microservices that handle requests, but as we will see later, we are currently a long way from that goal.

If we think about our system, as we have described it, there is clearly a flow, and with each advance, the data goes from being potentially unstructured to having a more defined structure. Specifically, and in terms of data storage, we have the following phases:

Data Lake: No hierarchy required, any format is accepted.

Data Warehouse: It follows a hierarchy of directories and formats. Formats can be quite different for the same type of data.

Local Project: It follows a hierarchy of directories and formats. Formats are always the same for the same type of data.

Online Project: The data is indexed following a closed table and relationship scheme.

It is at the midpoint between these phases that *ETL*s make sense.

2.2.1.5. Data transformation

In the case of *Data Lake*, in order to preserve the original contents, only a loading and extraction process is carried out, so it only depends on microservices that are able to obtain the target content and store it with the corresponding tags. Otherwise, in the case of the *Data Warehouse*, once extracted, the necessary transformations must be carried out to follow its standards. *VOLCANBOX*, on the other hand, is prepared to carry out all the necessary transformations automatically, always that the formats you receive follow the specifications of the Data Warehouse.

To describe these processes, we will take as an example the case of Short and Long term analysis. The data collected from the template shared with partners, enriched by bibliographic data to be stored into a spreadsheet that has the .ods format and meets the requirements of *VOLCANBOX*.

Admittedly, some transformations could have been avoided if the final *VOLCANBOX* compatible template had been available, but it was not yet defined. In future data requests, the new template will be sent in order to avoid this transformation.

The following is an example for each case:

HASSET Long Term

The data collected from the Long Term template must be partially transformed and stored in a spreadsheet. The transformations that must be performed in order to be compatible with *VOLCANBOX* are as follows:

- Location field. Up to a maximum of 5 areas listed from 1 to 5 will be defined, based on the information collected in the *Long Term Template*. The corresponding number will be entered in the "location" field.
- Hazard Group Camp. Up to 12 Hazard Groups will be defined, listed from 1 to 12. Each of the groups consists of a combination of hazard and extent. The corresponding number will be entered in the "Hazard Group" field.

The following is an example of the spreadsheet corresponding to La Palma transformed to be introduced in the *HASSET Long term*:

	Unrest	Origin	Outcome	Location	Composition	Size	Hazard Group	Observations
1480	Yes	Magmatic	Magmatic Eruption	3	Mafic	1	Group 3	lava flows abd lapilli
1585	Yes	Magmatic	Magmatic Eruption	3	Mafic	1	Group 5	
1646	Yes	Magmatic	Magmatic Eruption	4	Mafic	1	Group 6	2 eruptive vents, very fluid alva flow emission
1677	Yes	Magmatic	Magmatic Eruption	4	Mafic	1	Group 7	2 emission centres, lava flows, pyroclasts, scoria and lapilli
1712	Yes	Magmatic	Magmatic Eruption	3	Mafic	2	Group 8	lava flows emitted from 2.5 km long fissure
1936-39	Yes	Seismic	No Eruption			0	Group 1	periods of frequent and intense seismicity maybe related to submarine eruptions
1949	Yes	Magmatic	Magmatic Eruption	3	Mafic	2	Group 9	phreatmagmatic pulses, pahoehoe lava, 3 vents, seismicity felt before eruption, lava flows reaching the sea
1971	Yes	Magmatic	Magmatic Eruption	4	Mafic	1	Group 10	seismicity felt before eruption, strombolian behaviour, emission of tephra and lava
2017-18	Yes	Other	No Eruption	4		0	Group 4	
2021	Yes	Magmatic	Magmatic Eruption	3	Mafic	2	Group 2	multi-phased (?), large volume of lava and fallout, still ongoing

Figure 32.- HASSET long-term data of La Palma

Unrest	Origin	Outcome	Location	Composition	Size	Hazard Group
Yes	Magmatic	Magmatic Eruption	1	Mafic	0	Group 1
No	Geothermal	Phreatic Explosion	2	Felsic	1	Group 2
No Event	Seismic	Sector Failure	3		2	Group 3
	Other	No Eruption	4		3	Group 4
			5		4	Group 5
					5	Group 6
					6	Group 7
					7	Group 8
					8	Group 9
						Group 10
						Group 11
						Group 12

Extent	Abbreviation
Large	l
Medium	m
Small	s
None	

Zone	Name
1	Taburiente West and Bejando
2	Taburiente East
3	Upper Cumbre Vieja
4	Lower Cumbre Vieja
5	Costal Zone around the Island

Size	Name
0	Low
1	VEI 1
2	VEI 2
3	VEI 3
4	VEI 4
5	VEI 5
6	VEI 6
7	VEI 7
8	VEI 8+

Group Nº	Lava Flows	Pdc	Fallout	Ballistic	gas release		Seismicity
Group 1							m
Group 2	l		l				l
Group 3	l		m		s		
Group 4					s		l
Group 5	m		m	s	m		m
Group 6	m		l		s		m
Group 7	s		s		s		
Group 8	m	s	s				
Group 9	l	l	l	m	m		l
Group 10	s		m	s	s		m
Group 11							
Group 12							

Figure 33.- Structure of the VOLCANBOX HASSET long-term template

HASSET Short Term

As for unrest data, compiled from the Short Term Template and expanded with data from catalogues and newsletters published by various volcanological observatories (among others), they have also been transformed and stored in spreadsheets in .ods format. The transformations that have had to be carried out in order to meet the requirements of the *HASSET Short Term* are as follows:

- Date must be in YYYY_MM_DD format
- The "Id" column should include the bulletin number
- Numbers with decimals must be 00.00 (English format)

The following is an example from the El Hierro transformed spreadsheet for introduction to the *HASSET Short Term*:

Group	Name	Background	Variation Range	Id	Date	Id	Date	Id	Date	Id	Date	Id	Date	Id	Date	Id	Date
				22	2011_07_22	23	2011_07_23	24	2011_07_24	25	2011_07_25	26	2011_07_26	27	2011_07_27	28	2011_07_28
				Value	Changes	Value	Changes	Value	Changes	Value	Changes	Value	Changes	Value	Changes	Value	Changes
Seismicity	Seismicity increase	0.00	0.00	0.00		0.00		0.00		0.00		0.00		2.00		0.00	
Seismicity	RSAM acceleration increase	0.00	0.00	0.043		0.047		0.051		0.054		0.053		0.052		0.055	
Seismicity	Accumulated energy released rate increase	0.00	0.00	3.18E+09		2.15E+09		4.30E+08		5.73E+08		1.50E+09		3.00E+09		7.27E+08	
Seismicity	Lateral migration of seismicity	0.00	0.00		N		Y		Y		Y		N		N		N
Seismicity	Vertical migration of seismicity	0.00	0.00	10.09		10.72		10.53		13.40		8.45		8.93		10.33	
Seismicity	Deep seismicity	0.00	0.00		-		-		-		-		-		-		-
Seismicity	Shallow seismicity	0.00	0.00	0.00		0.00		0.00		0.00		1.00		4.00		1.00	
Seismicity	VT events	0.00	0.00	202.00		135.00		65.00		71.00		121.00		130.00		76.00	
Seismicity	LP events	0.00	0.00		-		-		-		-		-		-		-
Seismicity	Tremor events	0.00	0.00		-		-		-		-		-		-		-
Seismicity	Hybrid events	0.00	0.00		-		-		-		-		-		-		-
Seismicity	Overall seismicity	0.00	0.00		-		-		-		-		-		-		-
Gas	Gas flux increase	0.00	0.00		-		-		-		-		-		-		-
Gas	H2O increase	0.00	0.00		-		-		-		-		-		-		-
Gas	CO2 increase	0.00	0.00		-		-		-		-		-		-		-
Gas	SO2 increase	0.00	0.00		-		-		-		-		-		-		-
Gas	Fluids temperature increase	0.00	0.00		-		-		-		-		-		-		-
Gas	Overall gas increase	0.00	0.00				-		-		-		-		-		-
Deformation	Strain variation	0.00	0.00	0.015	-	0.014		0.012		0.014		0.014		0.015		0.016	
Deformation	Inflation rate increase	0.00	0.00		-		-		-		-		-		-		-
Deformation	Lateral migration	0.00	0.00		-		-		-		-		-		-		-
Deformation	Vertical migration	0.00	0.00		-		-		-		-		-		-		-
Deformation	Dg/Dh anomaly	0.00	0.00		-		-		-		-		-		-		-
Deformation	Overall ground deformation increase	0.00	0.00		-		-		-		-		-		-		-
Deformation	n (m)	0.00	0.00	-0.01743		-0.01706		-0.01763		-0.01668		-0.01656		-0.01730		-0.01661	
Deformation	e (m)	0.00	0.00	-0.00933		-0.00987		-0.01101		-0.01039		-0.01043		-0.00864		-0.00811	
Deformation	u (m)	0.00	0.00	-0.00730		-0.00640		-0.00685		-0.00750		-0.00585		-0.01787		-0.00974	
Others	Fractures	0.00	0.00		-		-		-		-		-		-		-
Others	Phreatic explosions	0.00	0.00		-		-		-		-		-		-		-
Others	Fresh magma	0.00	0.00		-		-		-		-		-		-		-

Figure 34.- Database template used for the HASSET short-term in VOLCANBOX

It should be said this and others processes can be carried out with the help of tools such as *Hevo Data, Pentaho kettle, GeoKettle, Python scripts* etc.

Volcanic Zone

A volcanic area refers to the area covered by certain data in terms of georeferencing.

Figure 35.- Sketch illustrating the extraction from the Data Warehouse to create a project

For each Volcanic Zone*,* there will be a *Data Warehouse* that will contain all the data referring to its geographical extension -Basically, in terms of implementation, it is actually a large distributed warehouse that contains all the warehouses of all the volcanic zones, but we have thought that giving this vision would help the user to work more comfortably and focus on the case of study in question-.

On the other hand, when you want to study a subzone - which may contain data from one or more volcanoes - a new *VOLCANBOX Project* will be created.

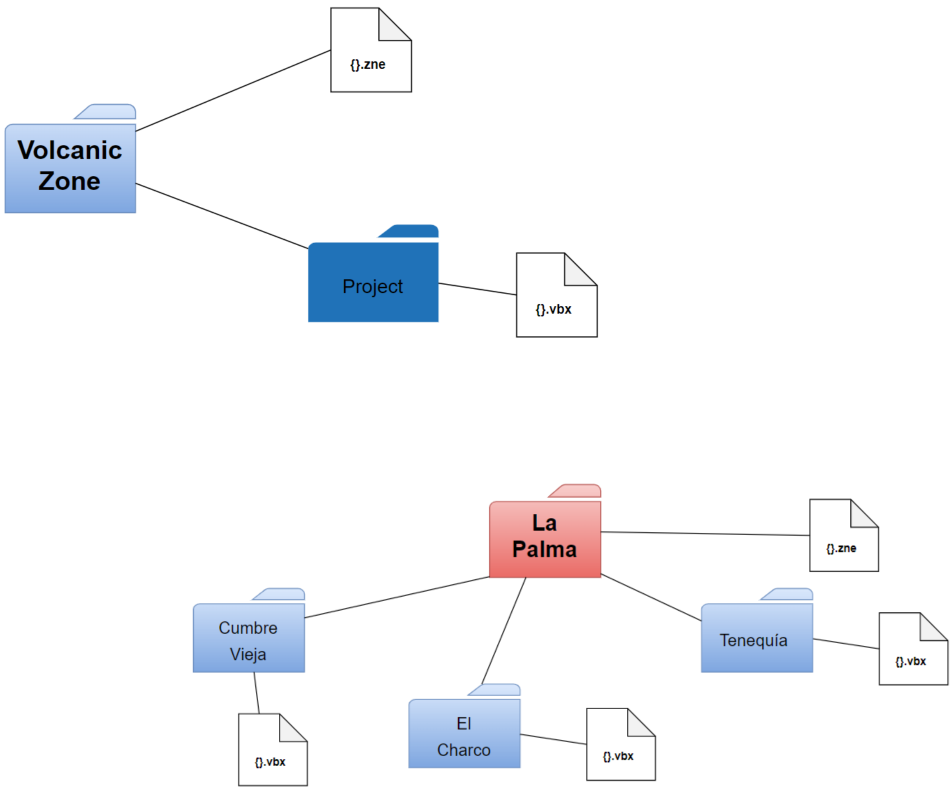


Figure 36.- Diagram illustrating hieratic structure of a Volcanic Zone and a particular project

For example, *La Palma* is a *Volcanic Zone* that in geographical terms contains the following volcanoes: El Charco, Cumbre Vieja and Teneguía. The *Data Warehouse* of La Palma will therefore contain all the data needed to create a *VOLCANBOX Project* for each of the aforementioned volcanoes. These projects will be stored within the same volcanic area to which the volcano they study belongs. It may also be the case that it contains projects for two or more volcanoes.

On the other hand, all zones contain a metadata file in *Json* format with '*.zne'* extension which, similar to *Data Lake* tags, allows you to index the information to retrieve it by applying different filters. The file contains the following fields:

- **Name:** Name of the Volcanic Zone.
- **Country:** Country
- **Extension:** Geographical coordinates that refer to the total Volcanic Zone.
- **Geodynamic Setting:** Tectonic regime that characterizes the Volcanic Zone -for example, subduction, ridge, oceanic, hot, etc.-
- **Types of Volcanism:** Describes whether they are central volcanoes or monogenetic fields.
- **Important Volcanoes:** List of most representative volcanoes in the area.
- **Composition:** Main chemical composition of magma.
- **Eruptive dynamics:** Briefly describe the main types of eruptions.
- **Historical volcanism:** Existence or not of historical volcanism with eruption or not.

- **Description:** Field where the user can enter extra information or which does not fit in the other fields.

2.2.2. Data Warehouse

Following the architecture design, we have been inspired by the Data Warehouses of Big Data environments to create the next piece of our system. It is common to see articles where the virtues of a *Data Lake* are confronted with those of a *Data Warehouse*. However, when it comes to polyglot architectures like ours, the two subsystems can coexist and add value to the system.

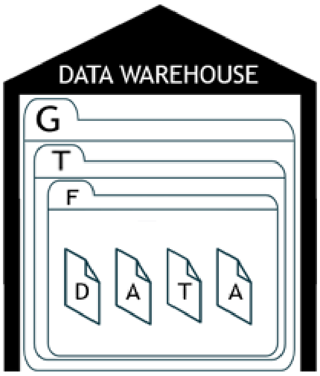


Figure 37.- Sketch illustrating the internal structure of the Data Warehouse

In our case it is a very simple *Data Warehouse* where only data that has gone through validation processes is stored where the necessary transformations have been applied to be compatible with *VOLCANBOX*. These transformation processes only apply if necessary. *VOLCANBOX* Application accepts several geodata formats, and any format accepted can be stored into the Data Warehouse.

This philosophy is followed to try to make minimal changes to the original data and to be able to recover it, because otherwise only the unvalidated version of *Data Lake*, or the modified version of the *VOLCANBOX Project*, could be recovered, probably containing modifications or errors–.

For example, in the case of *Spatial Analysis*, in order to be able to retrieve the contents stored in the *Data Warehouse* of a volcanic zone, the following directory hierarchy has been defined:

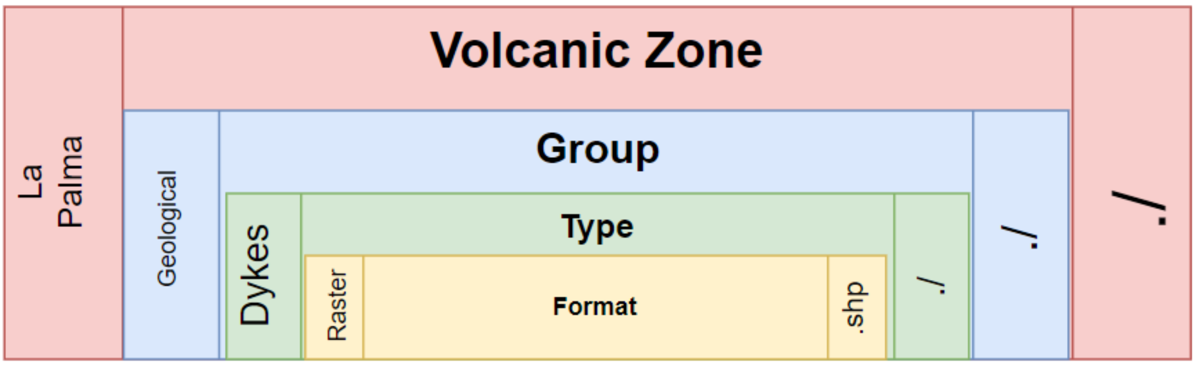


Figure 38.- Example of the data structure in a particular case study (La Palma Island) of spatial analysis

- **Group:** Set of information of the same type, for example, Geological, Geographical, Volcanological, Infrastructure,
  - **Type:** Refers to the type of structural element - Example: 'wind', dyke ',' fault ', etc.-
    - **Format:** Content type, for example, 'Document', 'raster', 'shape', 'chart','spreadsheet', etc.

2.2.3. VOLCANBOX Application

Given a volcanic area, a project is a directory that contains all the structured data needed to reproduce a risk assessment using the *VOLCANBOX* application, as well as its results.

The application is divided into sections - such as *Short Term Analysis, Probability Density Function, Lava Flows,* etc. - and these are grouped according to the type of analysis being performed. In order to use these sections, the user must first create a new project and choose or create a *Volcanic Zone* where to place it. The input and output data of the different experiments that the user carries out will be distributed in *Datasets* that the user will be able to store within the Local *Project*.

If you want to use sections with GIS functionality, the user will have to select a main digital elevation model, this action must be carried out at the time of creation of the project. Important information will be extracted from this model, such as: the geographical extension covered by the project, the height for each point of it, the resolution, the geographical reference system that will be used as a basis, etc.

This way, when a user wants to retrieve an experiment, all he has to do is open the target project, select the *Dataset* referring to it, and then continue working at the point where he left it. In case this section includes GIS sections, its *Datasets* will be associated with one more layer.

The goal is for the datasets to end up enriching both the *Data Lake* and the *Data Warehouse*. For example, imagine that a user obtains certain results using the *VOLCANBOX* application, and once validated, decides to enter them in *Data Lake*. Depending on the tags you use - or as determined by the system - you will be able to relate them to pre-existing data for: Carrying out comparisons, new analysis with Big Data techniques, generating new data sets, etc.

The application contains a section called *Library*, where the user can consult, upload or download, for each volcanic zone, all existing projects, as well as their datasets. In the current version of the application, you can only work with projects located on the computer where it is running, but it is planned to offer a network connection to work with remote libraries.

If we were to once again make a simile with the world of Big Data, the *VOLCANBOX* application would be a data mart.

To be able to create a project using the VOLCANBOX application, the user must first have created or imported at least one *Volcanic Zone* - choosing one is a sine qua non condition for creating a new project. The projects - as well as the *Volcanic Zones* - also contain a *'.vbx'* metadata file where a *Volcanic Zone* field is added. This field contains a replica of the entire contents of the

'.zne' file in the Volcanic Zone that was selected when you created the project. This process is carried out to allow users to import projects even though they do not have information regarding this volcanic zone. Needless to say, this is information that, despite being replicated, is not very important in terms of disk space.

The software, then, when an import is carried out, checks if this *Volcanic Zone* exists. If not, ask the user if they want to create this zone from the imported metadata, or prefer to specify it manually. If so, if you see a difference, ask if you want to update the local area - based on the metadata of the imported project - or instead keep the existing ones.

Since the application is designed to load and store data both locally and remotely - in future updates - two very different approaches have been designed.

2.2.3.1. Local Project

As for the local version, one of the initial requirements of the application is that the results generated are searchable by the most used external applications on the market - regardless of the hardware or operating system in which they run -, therefore, they need to be saved in formats that are compatible with them. To meet this requirement, the following formats have been chosen as the main pillars for storing information:

- **GeoTiff** : Its main advantages are its suitability for a wide range of applications and its independence from computer architecture, operating system and graphics hardware.
- **JSON** : It is a format, in plain text, this fact makes it suitable and secure for transfer between platforms and operating systems that do not easily share more complex types of documents. It is lightweight and its syntax and structure can be easily interpreted by applications that do not yet know what type of data they will receive.
- **Shape** : Its simple structure allows you to spatially describe vector features: points, lines and polygons, which represent, for example, winds, fissures, dykes, etc. Each element can have attributes that describe it.

All volcanic areas, as well as projects in this version, are saved in the *VOLCANBOX Library* folder. This folder is structured in folders referring to Volcanic Zones and these are structured in folders referring to *Projects*. All folders related to *Volcanic Zones* contain a *Json* format file with a *'.zne'* extension at the root of their directory, as well as those referring to projects with a *'.vbx'* file. These contain your metadata and are essential for its execution.

- **Name**: Name of the project.
- **Date**: Date the project was created.
- **Version**: Project version.
- **Responsible**: Responsible for the project.
- **Purpose**: Description of the project objectives.
- **Volcano**: Name of the volcano.

