Chapter 20

Volcanic hazard maps

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20.1 Introduction

Generating hazard maps for active or potentially active volcanoes is recognised as a fundamental step towards the mitigation of risk to vulnerable communities (Tilling, 2005). The responsibility for generating such maps most commonly lies with government institutions but in many cases input from the academic community is also relied on. Volcanic hazard maps communicate information about *a suite* of hazards including tephra (ash) fall, lava flows, pyroclastic density currents, lahars (volcanic mudflows) and debris avalanches (volcanic landslides). The hazard footprint of each of these depends, to a first order, on whether they are erupted into the atmosphere (and therefore dominated by transport in the atmosphere), or whether they form flows which travel along the ground surface away from the volcano. For each hazard type, the magnitude (volume) and intensity (discharge rate) of the event also determines the extent of the footprint. Tephra fall differs from the other hazards in that it can have proximal-to-regional and in extreme cases, global effects. The other hazard types characteristically affect the environs of the volcano, with the most mobile types, lahars and pyroclastic density currents, capable of reaching distal drainages over 100 km from the volcano.

It is of critical importance to understand that a wide variety of methods are currently employed to generate hazard maps, and that the respective philosophies on which they are based are equally diverse, as well as to acknowledge the notion that one model cannot fit all situations. Some hazard maps are based solely on the distribution of prior events as determined by the geology, others take into account estimated recurrence intervals of past events, or use computer simulations of volcanic processes to gauge potential future extents of impact. Increasingly, computational modelling of volcanic processes is combined with geological information and statistical models in order to develop fully probabilistic hazard maps.

20.2 Types of volcanic hazard maps currently in use

A preliminary review of hazard maps has recently been carried out by the authors. The review was based on 120 hazard maps, which were available either in print form, or electronically from legitimate sources on the internet, such as government institution websites. The hazard maps have been categorised into five main families depending on the type of information incorporated in the map and how it is conveyed (Figure 20.1).

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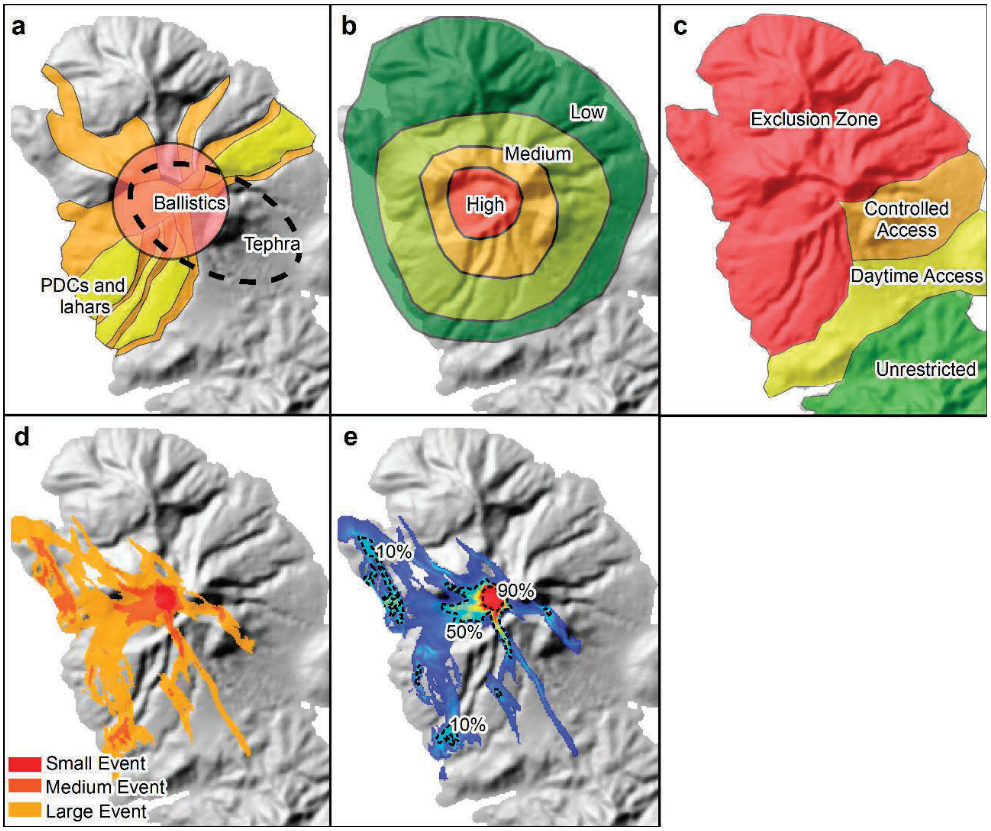

Figure 20.1 Examples of the five predominant hazard map types found during the review. a) geology-based map, b) integrated qualitative map, c) administrative map, d) modelling-based map and e) probabilistic map. These examples are not from a real volcano, they are based on a synthetic topography in order to demonstrate the variability in appearance of such maps for the same topography.

Geology-based maps: Mapped hazard footprints are based directly on the past occurrence of specific types of events. An important limitation of this type of map is that the geological record is an incomplete catalogue of events so that the distribution and extent may reflect previous events, but not all possible future events. Furthermore, the geological record can also be biased by preferentially preserving deposits from larger eruptions and because some deposits of very violent eruptions, such as those formed by volcanic blasts, are easily eroded.

Integrated qualitative maps: All available hazard information is amalgamated, resulting in simple, often concentric-type, hazard zones. The source of the information may be geology and/or modelling. These maps may be more effective for communication because they are simple. Relative hazard is communicated qualitatively [see Chapter 16 Tongariro].

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Modelling-based hazard maps: Involve scenario-based application of simulation tools often for a single hazard type.

Probabilistic hazard maps: Maps based usually on the study of a single hazard using stochastic application of computer simulations. The principal limitations are that these maps deal with a single hazard, are sometimes complex to interpret or communicate and include uncertainties associated with the simulation tool or model input parameters [see Chapter 6 Vesuvius].

Administrative maps: These maps are not designed to show hazard distribution, but instead combine hazard levels with administrative needs and are constructed specifically to aid in emergency management. These maps usually inherently contain information about hazard distribution, but the geoscience content may be somewhat opaque.

Based on the review, the hazards of most widespread concern, as indicated by frequency of occurrence on hazards maps are: lahars, pyroclastic density currents (PDCs), tephra fall, ballistics, lava flows, debris avalanches, and monogenetic eruptions (Figure 20.2a). Seventy-five percent of maps include lahars and/or PDCs and 63% include tephra. Less than half include lava and/or debris avalanches, while less than 10% include hazards associated with unknown source locations, such as monogenetic eruptions. Those maps based solely on the geologic history of the area are significantly more common (63%) than all other map types (Figure 20.2b). Integrated qualitative maps make up 17% of hazard maps. Hazard maps indicate likelihood, in some form, to show the relative degree of hazard affecting the map area. The likelihood of impact can be expressed quantitatively or qualitatively, explicitly or generally. It is noteworthy that 83% of all hazard maps use simple qualitative "high-med-low" designations to indicate level of probability of impact. Such designations, however, are open to wide interpretations.