- **Type**: Volcanic building type - for example: shield volcano, stratovolcano, caldera, dome, slag cone, maar, tuff ring, tuff cone, fissure.
- **Historical eruptions**: Dates of representative historical eruptions.
- **Hazard**: Contains for each danger to be studied, the conventions referring to the range of values that correspond to a long, medium, or small extension.
- **Dem**: Contains metadata related to the main elevation model of the project.
- **Volcanic Zone**: Replica of the content of the '.zne' file of the zone to which the project belongs.

Each *Project* will also contain two directories, one to store the *Datasets* in *Json* format and another to store the layers associated with them in *Geotiff* and Shape format. This directory structure is explained in detail below:

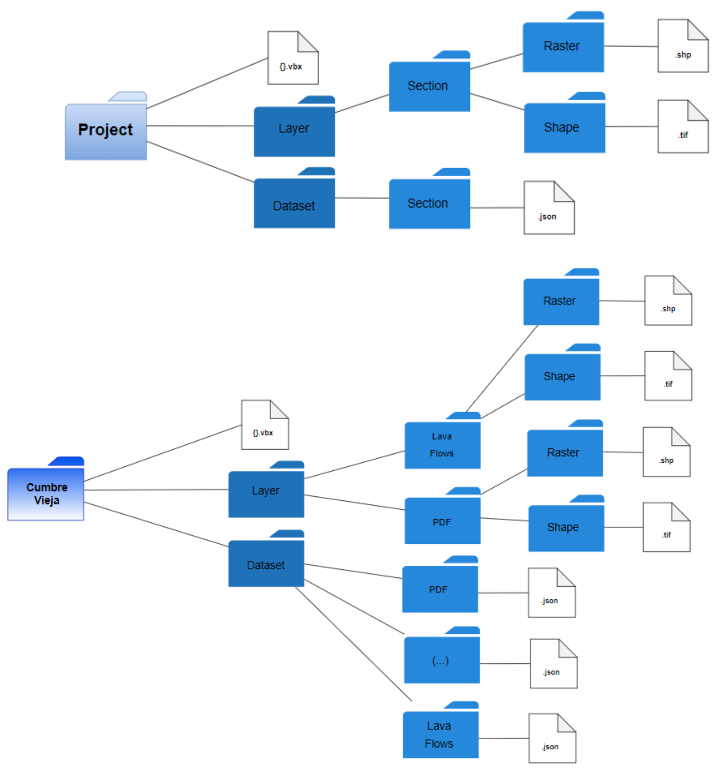


Figure 39.- Diagram illustrating the directory structure of a project

- **VOLCANBOX Library:**
  - **Volcanic Zone:**
    - **Project Name** : The root directory of the project is the only one that the user can name, but it is a requirement that if it exists, it is empty at the time of creating the project.
      - **Dataset** : Contains a directory for each available section
        - **Section** : For a given section, it contains all the *Datasets* belonging to the project in question.

- **Layers** : Contains a directory called Main Dem, also contains a directory for each section.
  - **Main Dem** : This directory contains all the files related to the main digital elevation model of the project.
  - **Section** : Contains, for a given section, a directory for each type of georeferenced data file generated by the application.
    - **Shape** : Count the vector files of the project.
    - **Raster** : Contains the maps generated with the application - elevation models, probability density maps, etc. -.

2.2.3.2. Online Project

In terms of *Project* loading and storage, the online functionalities of the application are designed to facilitate collaboration between members of the same or different teams. On the other hand, in the medium term, the goal is to use *VOLCANBOX* to create a large database with which, thanks to standardisation, computers can cross-check their data with those of other computers - provided they have of the appropriate permissions-, thus generating new content that creates a chain of feedback that exponentially increases the use of resources. For example, a user will be able to create a new project with their own information and enrich it to carry out operations such as:

- Compare the results obtained for the same *Volcanic Zone*.
- Compare the behaviour of two different *Volcanic Zones*, for example, to find patterns that offer knowledge.
- Enrich parameters for which not enough information is available.
- Real-time data provide.

On the other hand, despite being a desktop application, the prospect of generating software that can be easily translated into an online version has never been lost. This will allow taking advantage of the power of the current supercomputers to be able to work with models of high resolution, and to carry out operations that would not be possible in an average hardware.

In order for the application to be ready to support these features, the following conceptual scheme has been designed:

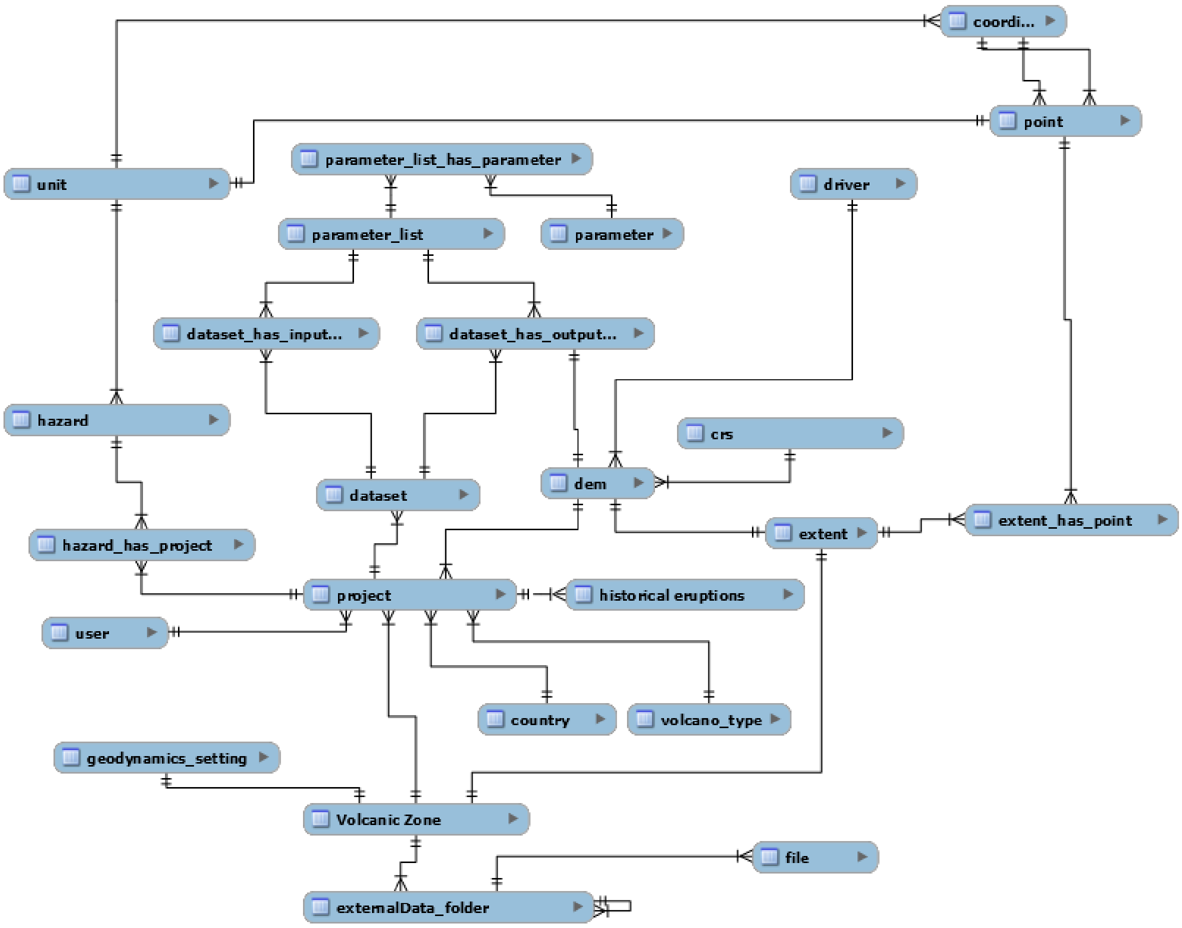


Figure 40.- Conceptual scheme of the structure of an on-line project

- **Volcanic Zone** :
  - Describes a particular volcanic area.
- **Project**
  - Describes the metadata described in the *'.vbx'* file. Either through their fields or through their relationships.
- **Section**
  - Describe the sections available in the app. *This table does not allow insertions by customers.*
- **Dataset**
  - For a certain section, it resolves the metadata needed to obtain all the data needed to run the experiment associated with it, as well as to retrieve the results.
- **Parameter**
  - Describes an input or output parameter of a dataset for a given section.
- **Hazard**
  - Describe the metadata of a type of hazard to study. It also solves some conventions, such as the range of values that correspond to a long, medium, or small extension.
- **United**
  - Describes a type of unit of measure.

- **Coordinates**
  - Describes the value of a coordinate.
- **Point**
  - Describe a location within the extent of the volcanic subzone under study. You can also describe the value for a couple of coordinates.
- **Driver**
  - Describes a geospatial data format compatible with *VOLCANBOX*.
- **User**
  - Describes a user's credentials. These are the email, first name, last name, and password
- **Geodynamics Setting**
  - Describes the possible tectonic regimes of a *Volcanic Zone*.
- **Country**
  - Describes the name of a country, and its reference code.
- **Volcano Type**
  - Describe the type of volcanic building.
- **Extent**
  - Describes a geographical extension for a layer or a Volcanic Zone.
- **Layer**
  - Describes a set of georeferenced data.
- **Crs**
  - Describes a coordinate reference system.
- **External Data Folder**
  - Describes the directories where the data that is structured within a given file is stored.
- **File** :
  - Describes the name, extension, format, and description of a file.

To simplify, all the tables referring to institutions, position, etc. have been omitted. In the event that a point contains a value, it must be linked to a unit that will describe the unit of measure of the value of the point. All points in a layer of a given project must be within the extent of a volcanic zone of a project.

The fact that we have chosen a relational scheme has been because in the end point of the chain where we are, where the data has been structured following certain, we can already store them following a predefined scheme, because we also know that this it will not change if the *VOLCANBOX* application does not, which would not escape our control. This allows us to take advantage of all the benefits of relational databases, without sacrificing more innovative features - which we will have to find in previous points of the gear, but which will be there.

2.2.3.3. Consultation and Visualisation

Consultation

In order to provide the reader with an example of how the different contents of the *VOLCANBOX Platform* are structured, a service has been enabled that communicates with the different parts of the platform. The documentation related to this is interactive and can be consulted via the following link:

https://www.volcanbox.com:5000/api/

By accessing the aforementioned link, the user will be able to see a list of the different microservices that can be consulted and for each of these the end points to the consultation methods currently available. For each method a general description is shown, the type of method and a description of the input and output parameters, in addition, an interactive form is also included that allows you to enter the input parameters to make a request of execution.

At the time of writing, only server-level security protocols have been implemented, but not in service level. It is important to note that the purpose of this service is simply to allow users to download a sample of the content that has been generated. On the other hand, it can be useful to give an idea of how the whole system may or may not be transparent to the user depending on the needs, permissions, etc.

The final points of interest currently implemented can be consulted through the section, *VOLCANBOX*, via the following link:

https://www.volcanbox.com:5000/api/volcanbox/

This works as a discovery and therefore returns all available query methods. Similarly, a direct discovery of the different subcomponents can now be made using the following links:

https://www.volcanbox.com:5000/api/volcanbox/lake/

https://www.volcanbox.com:5000/api/volcanbox/warehouse/

https://www.volcanbox.com:5000/api/volcanbox/project/

For a better understanding of the methods and as an interactive tutorial, it is recommended to use the respective section of the documentation.

Visualization

In order to visualise the information, a great effort has been made so that the user can choose the application that he decides, regardless of, at what stage in terms of structuring it is. It is recommended, but from now on, to work with the VOLCANBOX application - the launch of its first release is imminent - to consult and perform new evaluations….

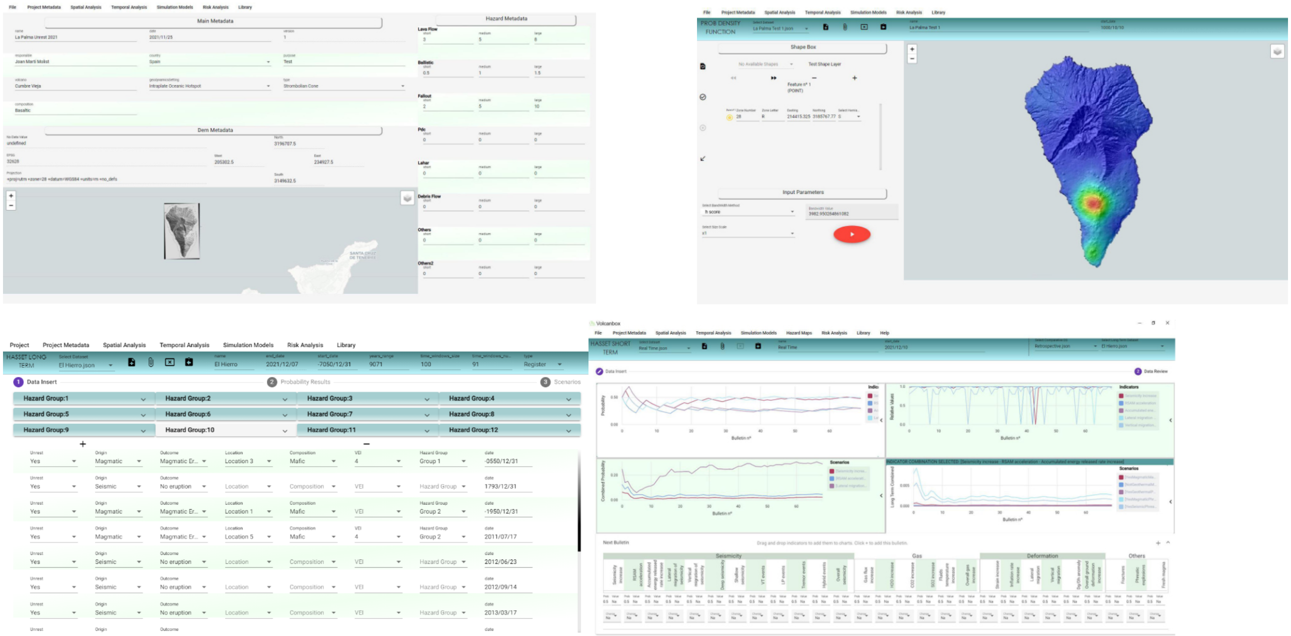


Figure 41.- Selection of different screen views generated by VOLCANBOX as part of a project

2.3. VOLCANBOX: the concept

Despite we have already introduced VOLCANBOX in the previous sections, we have still not explained in detail the concept behind it. In essence, VOLCANBOX is a multi-platform software package that integrates in a systematic and sequential way a series of well-tested tools addressing various aspects of the volcanic hazard assessment and risk analysis process (Fig. 42). The idea behind VOLCANBOX is to provide community planners with long-term hazard assessments and vulnerability analysis during quiescent times and supply first responders with short-term hazard assessments and cost-benefit analysis as volcanic unrest unfolds.

However, VOLCANBOX is much more. Modern assessments of volcanic hazards rely on probabilistic approaches, where volcanologists develop models that combine eruptive scenarios and their expected recurrence with information on population distribution, infrastructure vulnerability, and other factors that help calculate risks to the general public. With these models, decision makers can conduct a holistic analysis of a volcanic crisis, including assessments of costs versus benefits. Scientists and civil authorities do not always work sufficiently closely to enable the authorities to always understand the science behind hazard assessments. Also, the scientific community has not always clearly understood the needs and exact requirements of officials. As a result, the collaboration between scientists and community planners is not always as successful as it could be. Scientific literature offers a considerable number of methodologies and tools addressing hazard assessment. However, community planners sometimes prefer to use their own approaches and ignore these methodologies and tools, which end up being only a good academic exercise. Because probabilistic methodologies play such a prominent role in volcanic hazard assessment, scientists seek to develop methodologies and protocols to bridge this disconnect. These methods aim to provide better scientific support to the civil authorities who must base their decisions on them. In this vein, VOLCANBOX was born with the help of the EC ECHO Grants VeTOOLS and EVE.

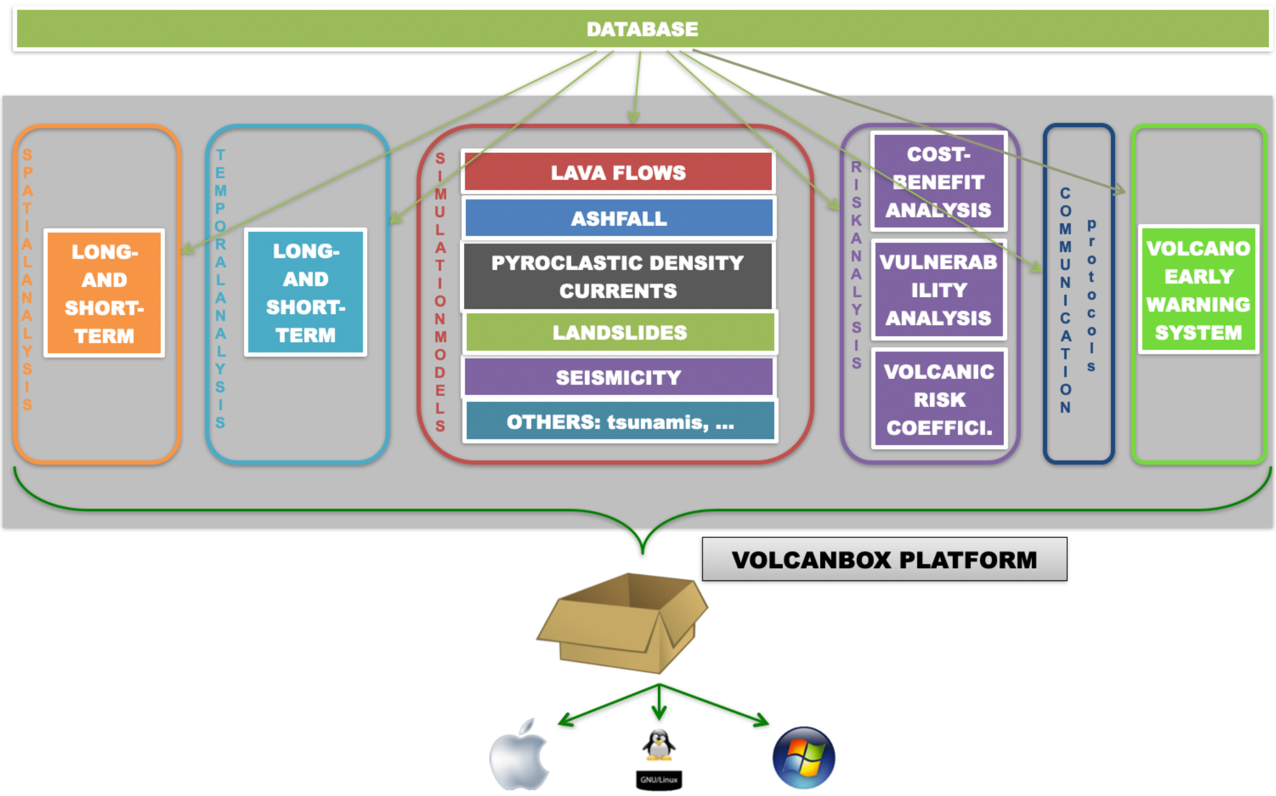


Figure 42.- Structure of the VOLCANBOX platform

The design of VOLCANBOX has been based on the obligation to accomplish six main conditions: 1) it must be multiplatform (Windows, Mac, Linux), 2) durable (Resistant to the passage of time, not subjected to any particular version of libraries, external software packages, or operational systems), 3) independent (resolving without the need for other GIS or similar tools), 4) easy (to install, configure and use, with a modern and user-friendly graphical interface), 5) light (executable using medium hardware), and 6) scalable (in terms of features and performance). Accomplishing all these requirements has obliged to elaborate a completely new software package that could integrate all available programs into a proper, independent new GIS platform. In the VeTOOLS project all available e-tools where integrated into the open source, open access QGIS platform, but immediately it was realised how difficult it was going to keep them updated each time that a new version of QGIS was implement. This is why, it was finally decided to construct our own GIS platform independent from any other. All details concerning the software code and its elaboration are described in Martínez-Sepulveda et al (in prep a and b).

Currently, the VOLCANBOX platform includes a database design (explained in the previous section), an open platform for debugging computer code created to structure and store all data necessary to conduct hazard assessment. The platform is structured in six modules: spatial analysis, temporal analysis, simulation models, risk analysis, communication protocols, Early Warning System.

Each of these modules includes different e-tools, most of them developed in the VeTOOLS and EVE projects, but other elaborated separately. These tools include as the core of the platform: Quantum Geographic Information Systems (GIS) for Volcanic Susceptibility (QVAST) (Bartolini et al., 2013), which provides quantitative assessments of a new eruptive vent; Hazard Assessment Event Tree (HASSET) (Sobradelo et al., 2014), an event tree structure that uses Bayesian inference to estimate the probability of occurrence of a future volcanic scenario; Volcanic Risk Information System (VORIS) (Felpeto et al., 2007), a GIS-based tool that allows users to simulate lava flows, fallout, and pyroclastic density current scenarios; Volcanic Damage (VOLCANDAM) (Sciani et al., 2014), which generates maps that estimate the expected damage caused by volcanic eruptions; and Bayesian Decision Model (BADEMO) (Sobradelo and Martí, 2015), which enables a previous analysis of the distribution of local susceptibility and vulnerability to eruptions to be combined with specific costs and potential losses; and the VEWS, the volcano early warning system developed as part of the EVE project. Moreover, the platform integrates other tools or models that have been developed by other authors (e.g., LaharZ (Schilling, 1998), Qlava (Mossoux et al., 2016, Peack Ground Acceleration (Nuñez, 2017), IMEX_SfloW2D 1.0 (Vitturi et al., 2018) etc), etc). Also, although volcanic eruptions are infrequent, they present multiple hazards and thus create similar or even greater problems than more frequent natural events. For that reason, VOLCANBOX is open to incorporate other existing tools for assessing potentially related hazards, including earthquakes, landslides, and tsunamis.

VOLCANBOX is designed with the aim to make scientific information understandable for decision makers and community planners who manage risk in volcanic areas. Through step-by-step instructions, scientists using VOLCANBOX show community planners how to identify the most probable eruptive scenarios and their potential effects, which helps officials triage emergency responses in the event of an eruption. These instructions were developed after testing VOLCANBOX with civil protection agencies in Spain, the Azores, Italy, Reunion Island, and Iceland.

Before using VOLCANBOX, experts must engage community planners to discover what they need. In this way, experts who effectively use VOLCANBOX will actively work with civil protection agencies to share, unify, and exchange procedures, methodologies, and technologies, thereby reducing the effects of volcanic disasters by improving assessment and management of volcanic risk.

2.4.- The VOLCANBOX interface

When opening VOLCANBOX the user can immediately visualise the interface of the platform. This has been designed to be simple, friendly and easy to use (Fig. 43). The idea is to present to the user as a first screen a tools bar containing a tab for each module, in addition to those corresponding to the description of the project, metadata, library (containing all the input and output files required to develop one or more related projects) and help (containing tutorials, manuals and other additional information) (Fig. 43)

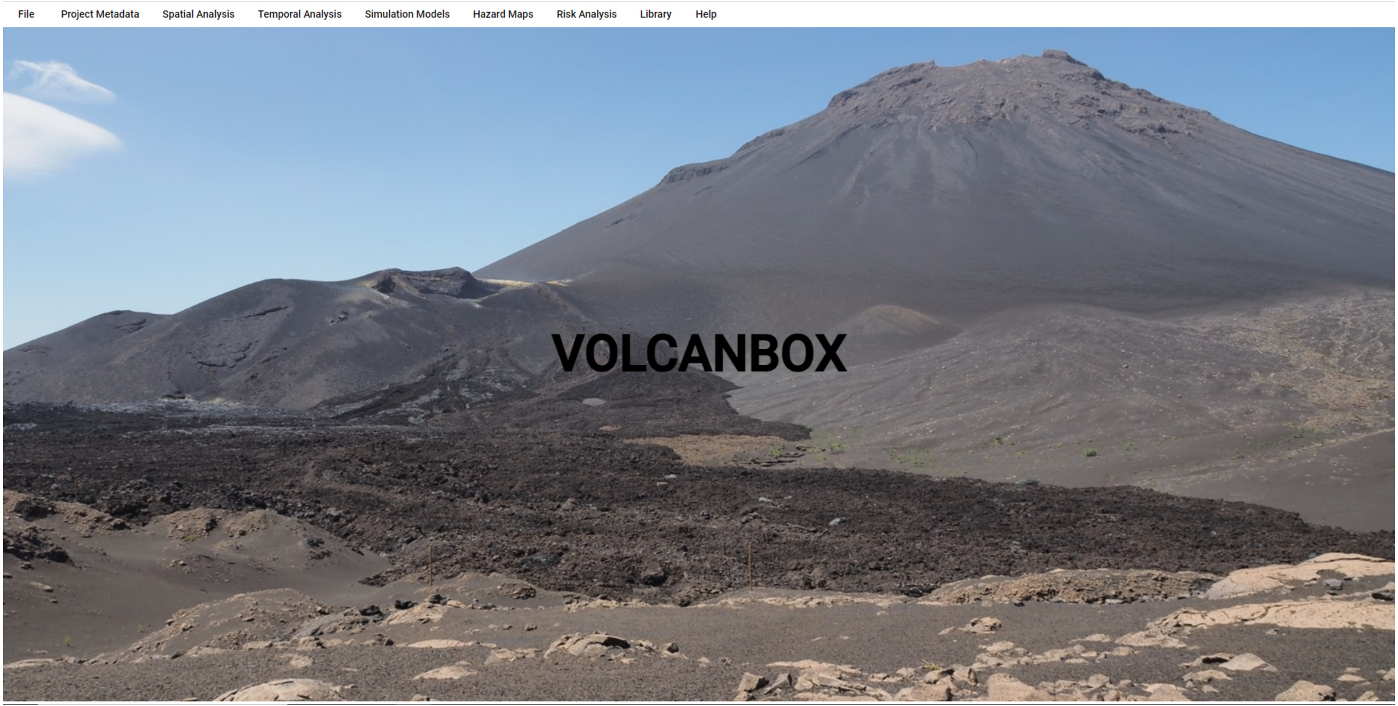


Figure 43.- Front page of VOLCANBOX application

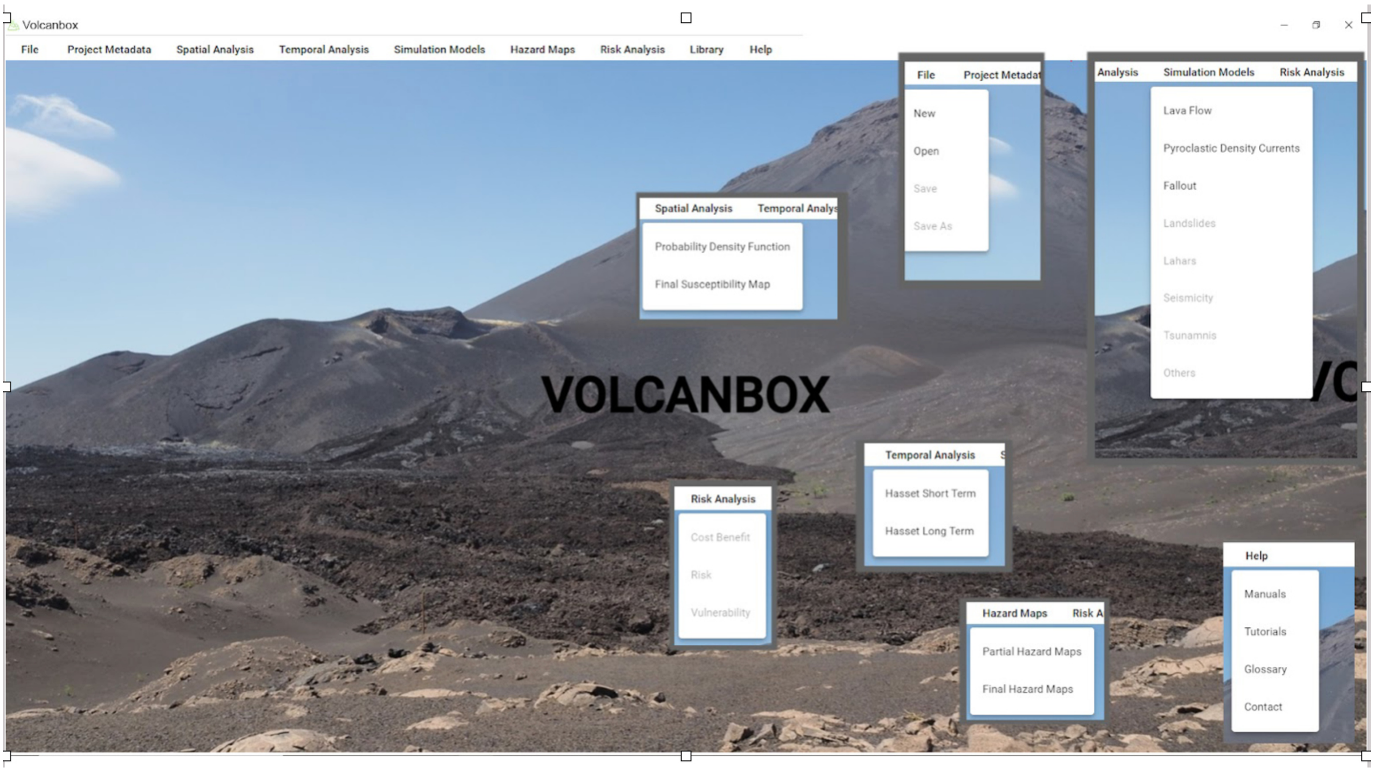


Figure 44.- Visualisation of some of the drop-down menus shown when pressing on tabs included in the tools bar

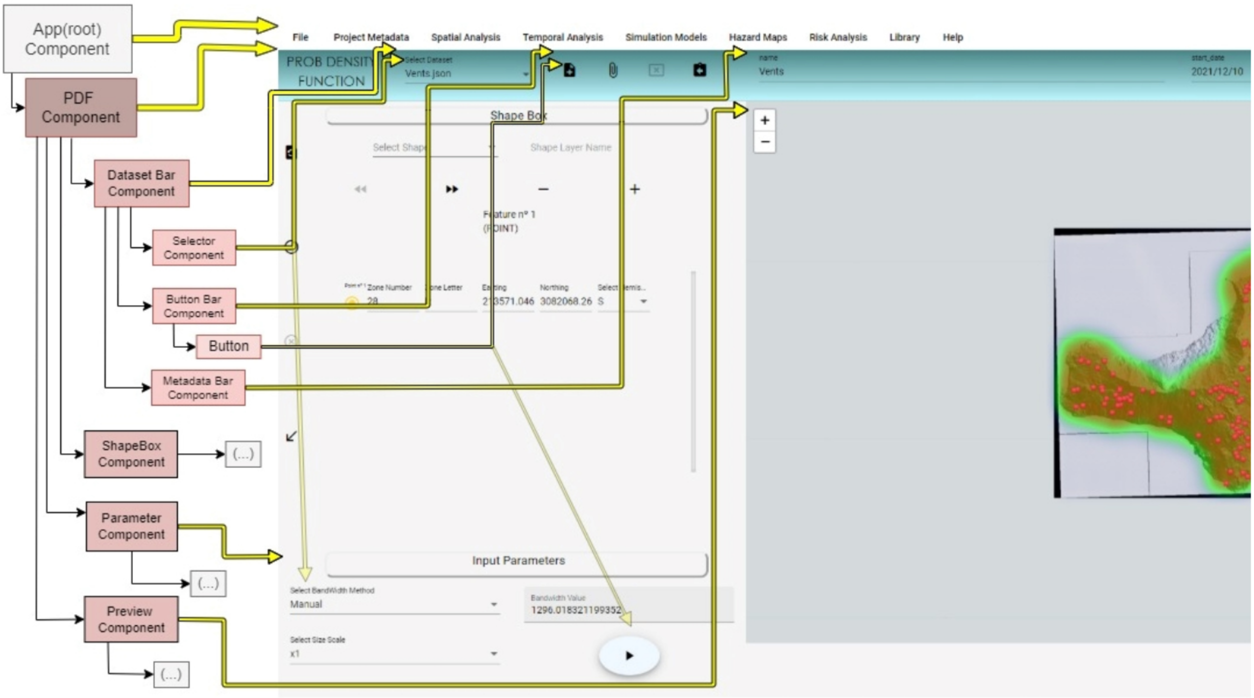


Figure 45.- Modular design of VOLCANBOX

When each of the tabs included in the tool bar is pressed a drop-dawn menu appears indicating the different options included in each of them. As VOLCANBOX is designed according to the systematic and sequential methodology for conducting hazard assessment and risk analysis described the first part of this handbook, it is assumed that each project will be developed following the sequence of options listed from left to right in the tools bar, although depending on the project to work with not all may be necessary. Therefore, they are described below in the same order.

2.4.1. File

File offers the following options:

•*new volcanic zone*: This is the first option that the user must identify the first time that a particular volcanic zones is selected. It will define the coordinates and other characteristics of current volcanic zone where the following project (s) will be linked to: The information required here includes:

- ✳*Name*: Names of the volcanic zone
- ✳*Country*: Country
- ✳*Extension*: Geographical coordinates that refer to the total area corresponding to the volcanic zone
- ✳*Geodynamic setting*: Tectonic regime that characterises de volcanic zones (e.g., subduction, oceanic ridge, hot spot, continental rift, etc)
- ✳*Types of volcanism*: It describes whether it contains central or monogenetic volcanoes or both
- ✳*Important volcanoes*: List of the most representative volcanoes in the area

- ✳*Composition*: Main chemical composition of magmas
- ✳*Eruptive dynamics*: Brief description of the main types of eruptions
- ✳*Historical volcanism*: Existence or not of historical eruptions
- ✳*Description*: Field where the user can enter extra information or which does not fit in the other fields

- •*edit volcanic zone*: Option to be used when some data about the current volcanic zone need to be updated
- •*new project*: To give a name to a new project and start working on it
- •*open project*: To open a project in progress and to continue working on it
- •*save project*: To save the current project
- •*save project as*: To save the current project but changing its name
- •*exit*: To leave de application

2.4.2. Project metadata

Opens a menu allows the user to introduce all the information that will be required to identify the current project. The information to be incorporated is divided into three groups: main metadata, DEM metadata, and Hazard metadata. Main metadata refers to general information on the current project and includes:

- *Name*: Name of the project.
- *Date*: Date the project was created.
- *Version*: Project version.
- *Responsible*: User responsible for the project.
- *Purpose*: Description of the project objectives.
- *Volcanic Zone*: name of the volcanic zone
- *Volcano*: Name of the volcano.
- *Type*: Type of volcanic edifice - e.g.: shield volcano, stratovolcano, caldera, dome, slag cone, maar, tuff ring, tuff cone, fissure.
- *Historical eruptions*: Dates of representative historical eruptions.

DEM metadata contains information on the digital elevation model to be used in the project. This information includes main coordinates specifically defining the working area, the coordinates system and the projection system. It also includes a 2D visualiser of the DEM to be used during the project. This allows the user to have control of the working area and to realise if this is sufficient or needs to be enlarged or reduced.

Hazard metadata contains for each hazard to be considered, the conventions referring to the range of values that correspond to a long, medium, or small extension. This needs to be defined by the user for each particular project according to the existing information on past eruptions and their products. This information will be used when conducting spatial and temporal analyses.

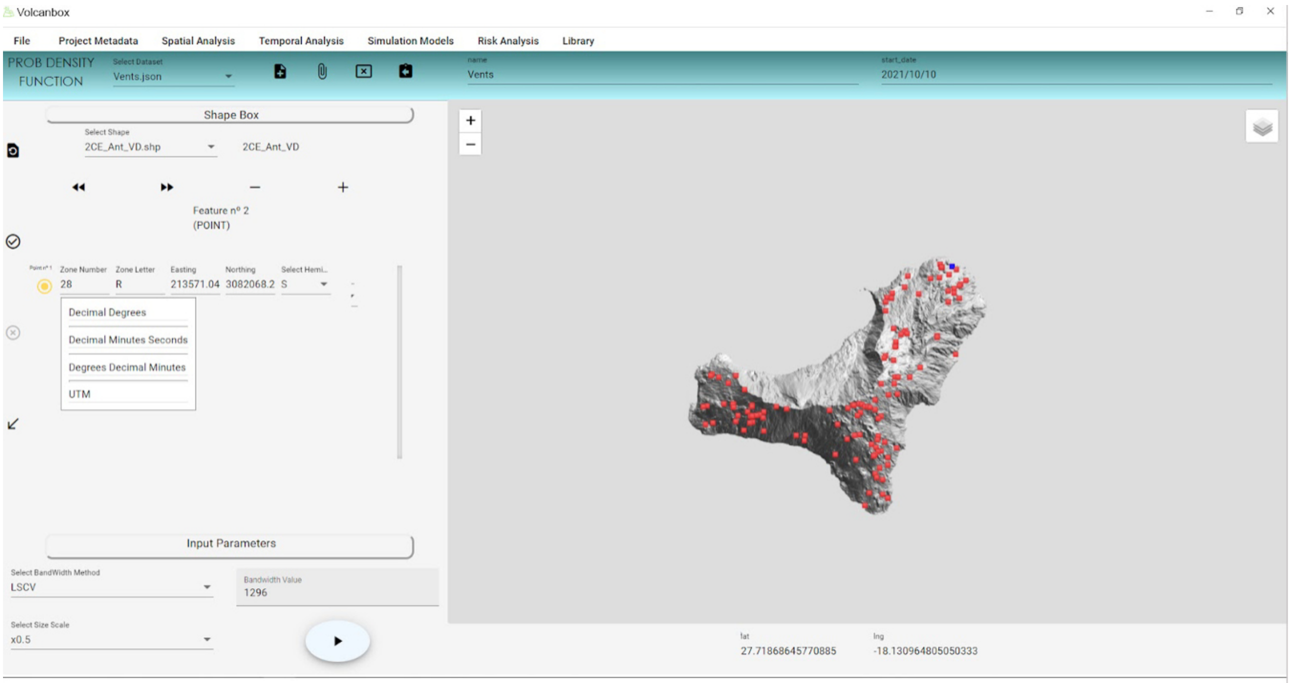


Figure 46.- Example of a shape-file of a data set corresponding to points (vents location at El Hierro Island, Canary Islands)

2.4.3. Spatial analysis

The first step for the quantitative assessment of volcanic hazard is the development of susceptibility maps, i.e. the spatial probability of future vent opening, based on the past eruptive activity of a volcano. This challenging issue is generally engaged using probabilistic methods that estimate probability density functions (PDFs) by calculating a kernel function at each data location. Data used to calculate volcanic susceptibility are field structural data including in situ stress field measurements (usually measured using boreholes), the location of eruptive vents, and structural alignments (fractures, faults, cone alignments and dykes). Indirect data obtained from theoretical 3D stress field models and structural geophysical data (gravimetric, magnetic, seismic, etc.) can also be used. All these structural elements combined provide an indication of the corresponding state of stress of the volcanic system. Each set of structural data are included in shape file, which may be made of points (e.g., location of vents), lines (e.g., cone alignments) or poligons (e.g., fumarolic areas). For each set of data, it is necessary to calculate the corresponding PDF. The smoothness and the modelling ability of the kernel function are controlled by the smoothing parameter, also known as bandwidth. VOLCANBOX incorporates the tool QVAST (Bartolini et al., 2013), originally designed to be included in the open source Geographic Information System Quantum GIS, and now redesigned according to the format and formal constraints imposed by the new platform. QVAST permits to choose the appropriate method to evaluate the bandwidth for the kernel function, depending on the input parameters and the shape-file geometry, and to evaluate the PDF with the Gaussian kernel. The choice of the optimal bandwidth is difficult and will depend on the field size and degree of cluster and will determine the probability distribution at distance from volcanic structures or eruptive vents. QVAST provides a number of different methods for estimating optimal bandwidths: the Least Square Cross Validation (LSCV) (Capello et al., 2013) for volcanic structures with linear geometries (e.g. dykes, eruptive fissures, faults) and three further methods for

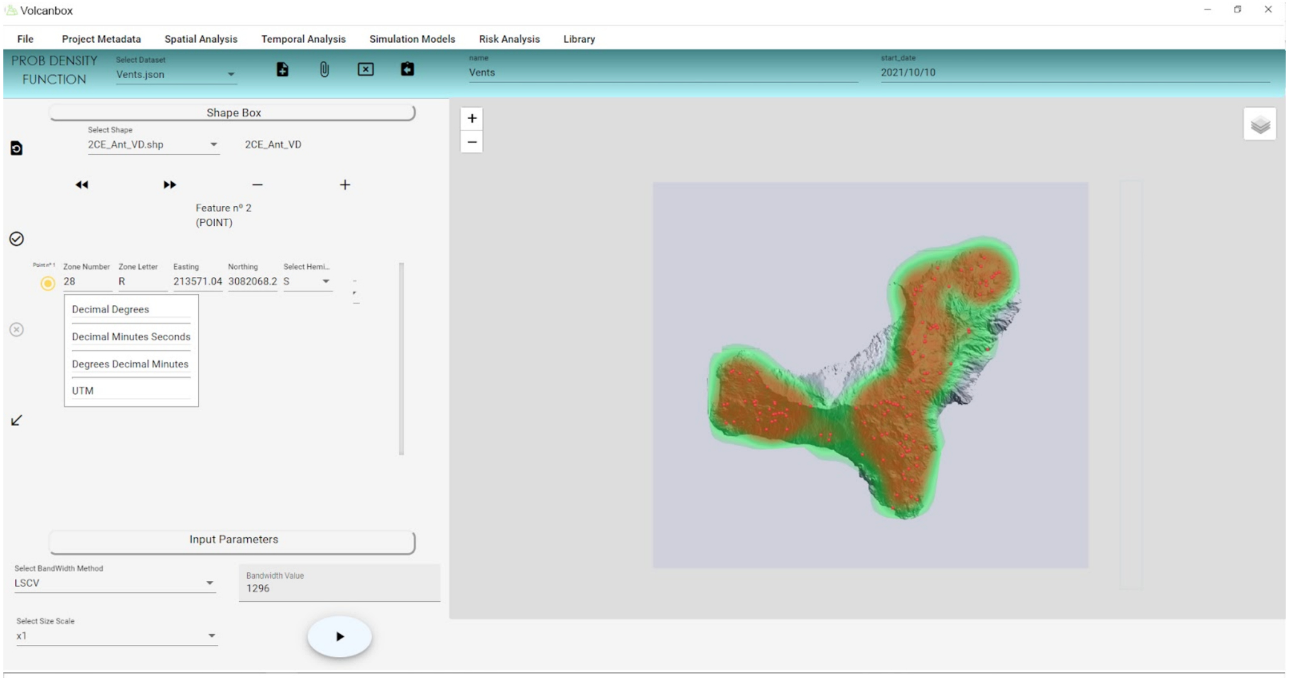


Figure 47.- Example of a PDF map corresponding to the data set of Fig. 46

non-linear eruptive vents, LSCV (Capello et al., 2013), the h_opt score (Silverman, 1986) and the SAMSE selector H (Connor and Hill, 1995) (see Bartolini et al., 2013 for more information). The value assigned to the bandwidth parameter in a kernel function has a substantial effect on results. When choosing small values for the bandwidth, the kernel function gives high probability estimates in the vicinity of existing volcanic structures. Conversely, when high values are assigned, probability estimates are distributed in a more homogeneous way throughout all of the studied area. When different input datasets are available for the area, the total susceptibility map is obtained by assigning different weights to each of the PDFs, which are then combined via a weighted summation and modelled in a non-homogeneous Poisson process.

The Spatial Analysis menu offers two options: probability density function and final susceptibility map (Fig. 44).

2.4.3.1. Probability Density Function

The first opens a window where the user can create or import the different structural data sets that will be needed to calculate the volcanic susceptibility (Fig. 46). For the different shape-files (points, lines or polygons), one for each data set or structural element, it will be necessary to introduce the coordinates system, the position of each element, the bandwidth method to be used, and the working scale, and the system will calculate automatically the value of the bandwidth. Once the shape-file is created, it must be saved into the current project, and the system is ready to calculate PDF for this data set (Fig. 47). After that and saving again the result, the system is ready to create a new shape-file and the corresponding PDF, and thus as many as structural elements (datasets) you want to combine.

2.4.3.2. Final Susceptibility Map

Once all the structural elements have been introduced as shape-file and all the individual PDFs have been obtained, the total volcanic susceptibility map option will allow the user to combine them, weighting them according to their relevance and reliability, as it has been explained in previous sections. This will generate the total susceptibility map that will tell the user where the highest probabilities of hosting a new vent are located, and which will be used latter to calculate eruptive scenarios (Fig. 48).

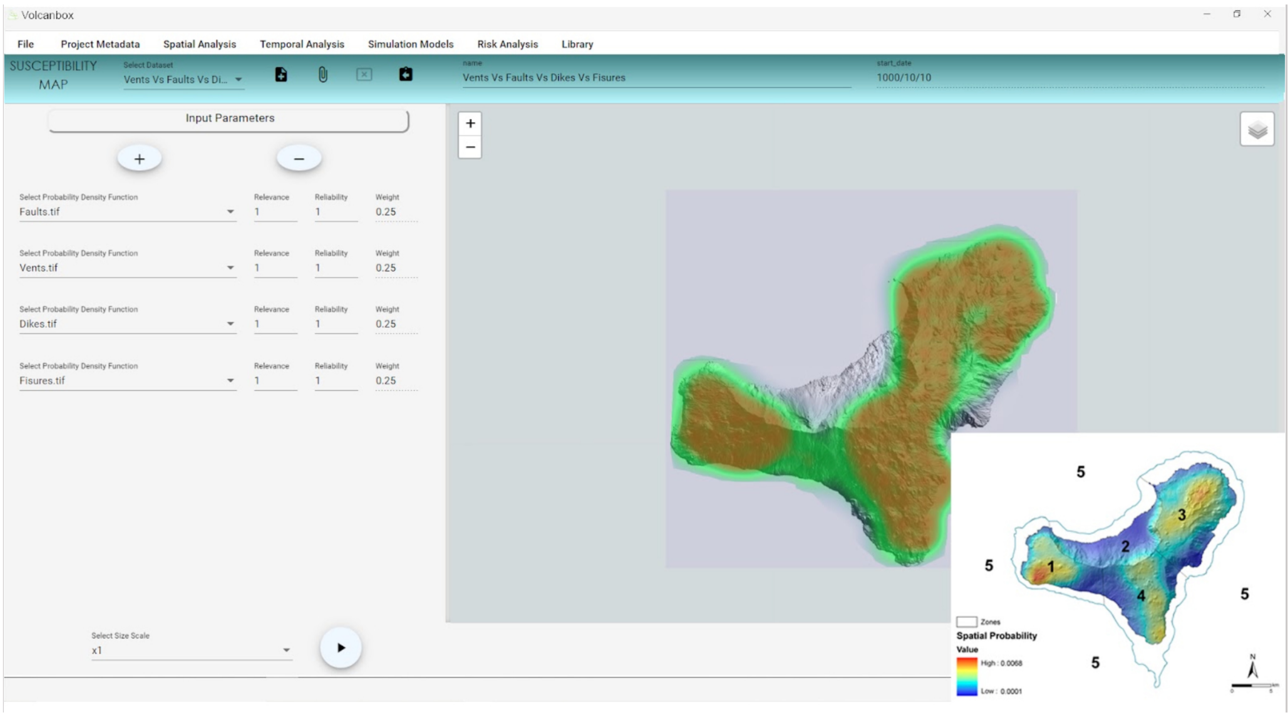


Figure 48.- Example of a total susceptibility map obtained by combining all individual PDFs (in this case vents location, vents lineations, dykes, faults and fissures, at El Hierro Island, Canary Islands). The scale of colours may be adjusted by the user

2.4.3.3. Spatial analysis during unrest (short-term)

The correct identification and interpretation of unrest indicators are useful for forecasting volcanic eruptions, delivering early warnings, and understanding the changes occurring in a volcanic system prior to an eruption. Such indicators mark the position of magma inside the volcanic system, so they may play an important role in upgrading previous long-term volcanic hazard assessments and help grasp the complexities of the preceding period of eruptive activity. In particular, monitoring data will help update the volcanic susceptibility map obtained in the long term only considering past geological information. Introducing this new information as additional structural datasets and combining them adequately with the previous ones we will obtain a new susceptibility map that may be updated each time new monitoring information arrives. In this way, we can study the evolution over time of the unrest and how the probabilities of hosting a new vent change (Fig 49).

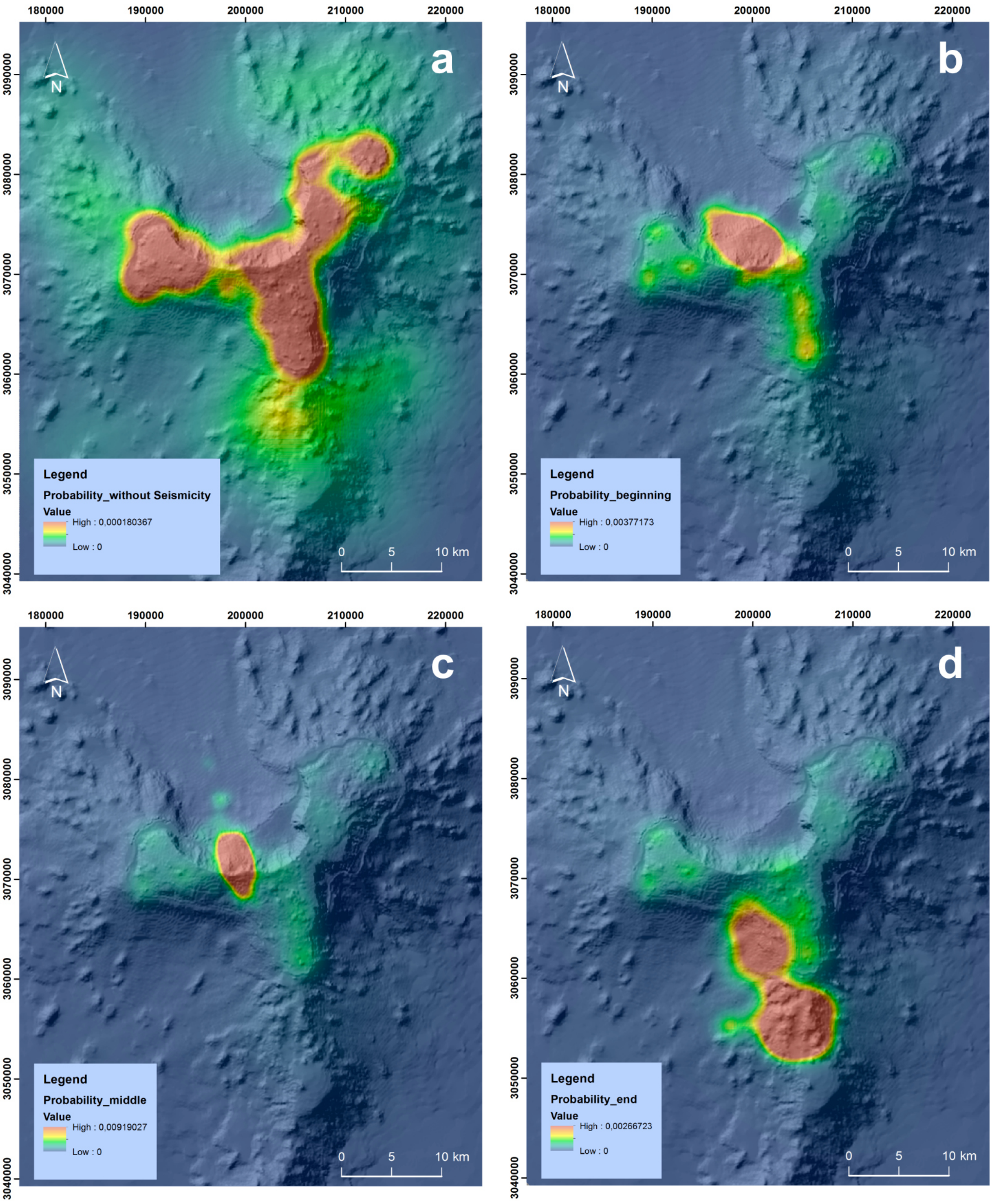


Figure 49.- Example of a retrospective application of the short-term susceptibility maps in the case of El Hierro (Canary Islands) pre-eruptive unrest (April-October 2011). Susceptibility maps obtained from: a) the volcano-structural data (long-term hazard assessment, without monitoring data); and introducing in it the monitoring information (seismicity and ground deformation) at different days during the pre-eruptive unrest: b) the first days of unrest; c) in the middle of the unrest; d) the days before the submarine eruption.

During the development of the EVE project we had de opportunity to apply this technique in real time in the case of the Reykjanes Peninsula eruption, in Iceland, which started on the 19th of March 2021 and lasted active for sis months. This eruption was preceded by nearly two months of unrest in which seismicity and ground deformation was high and changing focus all the time. Since the beginning of unrest, VOLCANBOX tools where used to daily update the volcanic susceptibility map and to produce eruption scenarios according to the new location of the new vent and the lava flow scenario that derived for the first days of the eruption (Fig. 50).

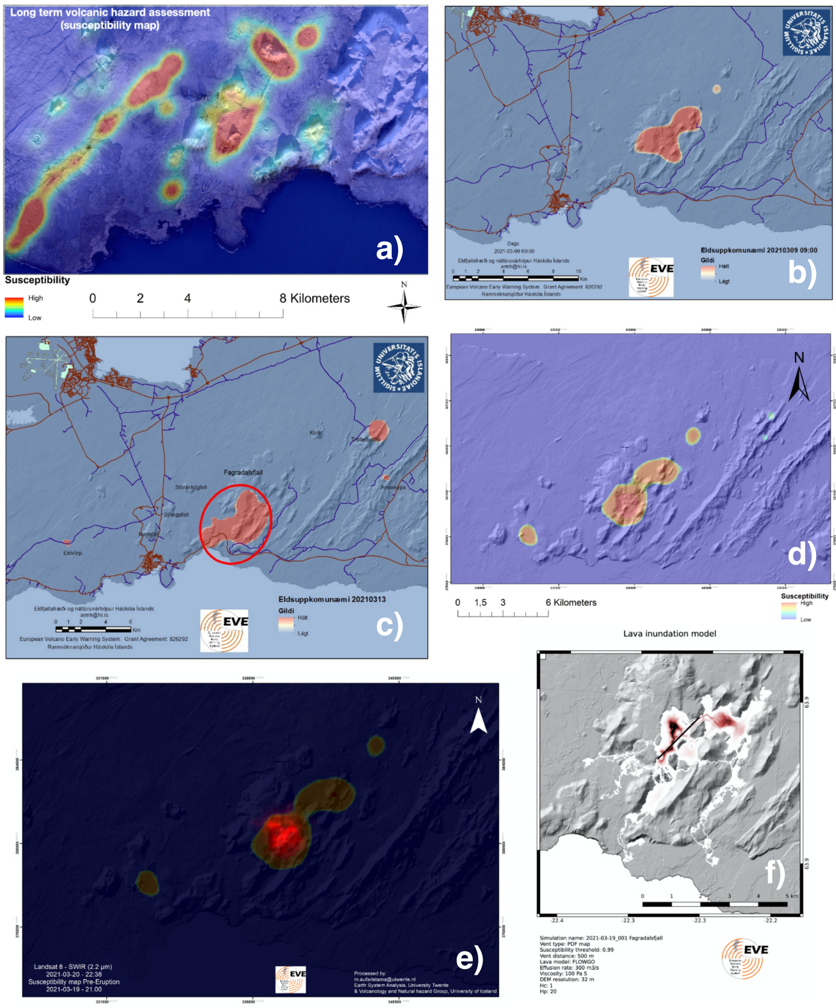


Figure 50.- Real time short-term hazard assessment and eruption forecasting during the pre-eruption unrest at Reykjanes Peninsula (Iceland) February-March 2021. a) Long-term volcanic susceptibility map. b) Short-term (long-term plus real time monitoring data) susceptibility map of March 9. c) Short-term susceptibility map of March 13. d) Short-term susceptibility map of March 19 (12 hours before the eruption onset). e) Superposition of the previous image with the satellite image showing the eruption vent (red area) on March 19. f) Short-term lava flow hazard assessment made on March 19 (12 hours before the eruption onset).

2.4.4. Temporal analysis

As it has been indicated before, temporal analysis refers to the eruption frequency or eruption recurrence of a volcanic system and is calculated using stratigraphic, geochonological and historical data. Taking into account that volcanic hazard is the probability of any particular area being affected by a destructive volcanic event within a given period of time (Blong 2000), to quantify volcanic hazard, we will need to estimate probabilities of occurrence of a particular eruptive scenario in time and space. The spatial analysis we have described in the previous section provides the clues to anticipate the location of potential new vents and, thus, to reproduce eruptive scenarios that will inform us about the potential extent of the expected hazard. The temporal analysis will identify the most probably eruptive scenarios for a particular time window.

Future probabilities of occurrence of an eruptive scenario can be analysed for both the short term and long term. Short and long-term forecasts of eruption are defined based on the expected time interval over which the volcanic system enters unrest and/or shows significant variations. For the purpose of our analysis, long-term volcanic hazard refers to the time window before the volcanic system goes into unrest, and short-term volcanic hazard refers to the unrest phase. Consequently, long-term forecasting is mainly based on geological, historical and geochronological data, and theoretical models, while short-term forecasting is complemented with information from continuous monitoring.

VOLCANBOX incorporates the tool HASSET (Hazard Assessment Event Tree), developed by Sobradelo et al. (2014), to conduct long and short term temporal analysis. HASSET is a probability tool built on an event tree structure that uses Bayesian inference to estimate the probability of occurrence of a future volcanic scenario. It also evaluates the most relevant sources of uncertainty in the corresponding volcanic system. The objective of this e-tool is to outline all relevant possible outcomes of volcanic unrest at progressively greater detail and to assess the hazard of each scenario by estimating its probability of occurrence within a future time interval. 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 towards increasingly specific subsequent events and a final outcome. In particular, and based on comparisons with previous event trees for volcanic eruptions, HASSET accounts for the possibility of (i) flank eruptions (as opposed to only central eruptions), (ii) geothermal or tectonic unrest (as opposed to only magmatic unrest), and (iii) felsic or mafic lava composition, as well as (iv) certain volcanic hazards as possible outcomes of an eruption, and (v) the distance reached by each hazard. The temporal analysis menu has two options: HASSET long-term and HASSET short-term.

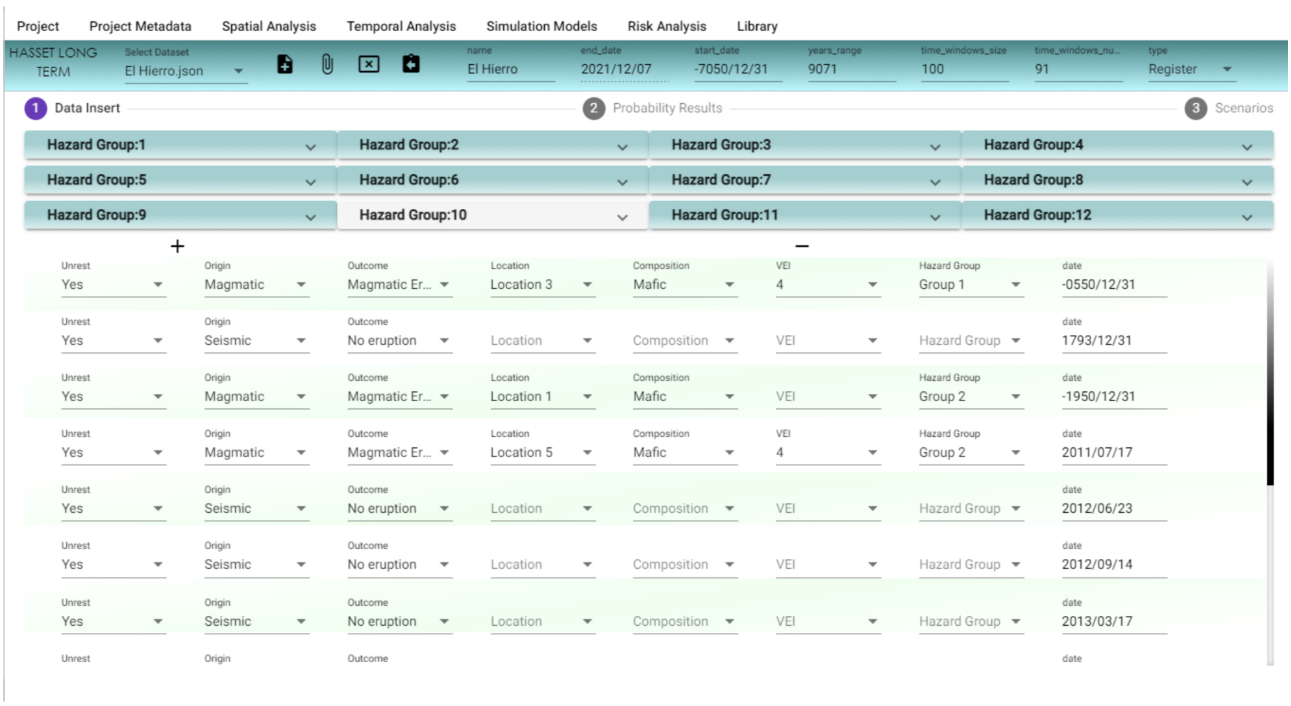


Figure. 51.- Screen view showing the data to be included in the system in the version of registers. Each row corresponds to an event.

2.4.4.1. HASSET Long-Term

The HASSET long-term interface offers two options to enter the data into the system manually. One is by entering the data, register by register, of the different events recorded (Fig. 51). The second option is by entering the totals obtained the full set of records (Fig. 52). This information consists of the data concerning each node of the event tree, which are obtained from the geological and/or historical records, plus the uncertainty estimates (aleatoric and epistemic) for each data in particular. First we will go to the data insert window and select which option to use, records or totals. In any case it is necessary first to introduce the information concerning the time range we consider for our analysis, and the probability estimate time window, and if these numbers are correct, we will be allowed to enter the rest of information (Fig. 51). The time range refers to the time length of the period we are considering in our analysis, which will always go from a starting date that the user chooses to the date in which the project is being prepared. The time window refers to the time period for our forecast and will represent the time window range to evaluate the probability to have at least one eruption. Once this information is introduced into the systems, it will automatically calculate the total number of time windows, being this a way to calculate if these numbers are correct, as the system will not progress in case of error. For example, if our time range is a historical period of eight hundred years and we want to estimate the probability of at least one eruption in the next ten years, we have eighty time intervals of data for the study of ten years each. For each branch we count the number of intervals where at least one event of that type has occurred. So, the number of time intervals is the result of the ratio between the dataset time interval and the probability time interval. This is evaluated automatically and checks if this value corresponds to the sum of the introduced episodes of unrest and no unrest.

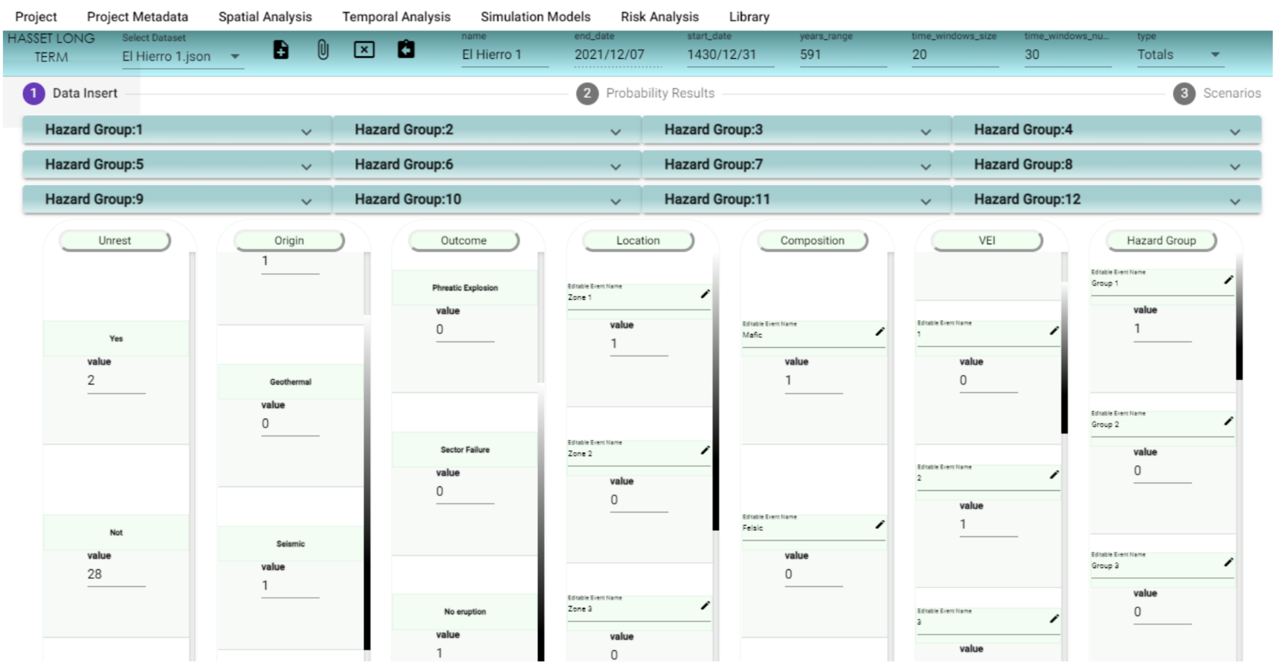


Figure 52.- Screen view showing the data to be included in the system in the version of of totals.

Each possible volcanic scenario is a combination of one branch per node evolving from a more general node of unrest (yes or no) to the more specific node of the extent of the hazard (Sobradelo and Martí, 2010). They should represent all possible eruptive scenarios that have occurred from that particular volcano or volcanic area. This implies to have conducted a very detailed study of past eruptive behaviour of the volcano or volcanic zone. The lack of accuracy in such task may result in the existence of scenarios that have not been identified but have occurred in the past and may occur again in the future. Below is a detailed explanation of each node and corresponding branches. It is possible to stop at a particular node if we want to evaluate the hazard at a more general level. Each possible volcanic scenario is made up from the following nodes:

- *Node 1*, **Unrest**: Yes or No. Given that we have the capacity to differentiate the origin of the precursory signals, we define unrest in a particular time window as any modification of the background activity of the volcano or volcanic area recorded by the monitoring network, and which may or may not be followed by an eruption of any kind.

- *Node 2*, **Origin**: We define four possible sources of unrest, which comprises events (above background) recorded by the network, that are likely to happen: magmatic, geothermal, seismic, and other. Assuming we can define the precursors that identify the source of the unrest, it is crucial in a complex volcanic system to differentiate between unrest caused by internal triggers or caused by external triggers, which ultimately may condition the outcome and further development of the system. Every eruption type, including a phreatic episode, requires the presence of fresh magma at shallow depths in the volcanoes. However, we do not discard the possibility of starting an eruption process from an unrest directly associated with the hydrothermal system or even due to external triggers, such as regional tectonics, if eruptible magma is already present in the system. It is also important to mention that the interior of a volcanic system may react to changes in the regional stress field or regional tectonics, so a seismic trigger for unrest cannot be ruled out.

- *Node 3*, **Outcome**: We consider here the outcome of the unrest being of four different types: magmatic eruption, sector failure, phreatic explosion (triggered by unrest of any type, where no magma is expelled in the eruption), no eruption (there is unrest but no further outcome develops). It is important to address the hazard associated with non-eruptive scenarios in the event of unrest. That is, the hazard could arise in response to internal or external triggers that do not evolve into a magmatic eruption but rather originate a sector failure or a phreatic episode. These volcanic scenarios should not be left out when assessing volcanic hazard, especially for a volcano with a hydrothermal system or a shallow aquifer. Magmatic eruptions can be preceded directly by magmatic unrest, which may or may not itself be preceded by sector failure. A magmatic eruption can also be triggered indirectly by geothermal or seismic unrest, in which case, externally driven decompression of the shallow volcanic system would be required. This could be achieved by sector failure or tectonic fracture opening. When the unrest is geothermal or seismic, for a magmatic eruption to occur, an initial sector collapse or fracture opening is needed to decompress the whole system. In discussing a magmatic eruption which was originated by geothermal or seismic unrest, we assume that a sector failure or a tectonically induced fracture opening has previously occurred. Sector failure alone, triggered by magmatic, geothermal, or seismic unrest, corresponds with the sector collapse itself, not being followed by an eruption. A sector failure followed by a magmatic eruption is considered in the previous branch (magmatic eruption), caused indirectly by a magmatic unrest triggering a sector collapse.

- *Node 4*, **Location**: The user is allowed to segment possible locations for an imminent eruption from the volcano or volcanic area into five different areas, which can be customised and named accordingly. By default, we have named them as central, north, south, east, and west, and the coverage area for each location would vary for each volcanic system according to general topography, location previous vents, structural constraints, and/or important topographic barriers which may impose a different level of hazard and risk depending on what side of the volcano the eruption occurs. Eruption scenarios and particularly the area occupied by each hazard will depend on the location of the eruptive vent, so constraining this last is so important.

- *Node 5*, **Composition**: The magma composition will determine two main types of eruptions associated with different hazard implications, as more evolved magmas (felsic) are generally richer in gas and, consequently, associated with more violent eruptions than less evolved magmas (mafic). For simplicity in the model we consider only two branches (felsic and mafic) and assume they are exclusive, an thus a branch for mixed composition is left out.We are aware some compositions can be a mix of both mafic and felsic magmas, but for the purpose of the hazard estimation, we will assume that a magma with felsic composition will fall in the category of felsic, regardless of the proportion.

- *Node 6*, **VEI**: This node represents the size of the eruption, expressed in terms of the volcanic explosive index (VEI), which varies from 0 to 8 in logarithmic scale (Newhall and Self, 1982)

- *Node 7*, **Hazard group**: This node represents a modification with respect to the original event tree of Sobradelo and Martí (2010). As Bayesian inference implies that all branches included in the same node must be exhaustive and mutually exclusive, and to avoid confusion about the inclusion of different hazard in the same node, we have decided to categorise each eruption or event by a particular group of hazards association. All the possible hazard groups, related to the different eruptions identified in a specific volcano o volcanic zones, are listed as part of the metadata at the beginning of the project, indicating for each the individual hazards that form the group and their characteristic extent. This is also selected by the user according to the extent of the eruption products that have been identified for each eruption. In case two eruptions produced the same hazards but with different ranges of extent, they will be characterised by a different group of hazards each.

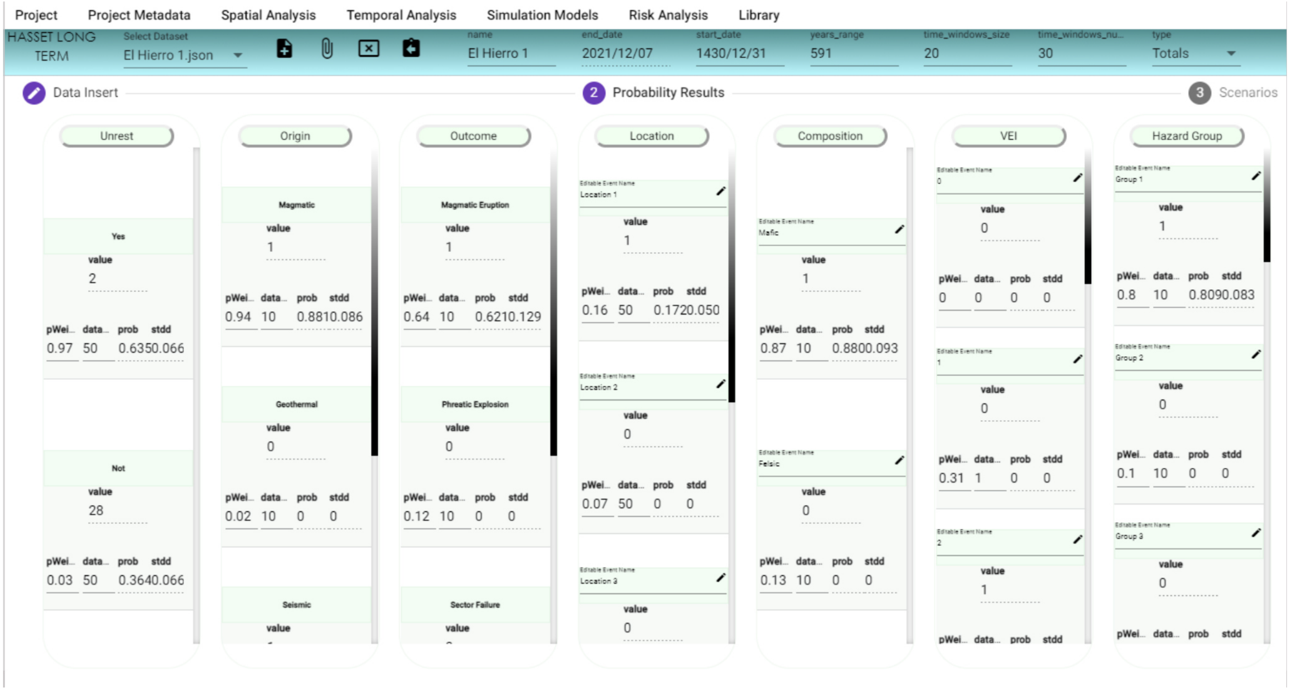


Figure 53.- Screen view showing the probability results option

Once this information has been introduced, be can move to the probability results screen where we will have to introduce the prior and data weights (e.g., uncertainty), and then the system will calculate the corresponding probabilities and standard deviations (Fig. 53).

Aleatoric (stochastic) and epistemic (data or knowledge limited) uncertainties are significant, and we need to find a way to correctly evaluate them. The aleatoric (stochastic) uncertainty is a consequence of the intrinsic complexity of a system, hence a limitation to our ability to predict the evolution of the system in a deterministic way. The aleatoric uncertainty introduces a component of randomness in the outcomes, regardless of our physical knowledge of the system. The epistemic uncertainty is directly related to our knowledge of the system and the quality of the data we have or the degree of confidence we have on our data. These uncertainties are expressed in HASSET as prior and data weight values, respectively. Prior weights are assigned between all the branches of the same node with the conditions that the total must be 1. In the case of data weights values may go from 1 (total ignorance) to 50 (or more) (total confidence) (Fig. 51). In case of non-informative priors it is recommended to assign weights equally distributed in the case of prior and a minimum value of 1 in the case of data.

Once the probabilities have been calculated we can move to the scenarios screen, which will be divided into three parts (Fig. 54). The upper part shows the results for each node in a graphic mode (pie charts). The lower part shows at the right the most probable scenarios up to maximum of five. The right part shows the probabilities of the customised scenarios that the user may create.

Here, it is also important to make a comment on the difference in using historical data and geological data. In very active volcanoes, considering the historical period from which written chronicles of eruptions and unrest events exists should be sufficient to undertake a temporal long-term a analysis. Also, a geological recognition of the products of the different eruptions occurred during the period considered will be necessary in order to identify eruption sequences and extend of the deposits, but they will have a good time control. However, if we deal with a volcano with very long recurrence periods, with no historical eruptions, we must rely only on the geological record. This implies less confidence on the data and probably less completeness of the volcanic stratigraphy, as part of the record may have been eroded out or buried by younger eruptions. In such cases, the probabilities we can obtain should be regarded as minimum values.

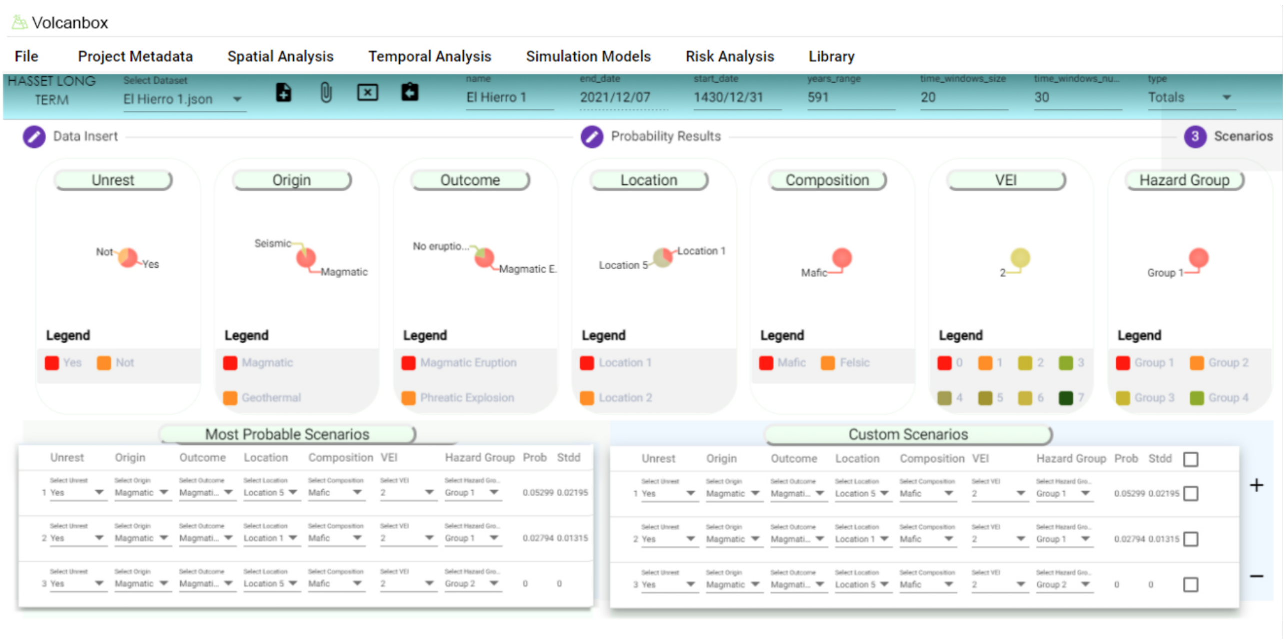


Figure 54.- Screen view showing the scenarios option

Another option that the system offers is to upload the datasets from a template file in excel format (see Fig. 33) that we should have prepared previously containing all the information required.

2.4.4.2. HASSET Short-Term

Short-term hazard assessment is an important part of the volcanic management cycle, above all at the onset of an episode of volcanic agitation (unrest). For this reason, one of the main tasks of modern volcanology is to use monitoring data to identify and analyse precursory signals and so determine where and when an eruption might occur. The tool HASSET short-term is implemented from that originally designed by Sobradelo and Martí (2015) and latter modified by Bartolini et al (2016) and shows the time evolution of unrest indicators in the volcanic short-term hazard assessment. This tool is designed for complementing long-term hazard assessment with continuous monitoring data when the volcano goes into unrest. It is also based on Bayesian Inference and transforms different pre-eruptive monitoring parameters into a common probabilistic scale for comparison among unrest episodes from the same volcano or from similar ones. This allows identifying common pre-eruptive behaviours and patterns. ST-HASSET is especially designed to assist experts and decision makers as a crisis unfolds, and allows detecting sudden changes in the activity of a volcano. Therefore, it makes an important contribution to the analysis and interpretation of relevant data for understanding the evolution of volcanic unrest.

Data are introduced into the system manually using the template shown in the corresponding screen displayed by the system when pressing the HASSET short-term button or uploading an excel file prepared externally with the same structure (Fig. 55). The first two columns of the dataset describe the different unrest indicators that are normally extracted from monitoring data. The next column (background) is for the background value of each parameter when the volcano is at rest. The following one (range) indicates the threshold value that the user or monitoring expert assumes as confident to consider that above it the system is increasing in activity. The next two columns refer to the absolute value and whether it means there is a change (Yes) (the value exceeds the threshold) or not (the value is lower than the threshold), compared with the previous value provided. For the first columns the value to compare with will be the background value. After that, two new columns are added each time new information arrives (new monitoring report or bulletin), for which we will also annotate an id and the date. This will continue until the volcanic system erupts or return to the background level of activity.

After the first set of data in addition to the threshold data is introduced, VOLCANBOX calculate the probability of expecting a change in that parameter for the next report or bulletin, so it makes a forecast of the behaviour or the system (Fig. 56). This implies that more data we will have, more precise will be this forecast. Anyway, it will define a pattern of behaviour that will be then compared with other unrest from the same volcano o from other similar volcanoes (Fig. 57).

Group	Name	Background	Variation Range	Id	Date	Id	Date	Id	Date	Id	Date	Id	Date	Id	Date	
				0		1		2		3		4		5		
				Value	Changes	Value	Changes	Value	Changes	Value	Changes	Value	Changes	Value	Changes	Va
Seismicity	Seismicity increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	RSAM acceleration	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Accumulated energy released rate increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Lateral migration of seismicity	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Vertical migration of seismicity	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Deep seismicity	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Shallow seismicity	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	VT events	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	LP events	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Tremor events	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Hybrid events	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Seismicity	Overall seismicity	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Gas	Gas flux increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Gas	H2O increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Gas	CO2 increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Gas	SO2 increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Gas	Fluids temperature increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Gas	Overall gas increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Deformation	Strain increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Deformation	Inflation rate increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Deformation	Lateral migration	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Deformation	Vertical migration	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Deformation	Dg/Dh anomaly	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Deformation	Overall ground deformation increase	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Others	Fractures	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Others	Phreatic explosions	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	
Others	Fresh magma	0.00	0.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	

Figure 55.- Template used by the HASSET short-term tools to introduce data into VOLCANBOX

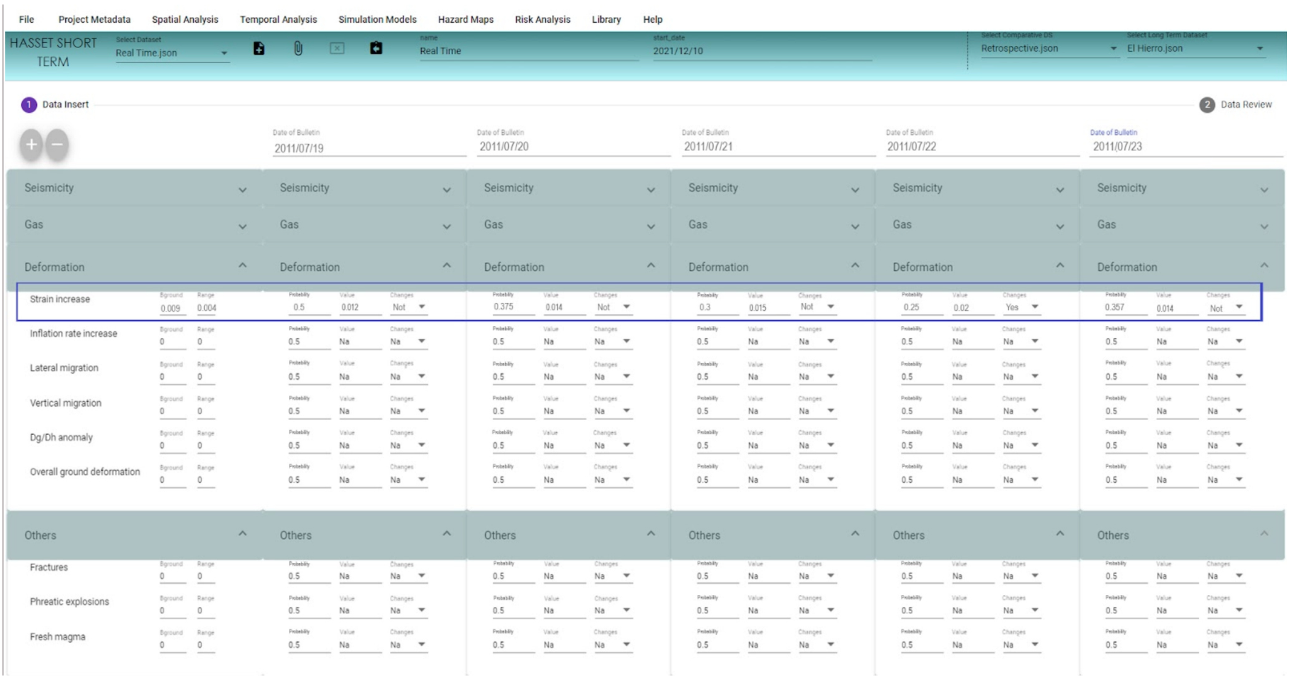


Figure 56.- Screen view of the HASSET short-term tool showing monitoring data and probabilities of change for the next bulletin.

Figure 57.- Screen view of the HASSET short-term tool showing the different visualisation options for the real time evolution of monitoring parameters and probabilities of change.

Figure 57.- Screen view of the HASSET short-term tool showing the different visualisation options for the retrospective comparison of the current evolution of monitoring parameters and probabilities of change with previous events from the same volcano or from other volcanoes.

The system also allow to compare the evolution of monitoring data with a previous long-term hazard assessment. When the short-term results are obtained, users can combine them with the long-term results by simply importing these last generated with the HASSET long-term tool or by entering the scenarios manually. The way in which these data are combined is the expected value of a particular scenario as a function of the expected value and variances of the variables that measure the uncertainty associated with monitoring data, weighted by the uncertainty associated with past events. Finally, the results obtained can be combined with past data (Fig. 57, Long-term combined tab). In fact, the previous analysis estimates the probability of the occurrence of a particular scenario in the short term based only on monitoring data. In addition to the monitoring data, it is also important to study the past behaviour of the volcano since this may be crucial in defining the potential outcome of the unrest period. By incorporating past behaviour into the monitoring data, we are computing the probability of the occurrence of a particular scenario in the short term, but this time based on monitoring and past data. So that the evolution of the short-term probability of a particular eruptive scenario may shift slightly now that we incorporate additional information on the past behaviour of the volcano.

2.4.5. Eruptive scenarios

Simulating eruptive scenarios caused directly (e.g. lava flows, fallout, surges) and indirectly (earthquakes, landslides) by an eruption requires a detailed analysis of the past activity of the volcano or volcanic area, and must take into account all the possible hazards associated with the eruptive activity. Hazard simulation models used by VOLCANBOX are probabilistic, based on the probability that a certain area will be affected by an eruptive process. They are simpler than deterministic models that consider a higher number of parameters and, consequently, require much more computing resources. To generate hazard maps, partial (single hazard) or total (all hazards), it is important to understand past eruptive behaviour and to employ physical simulation models that will permit the behaviour of future volcanic activity to be foreseen. In this type of approach, accurate and detailed geographic and cartographic data are required for high-quality analysis with a GIS.

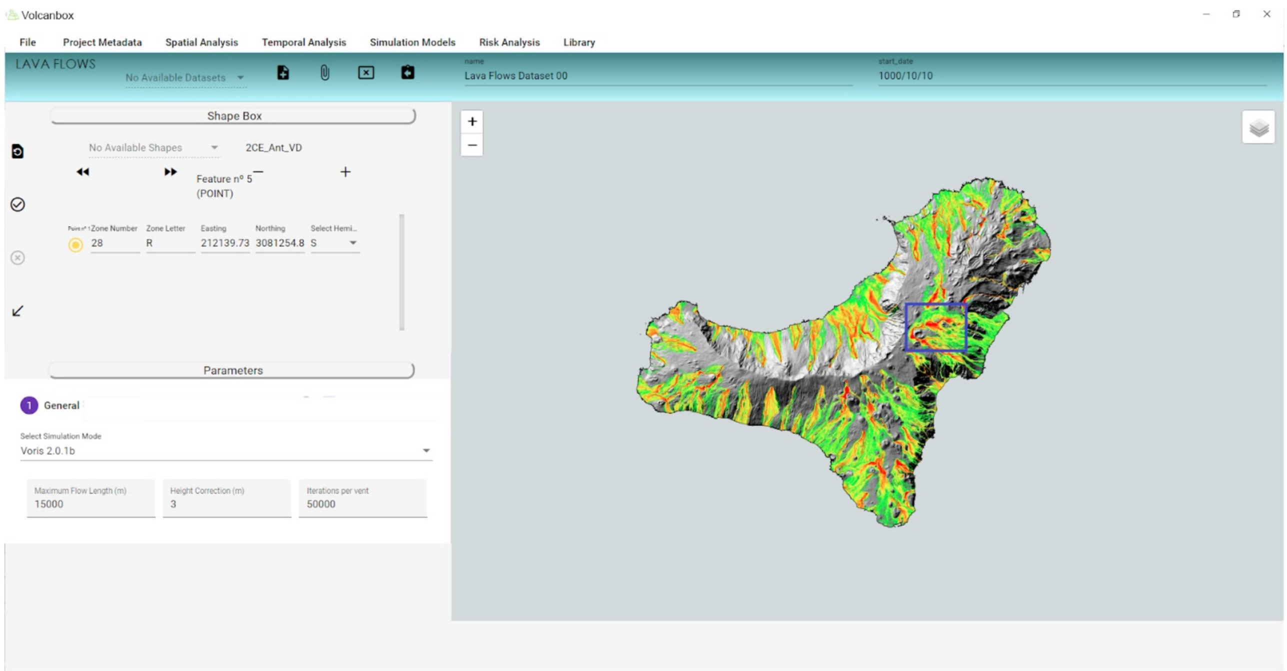


Figure 58.- Screen view of an example of lava flow simulation for the whole island of El Hierro, using the total susceptibility map shown in Fig. 48

Here, we briefly summarise some of the e-tools that are incorporated into VOLCANBOX. The most common hazards in volcanic eruptions are lava flows, fallout, pyroclastic density currents (PDCs), and lahars. Lava flow simulation (Q-Lava, Mossoux et al, 2016) is based on a probabilistic model that assumes that topography is the most important factor determining the path of a lava flow. The determination of the probability of each point being invaded by lava is performed by computing several random paths with a Monte Carlo algorithm. The principal input parameters include the DEM, the maximum flow length (the total runout distance of the lava flow), the height correction (a parameter than controls lava thickness), and the number of iterations (Fig. 58). Fallout simulation uses HAZMAP_2 of Macedonio et al (2005). Fallout simulation models are advection diffusion models that assume that away from the vent the transport of the particles from an eruption column is controlled by the advective effect of the wind, by diffusion due to atmospheric turbulence, and by the settling velocity of the particles (Fig 59). It simulates the sedimentation of volcanic particles at discrete point sources that predicts the corresponding ground deposits (deposit mode) HAZMAP is also able to evaluate the probability of overcoming a given loading threshold in ground deposits by using a set of different wind profiles recorded on different days (probability mode). The model for simulating PDCs is the energy cone model proposed by Sheridan and Malin

(1983). The input parameters are the topography, the collapse equivalent height (H), and the collapse equivalent angle (h) (Fig. 60). The intersection of the energy cone, originating at the eruptive source, with the ground surface defines the distal limits of the flow. To simulate lahars VOLCANBOS uses the free software package LAHARZ developed by Schilling (1998). It is a semi-empirical code for creating hazard-zonation maps that depict estimates of the location and extent of areas inundated by lahars. The input parameters for this model are the Digital Elevation Model and the lahar volume, which provide an automated method for mapping areas of potential lahar inundation.

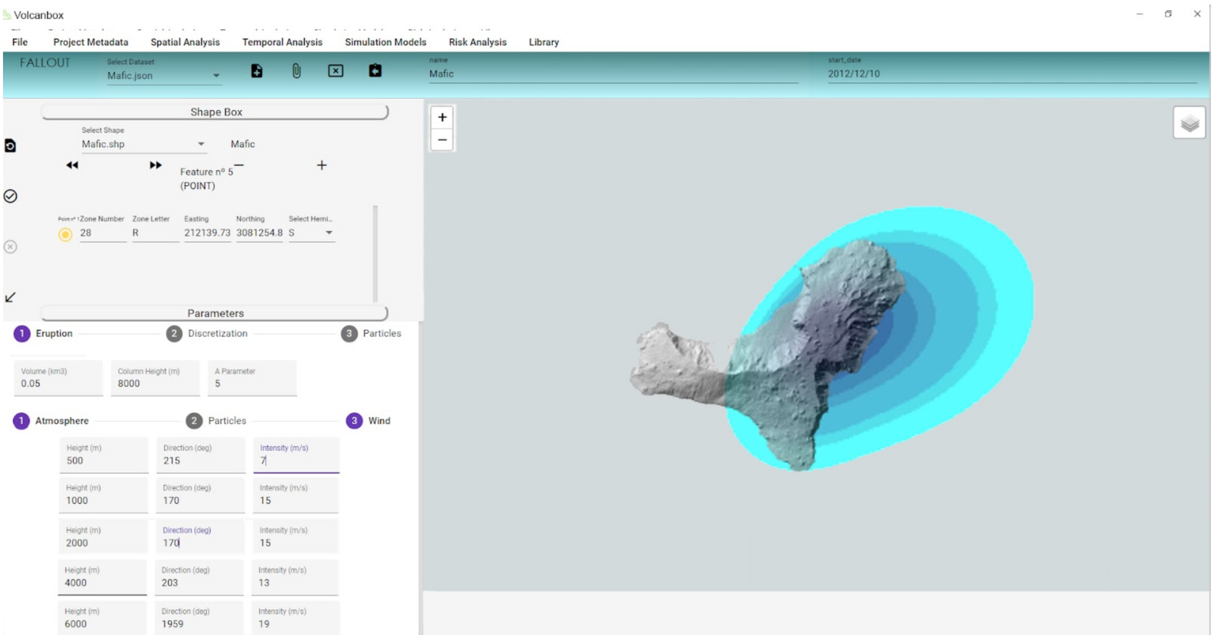


Figure 59.- Screen view of an example of airfall (fallout) single scenario simulation on the island of El Hierro, selecting a single point (vent) from the total susceptibility map shown in Fig. 48

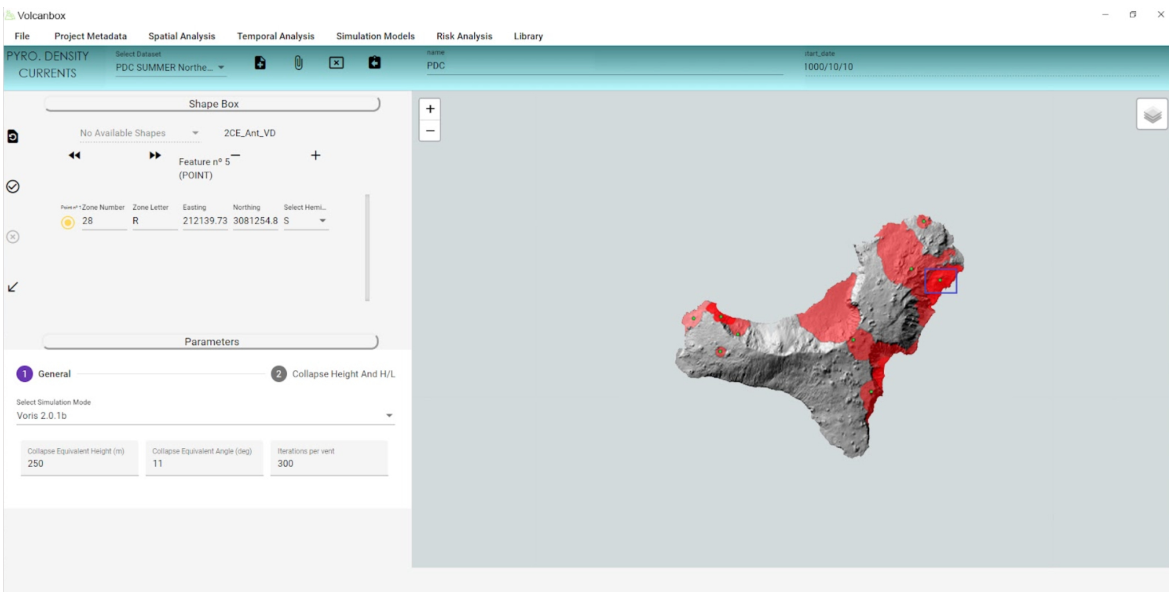


Figure 60.- Screen view of an example of PDCs total scenario simulation for the island of El Hierro, using the total susceptibility map shown in Fig. 48

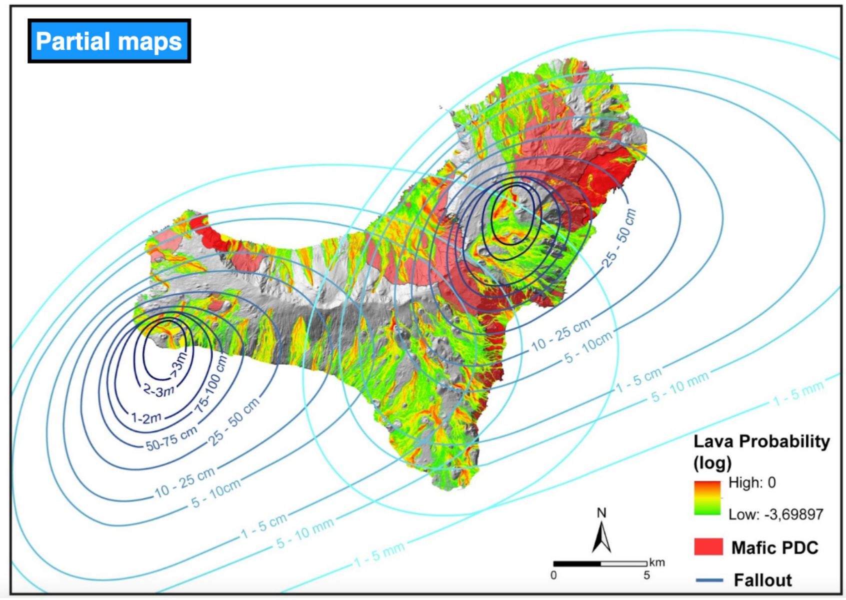


Figure 61.- Superposition of the hazard maps for each single hazard (lava flows, air fall, PDCs) for the island of El Hierro, using the total susceptibility map shown in Fig. 48

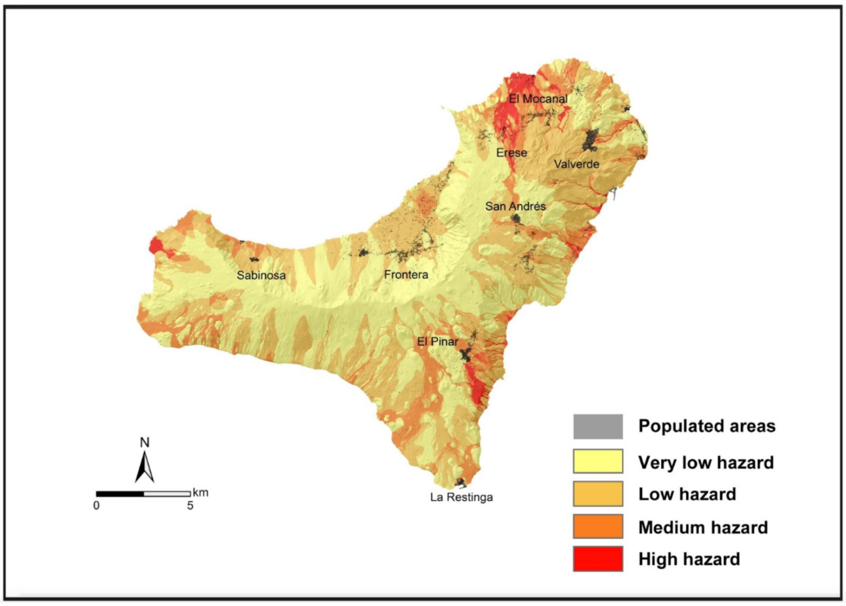


Figure 62.- Total quantitative hazard maps for the island of El Hierro obtained integrating the most probable scenarios of ash fallout, lahars, lava flows, and PDCs, using the total susceptibility map shown in Fig. 48. The degree of hazard is assigned depending on the number of hazards that may impact on each point and on the severity of such impacts.

The system allows the user to make single eruptive scenarios for each hazard (Figs 58-60), single hazard maps for particular a particular hazard considering the whole study area (Fig. 61), and total hazard maps obtained integrating obtained integrating the most probable scenarios affecting the study area (Fig. 62).

Once the corresponding simulation model of the expected hazard is selected, numerical simulations should be computed. Usually, this involves running a high number of simulations, either because of the size of the area susceptible of hosting a new vent or because of the characteristics of some of the input parameters required by the model (for example, if a hazard map for ash fallout is being elaborated, simulation for different wind fields should be computed). Numerical simulation models should be simple enough, so they should not have complex computational requirements, but also sufficiently accurate to represent the influence of their first order controlling parameters on the outputs. The equilibrium between these two requirements has been considered when designing and constructing VOLCANBOX, so the simulation models it offers are at the same time simple but accurate, considering the fact that most of the volcanic hazards are governed by complex systems of non-lineal equations, which should be simplified into the numerical simulation models required for volcanic hazard assessment. Each eruptive scenario, including a single hazard or several of them, may be reproduced from single vents (single eruptions) or may be considered for the whole area of study or for part of it, using the susceptibility map we have obtained in the spatial analysis (Fig. 61).

If we reproduce an eruptive scenario with a single hazard for all pixels in the map for which the volcanic susceptibility is not 0, and applying a number of iteration progressively higher as higher is the susceptibility value (the system does it automatically), we will obtain a single hazard maps for that hazard and for the area considered (Fig. 61). This needs to be done for each of the most probable hazards that may occur at that volcano or volcanic zone, and combining and pondering all them we will obtain the total hazard map (Fig. 62). These may be qualitative or quantitative depending on the purpose and the final user. The quantitative maps will indicate for each single point of the study area the exact probability of being affected by any hazard. This may result in a complex map difficult to read and understand. This is why in most occasions it is preferred to offer qualitative maps where different zones with a relative degree of hazard (e.g., very low, low, medium, high, very high) are included. The way to construct these qualitative maps may very and will depend on what the use wants to indicate. A single option is just to indicate number of hazard that may impact each particular point in the map, or to add to this the potential destruction each impacting hazard may cause. Anyway, these are options that the user will have to consider at the end of the process.

2.4.6. Risk Analysis

VOLCANBOX is essentially a system to conduct volcanic hazard assessment. Despite this , it also offers some others tools that are necessary when conducting risk analysis. Risk analysis requires to combine hazard assessment with quantitative analysis of potential losses. This implies incorporate vulnerability data and an estimate of the cost of potential losses. In essence, it it an economic concept for which the contribution of geoscientist is limited. Anyway, VOLCANBOX also offers some additional tools that may help in risk analysis but particularly in managing a volcanic crisis. These tools are a semiquantitative vulnerability analysis, a cost/benefit analysis, and the volcanic risk coefficient. All these tools appear when pressing the Risk Analysis tab in the tools bar.

2.4.6.1. Vulnerability analysis

Once we have obtained hazard maps, the next step consists of adding population, infrastructures, and land-use data to evaluate the vulnerability associated with the impact of a determined hazard. 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 in question and on the socio-economic characteristics of the environment. VOLCANDAM, developed by Scaini et al. (2014), is the e-tool that VOLCANBOX incorporates to achieve such purpose. It allows to generate maps estimating the expected damage caused by volcanic eruptions. VOLCANDAM consists of three main parts: exposure analysis, vulnerability assessment, and the estimation of expected damages. The exposure analysis identifies the elements exposed 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 vulnerability analysis defines a physical vulnerability indicator for all exposed elements, as well as a corresponding qualitative vulnerability index. Systemic vulnerability considers the possible relevance of each element in the system and their interdependencies by taking into account all exposed and non-exposed elements (people, buildings, transportation network, urban services, and productive activities). Damage assessment is performed by associating a qualitative damage rating to each combination of hazard and vulnerability, bearing in mind their specific contexts and roles in the system. The way one element can be damaged—and thus lose its functionality— depends in fact on the type of hazardous event and the characteristics of the element. The result is damage maps that can be displayed at different levels of detail, depending on user preferences. This tool aims to facilitate territorial planning and risk management in active volcanic areas.

Figure 63.- Steps in the vulnerability analysis in the VOLCANDAM approach (after Scaini et al. 2014). See text for details

2.4.6.2. Cost/benefit analysis

The evaluation of the "direct costs" and "factors" (indirect costs) that have an impact on the economic growth of an area affected by a volcanic event needs to take into account a number of elements. A cost-benefit analysis may assist the decision-making process by evaluating the economic impact of the different scenarios. To help on this purpose, VOLCANBOX incorporates the approach used by Sobradelo et al. (2015) (BADEMO), a Bayesian decision model that applies a general, flexible, probabilistic approach to the management of volcanic crises by combining the hazard and risk factors that decision-makers need for a holistic analysis of a volcanic crisis (Fig. 64). These factors include eruption scenarios and their probabilities of occurrence, the vulnerability of populations and their activities, and the costs of false alarms and erroneous forecasts. This model can be implemented before an emergency to (i) pinpoint actions for reducing the vulnerability of a particular area, (ii) identify the optimum mitigating actions during an emergency and how these may change as new information is obtained, (iii) assess after an emergency the effectiveness of a mitigating response and, in light of results, (iv) how to improve strategies before another crisis occurs. BADEMO (BAyesian DEcision MOdel) is part of this integrated approach, and enables the previous analysis of the distribution of local susceptibility and vulnerability to eruptions to be combined with specific costs and potential losses. Indeed, BADEMO should be seen as a tool for improving communication between the monitoring scientists who provide volcanological information and those responsible for deciding which action plans and mitigating strategies should be put into practice.

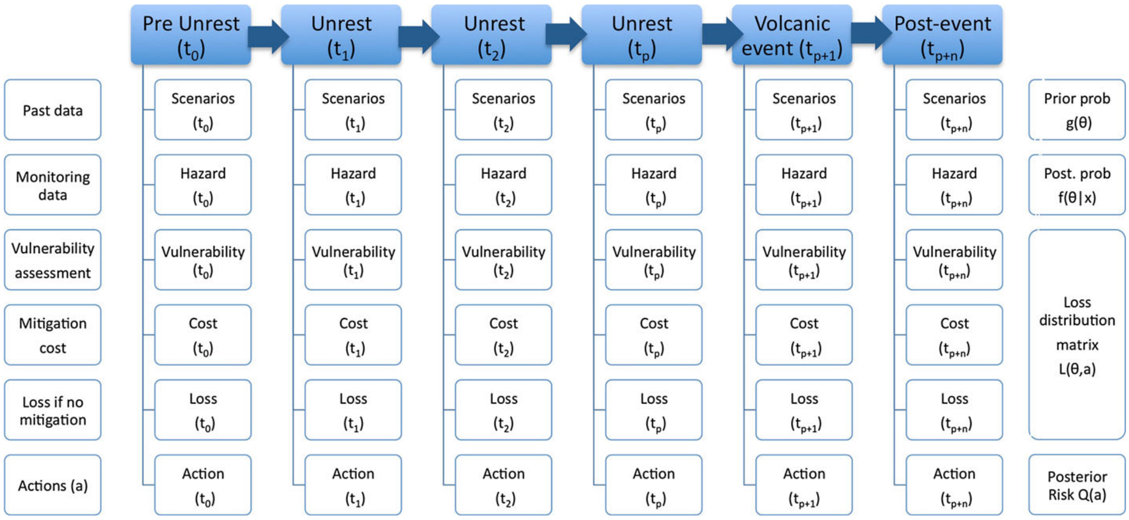
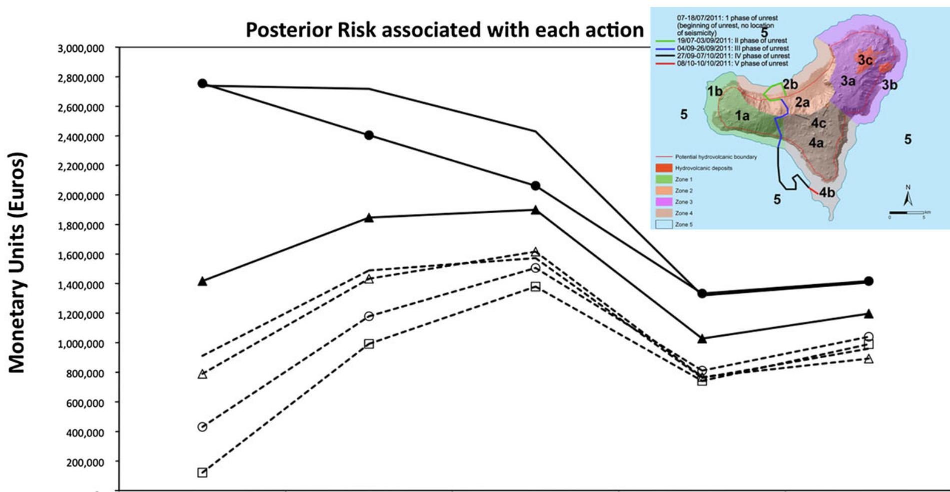


Figure 64.- Decision model structure used by BADEMO (Sobradelo et al 2015). General form of the decision problem as a hierarchical event tree structure made of four stages (nodes), pre-unrest, unrest, volcanic event, and post-event and six phases (branches) per stage, scenarios, hazard, vulnerability, cost, loss and mitigation



	Phase I (7-18 Jul 2011)	Phase II (19 Jul-3 Sep 2011)	Phase III (4-26 Sep 2011)	Phase IV (27 Sep-7 Oct 2011)	Phase V (8-10 Oct 2011)
a1 2b-Los Llanillos (s2)	431,209	1,179,730	1,506,629	812,125	1,041,148
a2 3b-Airport, Port, Tamaduste (s3)	1,417,926	1,847,306	1,900,170	1,028,928	1,197,698
a3 4b-La Restinga, Stop fishing (s4)	790,435	1,433,782	1,617,083	769,169	893,474
a4 2a-Frontera, Tigaday (s6)	2,754,841	2,404,718	2,062,506	1,333,853	1,417,879
a5 3a-Airport, Port, Valverde (s7)	2,739,676	2,718,355	2,430,089	1,320,862	1,408,498
a6 4a-Taibique (s8)	912,166	1,489,802	1,573,410	762,719	960,847
a7 Do nothing (s9)	121,948	993,241	1,380,584	742,687	991,007

Figure 65.- Example of the output provided by BADEMO, using the retrospective example of El Hierro eruption (2011-2012). Evolution of the posterior risk associated with different actions across the different phases of the volcanic crisis for a specific eruptive scenario. The inset map shows the hazard zones as indicated in Fig. 48, and the position of seismicity during each phase of unrest. See Sobradelo et al 2015 for detailed explanations

2.4.6.3. Volcanic risk coefficient

VOLCANBOX includes the Volcanic Risk Coefficient (VRC), an simple index useful for comparing the degree of risk arising from different volcanoes, which may be used by Civil Protection Agencies and Volcano Observatories to rapidly allocate limited resources even without a detailed knowledge of each volcano. Volcanic Risk Coefficient is given by the sum of the Volcanic Explosivity Index (VEI) of the maximum expected eruption from the volcano, the logarithm of the eruption rate and the logarithm of the population that may be affected by the maximum expected eruption. The result is a logarithmic scale from 0 to 17 than ranks the potential risk of active volcanoes or volcanic zones in a n increasing order.

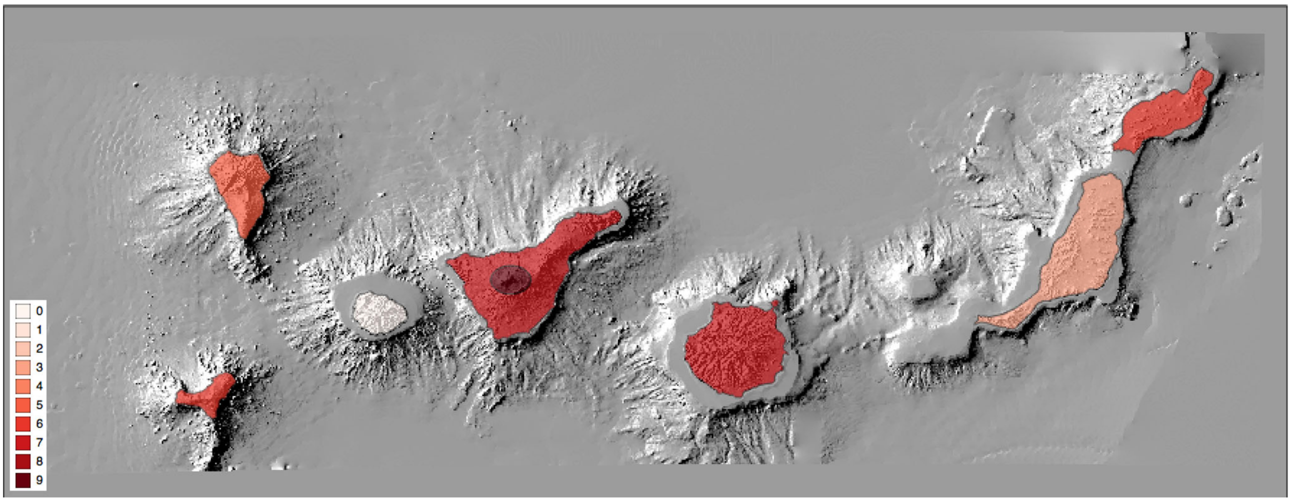


Figure 66.- Example of the VRC for Canary Islands. See Scandone et al (2016) for more details

2.4.7. Communication protocols

This is a module still not implemented in VOLCANBOX, but it will in the next months. The idea is to incorporate a summary of the communication protocols use by the different volcano observatories in Europe to inform about volcanic crisis to all actors and stakeholders involved in their management.

Scientific communication during volcanic crisis is essential to ensure their correct management. Communications between volcanologists and society (community, decision-makers, media, etc.) is receiving increasing attention in the last years and is becoming one of the most important issues of modern volcanology. It is also important to remark that scientific communication should be also present during the quiescence periods of active volcanoes as a way to contribute to risk perception and to improve the confidence that people have in scientific information, two important aspects in crisis management. Different communication strategies have been proposed during last years, in some cases based on practices followed in other natural hazards where experience in scientific communication is greater. However, despite the efforts made scientific communication in volcanology is still a pending task in many volcanic areas, in part due to the fact that volcanoes are complex systems, the predictability of which are subjected to high uncertainty. The idea with VOLCANBOX is to analyse the main aspects of scientific communication during volcanic crisis, and try to identify major problems and difficulties affecting the transfer of scientific information from volcanologists to the policy makers and general public. It also proposes to analyse some communication procedures presently applied in different jurisdictions, and highlighted difficulties and best practices from them. With this, it is expected to upload onto the VOLCANBOX system a series of recommendations to improve scientific communication during volcanic crisis, based on a common language and according to specific requirements for each level of communication: scientist-scientist; scientist-technician; scientist-Civil Protection; and scientist-general public.

PART 3: VOLCANO EARLY WARNING SYSTEM

3.1. Design

The different actors involved in risk management have their own protocols aimed at managing flows of actions of very different natures. These can be more or less complex depending on the needs. In order to facilitate coexistence with other protocols, *VEWS* must follow a simple protocol - to close the door to errors due to unnecessary complexity -, easy to implement- it must be a solution and not a new one headache- non-invasive - must not affect the operation of other protocols - so it must be easy to fit in as a one more piece within the ecosystem of each organisation.

This is why email and a *WebBlog* have been chosen as the primary tools for conducting communications and visualisation, respectively. In this way, regardless of the number of tools on the *Volcanbox* platform adopted by the user, he can be aware of all the alerts generated - and interact with them - with the simple fact of having access to the web and an email account.

E-mail is the main method of communication to the different actors of the new posts released. Posts can be of three types:

Alert : An alert is defined as an important event in terms of volcanic risk.

Update : This is a new post that provides additional information regarding a previous alert or update.

Closing : This is the post that ends the event that has generated an alert and its updates.

When an alert-type post is created, the user creates a thread that can be complemented with updates and a final closing post.

***WeBblog*,** on the other hand, is a tool where the user can post, consult, or interact with the different posts that are generated.

At the time of creating the alert, the user can choose which actors he wants to communicate the alert with. Actors will receive an email with a link to join the follow-up. If they subscribe, each time a new related post is generated - which may be an update or the alert closing - they will receive a new email with a new link. From these links, you can also consult and interact with the different related posts. The user who has made the posts may at any time modify the people to whom they wish to be notified.

The information included in *WebBlog* posts can include both images and text - with links to documents - and must be filled out using web forms. In order to facilitate the adoption of the system and automate the tasks, two additional tools have been defined:

Volcanbox section : It is implemented within the *Volcanbox* desktop application. It has the advantage of being able to automatically publish the results obtained by the application without having to manually publish.

EWS Js : Its function is to allow the main functionalities offered by the *WebBlog* tool to be added within a web page outside the *Volcanbox platform**.

**If the particular organisation has or wants to develop alternative analysis tools, it can use the source code to automate publishing tasks; however, we do not consider this re-implementation as part of our system*

3.2. Protocol

3.2.1. Users

In order to design the protocol, a user type has been defined for each of the tools mentioned in the previous section:

- **Volcanbox User:** uses the *Volcanbox* desktop application.
- **Volcanbox.js User:** uses the *VEWS Plug In*.
- **WebBlog User:** use *WebBlog*.
- **Risk Actor User:** Anyone involved in Risk *.

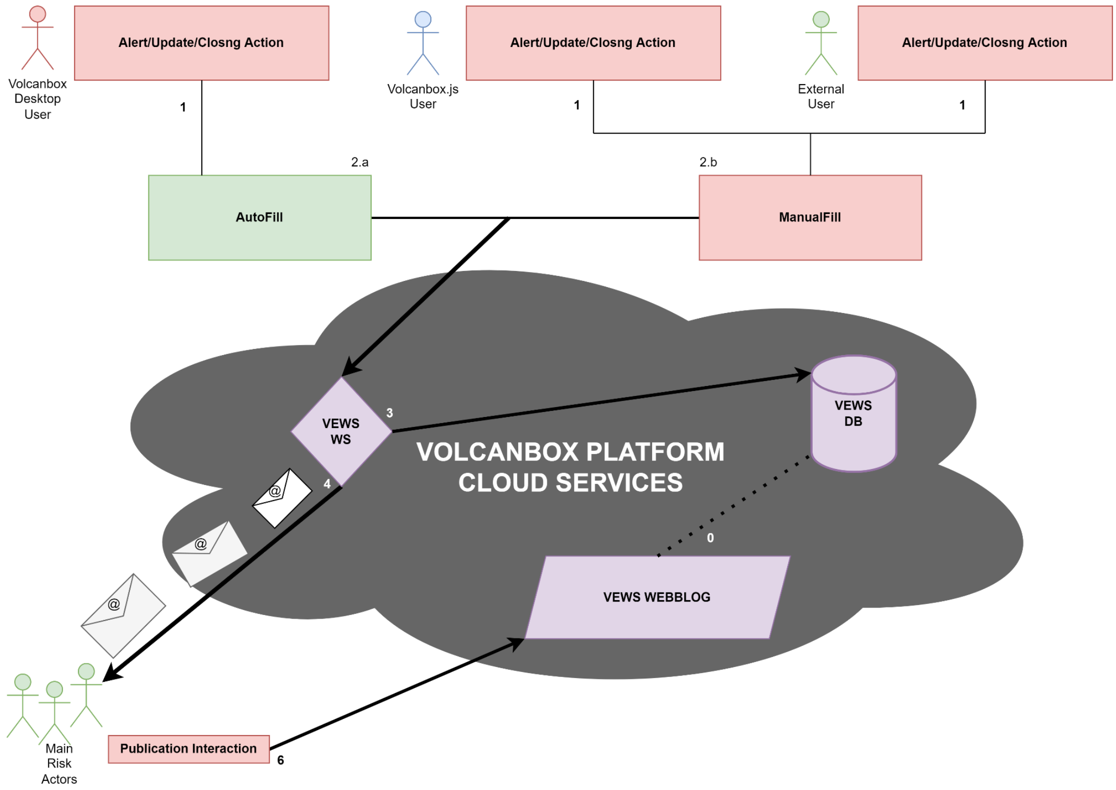


Figure 67. Simplified diagram showing the generation of a new post

3.2.2. Use case:

1) **Alert / Update / Closing Action (Any User Type):** An authorised VEWS user generates a new Alert or an Update or Closing of an existing one.
2) **Fill in options**
   a) **AutoFill Case (*Volcanbox App*):** The application automatically fills in all the necessary fields from the active project and sends them to a web service.
   b) **Manual Fill Case (Any User Type):** The user must fill in a template, with pre-established fields.
3) **Post Data Processing (VEWS Web Service):** The *WebService* receives the data, pre-processes it, validates it and stores it in a VEWS database. It also asks you to update the number of unreceived posts received so that the web blog can display a notice.

4) **Post Link Generation and Sending (*VEWS WebService*):** Generates a link and sends it to the target risk actors using email.
5) **New post Advice (*WebService*):**
   a) The main risk actors receive an email from which they can subscribe to the alert. The email contains a link to the **Volcano Early Warning Web Blog** that shows the alert to logged users.
6) **Post Interaction:**
   a) Authorised users can consult the posts at any time, as well as the contributions or suggestions that other users have made about them.

The diagram (Fig.67) shows how the WebBlog queries the database. This is a simplified diagram, as the consultation is actually done with the *Webservice* as an intermediary.

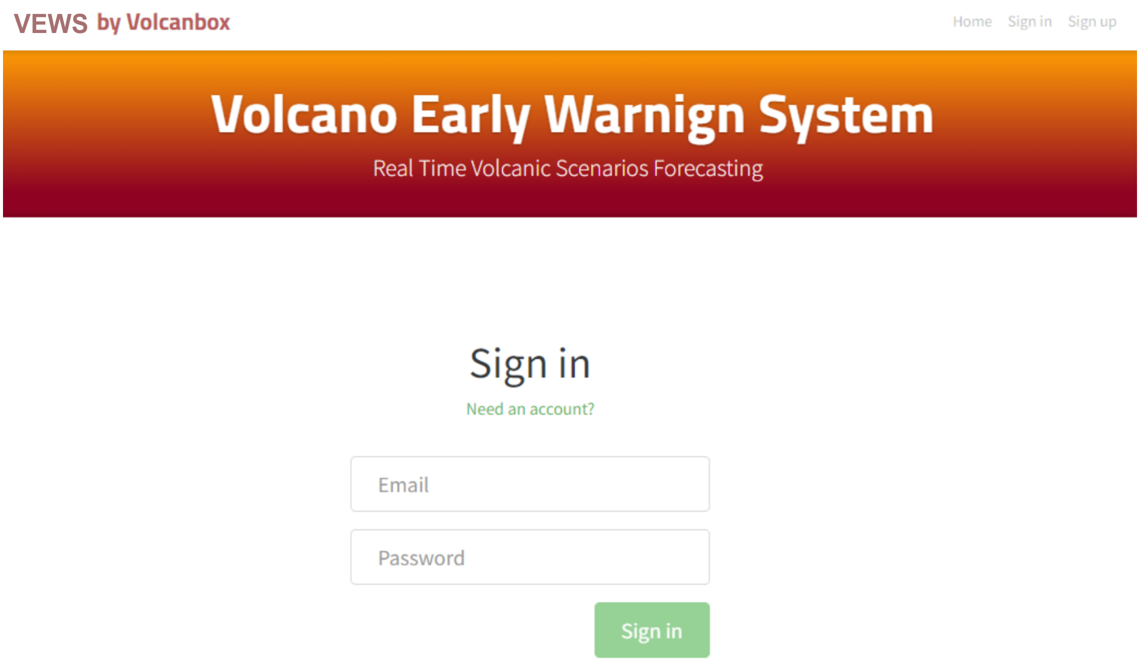
** One person can be part of more than one of these user groups, in fact being a user of any tool implies being an actor risk. At the same time, you may be using more than one tool, as these are complementary and not exclusive. However, a Risk Actor may have enough to subscribe to the emails of a post and consult the abstracts that are included in them.*

3.3. WebBlog

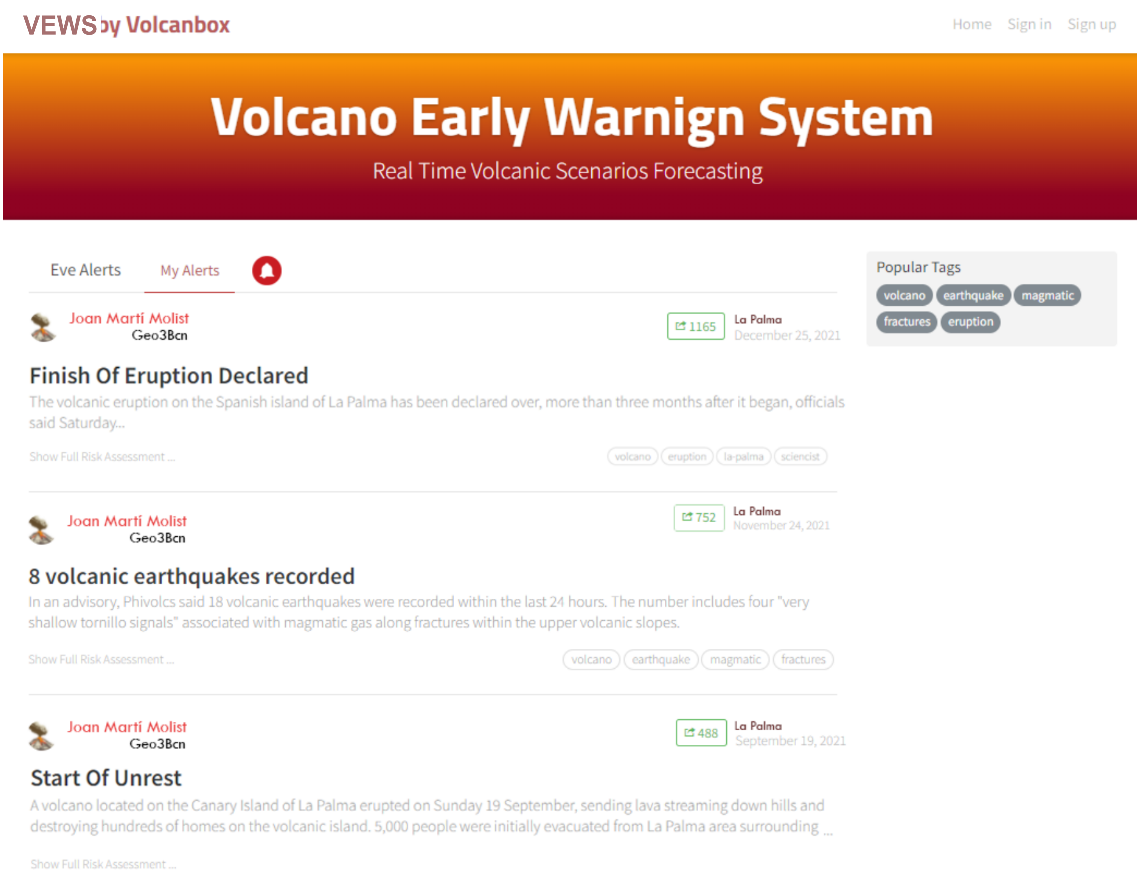
The ***WebBlog*** has been designed as an independent tool capable of solving all the actions that surround the life cycle of an alert, its updates and its closure. It also works as a newspaper library to consult information about past events. It is divided into the following sections:

3.3.1. Sign In/Up

Section that allows you to create a new account or login to a user



3.3.2. Home



Shows a general summary of alerts related to the user. These are divided into two main tabs.

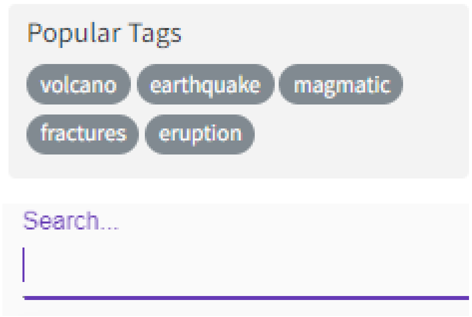
Tabs

My Alerts : Shows a summary of all the posts that the user has created.
Eve Alerts : Shows a summary of all the system posts to which the user has subscribed.

Notifications

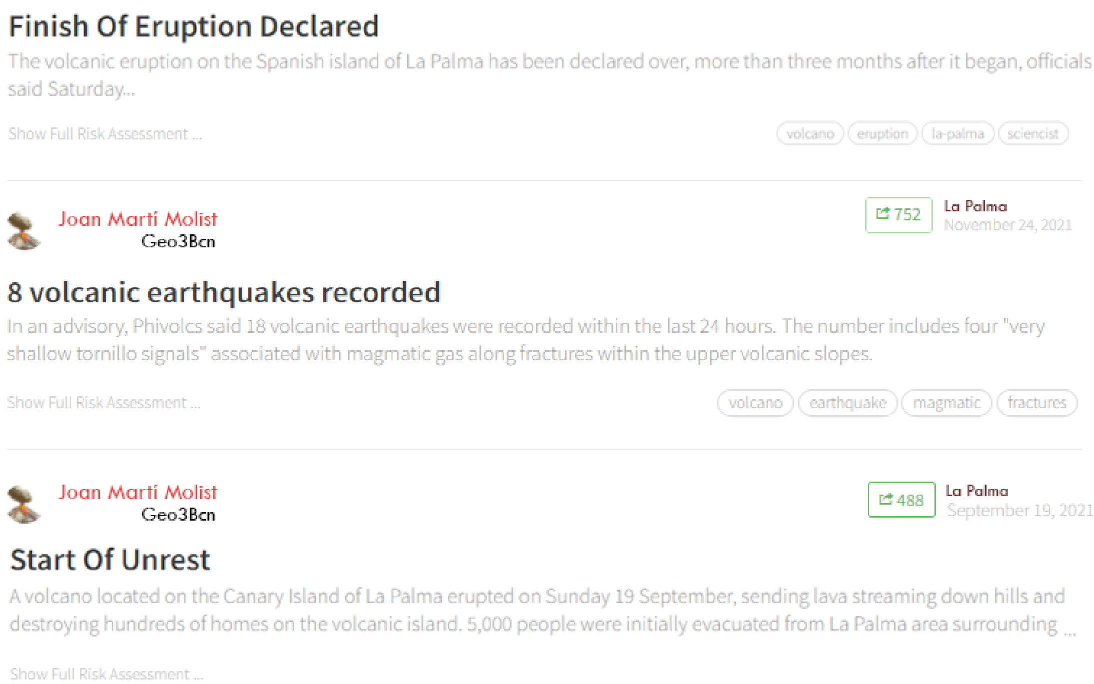
This button appears if there are new alerts that you have been invited to follow and allows you to access them through a drop-down menu.

Tag



The tag section allows the user to choose one of the tags selected by the system or to choose a manual one. Once selected, a new tab will be generated that will show all the posts tagged with that tag:

Previews

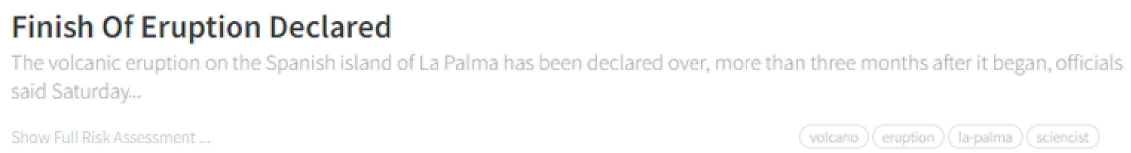


Preview header

They show the user who created the post, the organisation to which it belongs, the followers of that post, the name of the Volcano or Volcanic Zone referring to the post and the date on which it was made.

If the user clicks on the Volcano name of a post, a new tab will open with all the posts related with the volcano.

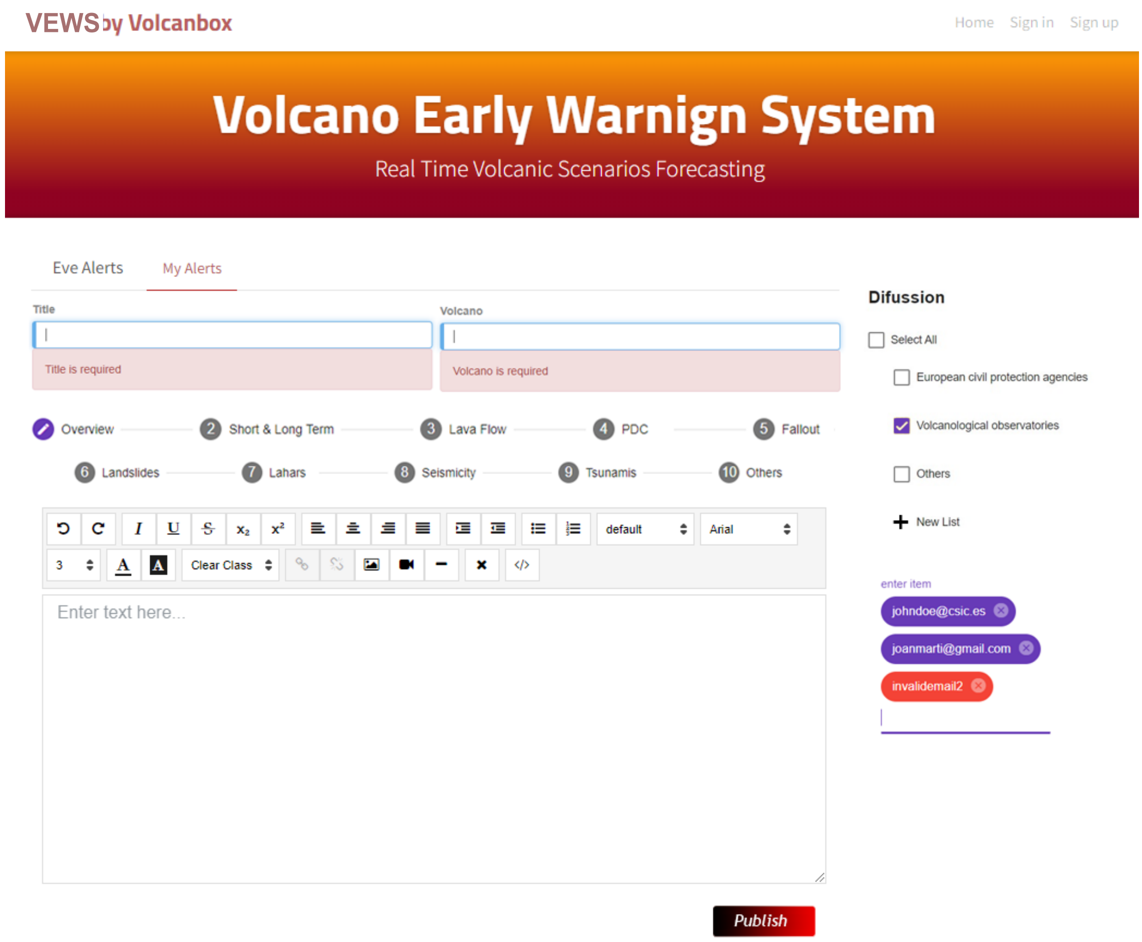
Content Preview



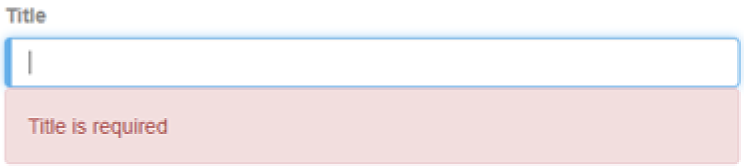
Shows a summary of the post

3.3.3. Post Creation

General view

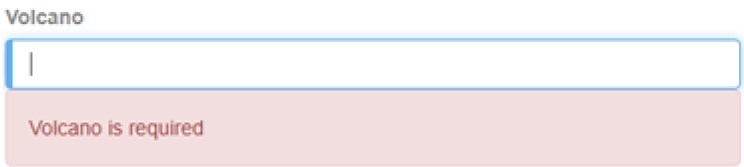


Post Title



Brief description of the event or reason for the post. It is a required field.

Volcano

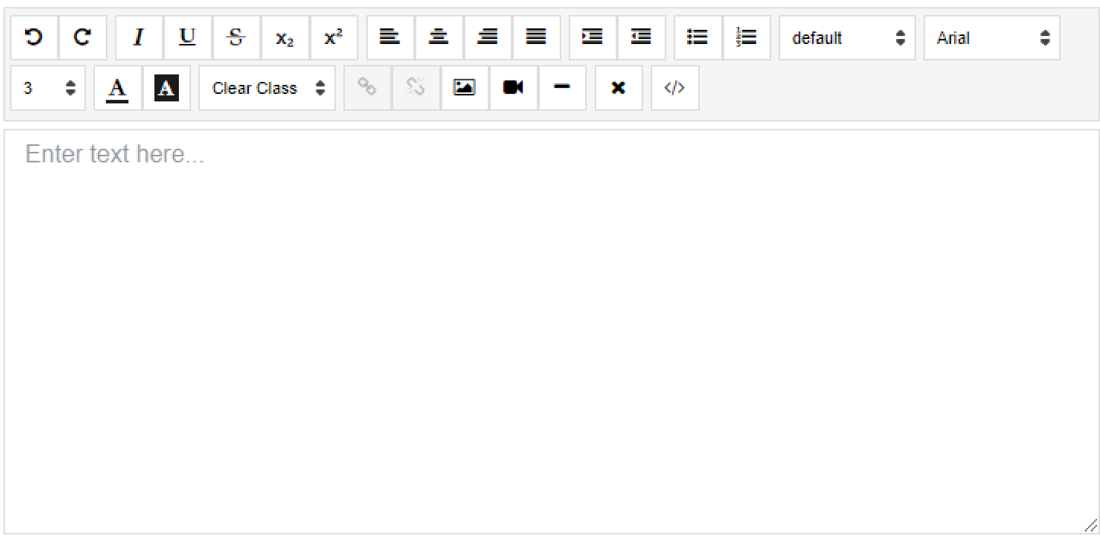


Name of the Volcano -or volcanic area- to which the post refers.

Section Stepper

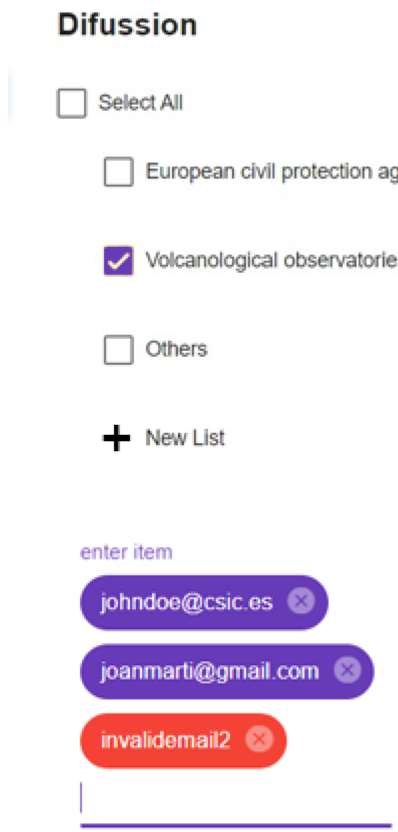
Menu that allows you to scroll between the different sections that a post can include.

Post Editor



It is a text editor from which the user can add the content they want to appear in the section of the post they are creating.

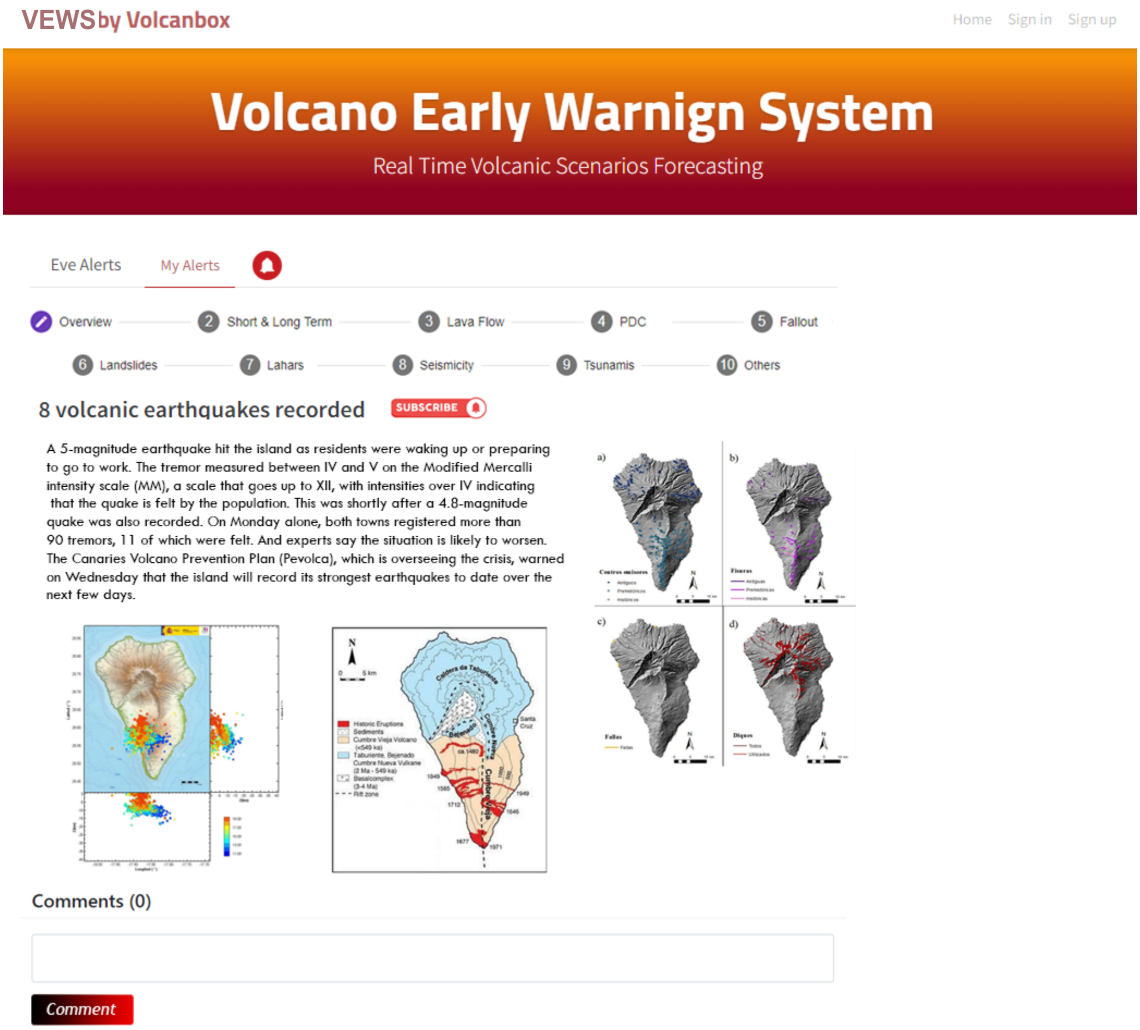
User aggregation list



Allows you to create a list of users to whom a post is going to be sent, either individually or through broadcast lists.

Post button

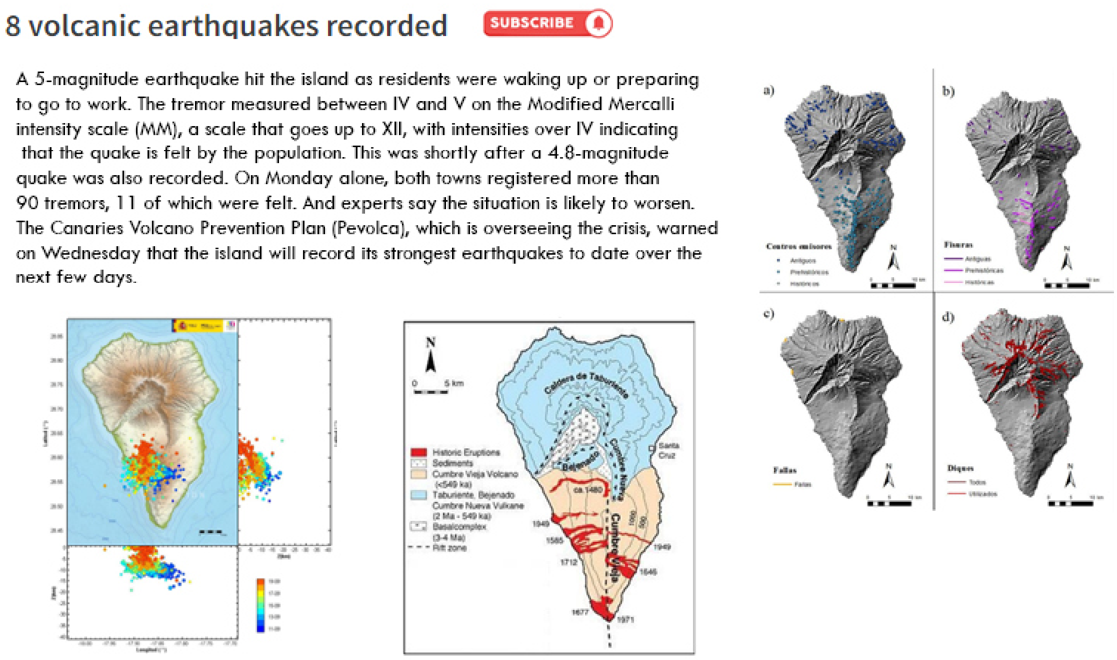
It sends the post to the Web Service so that it can process it, store it and communicate it to all the added users.



3.5. Post

It shows the information regarding a post and allows subscribing, as well as adding feedback in the form of comments.

Post content

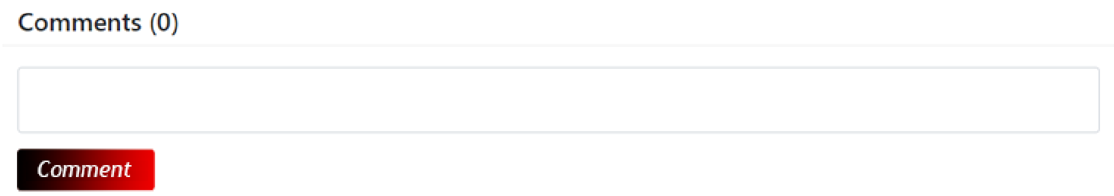


Shows the content of a certain subsection of the post.

Subscribe button

Activate or deactivate the subscription to a post.

Comments



Allows users to leave feedback about the post.

When there are comments, the number of these is shown in the title of the subsection, in addition, these can be read by clicking on the word comments or the number of comments.

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