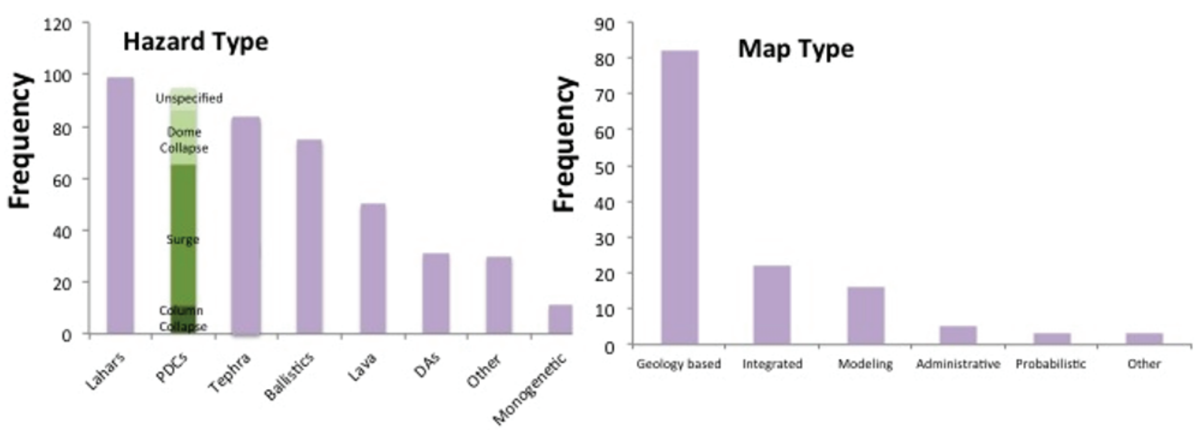

Figure 20.2 a) Types of hazards in the 120 maps reviewed, including: lahars, PDCs, tephra fall, lava flows, debris avalanches and monogenetic volcanism. PDCs were further distinguished based on specific type (column collapse, surge, dome collapse, or unspecified). b). Hazard maps can be subdivided into categories based on how and what information is conveyed. Those based solely on the geologic history of the area are significantly more common (63%) than all other map types. Map complexity increases to the right as the number of maps in that category decreases.

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20.3 Modelling and uncertainty quantification in hazard maps

The computational models used for hazard mapping comprise two main types: (i) complex fluid dynamics and solid mechanics models that attempt to capture as much of the underlying physics of a process as possible; (ii) empirical, or abstracted, models that capture the essence of a complex process. Most commonly it is the latter type of models that are used for hazard mapping (e.g. Iverson et al. (1998), Bonadonna (2005). Simulations are used to indicate the outcome of an eruptive scenario, or set of scenarios (i.e. applied deterministically); or, less frequently, uncertainty is taken into account through probabilistic application of the models (e.g. Bonadonna (2005); Wadge (2009)). Assessing the types of models suitable for use in generating probabilistic hazard maps relies on our understanding of the physical processes involved, but also on our appreciation of aspects of the real phenomena that are not sufficiently captured in models. Models that can be relatively quickly run, in stochastic mode, and are coupled with digital elevation models of volcanic topography or atmospheric wind data, are being increasingly tested and employed in the generation of probabilistic hazard maps during real volcanic crises. Forward modelling applications are still largely at an experimental stage, but ongoing developments of both appropriate models and methodologies pose exciting new opportunities which will likely become more commonplace (e.g. Bayarri et al. (2009)). An increase in the application of computational models to understand potential hazards, and their use in probabilistic hazard mapping, is also intricately bound with discussions on model suitability and inherent uncertainty.

20.4 Vision for future efforts

The volcanology community currently lacks a coherent approach in dealing with hazard mapping but there is general consensus that improved quantification is desirable. Harmonisation of the terminology is needed to improve communication both within volcanology and with stakeholders. In particular, successful approaches must address and quantify uncertainty related to (i) the incompleteness and bias of the geological record and the extent to which it represents possible future outcomes; (ii) the fact that analyses based on empirical models rely on *a priori* knowledge of the events; and (iii) the ability of complex computational models to adequately represent the full complexity of the natural phenomena. The variation in currently utilised approaches results in part from differences in the extent of understanding and capability of modelling the respective physical processes (for example tephra fall hazards are currently better quantified than other hazards). Probabilistic hazard maps, in particular, are highly variable in terms of what they represent. Yet there is the need for probabilistic approaches to be fully transparent; they are used to communicate and inform stakeholders, for whom an understanding of the significance of the uncertainties involved is also crucial. A recent initiative through the newly formed IAVCEI Commission on Volcanic Hazards and Risk, will focus on hazard mapping. The effort aims to undertake a comprehensive review of current practices with a view toward:

- constructing a framework for a classification scheme for hazard maps;
- promoting harmonisation of terminology;
- defining good practices for hazard maps based on experiences of usage.

Clearly, the needs of today's stakeholders for more quantitative information about hazards and their associated uncertainties also drives the need for further research efforts in priority areas. In particular, sources of scientific advancement that would aid in the production of a new generation of more robust, quantitative, accountable and defendable hazard maps would be:

- improved methods for probabilistic analysis, especially for lahar and PDC hazards;
- methods for undertaking hazard assessments for volcanic centres from which we have sparse data;
- uncertainty quantification;
- handling 'Big Data' generated by computational modelling;
- handling uncertainty in digital elevation models and evolving volcanic topography over time;
- forecasting of extreme events and their consequences;
- communicating probabilities associated with hazard and risk;
- approaches for multi-hazard, multi-scenario probabilistic modelling.

These are research problems that require multi-disciplinary expertise to solve. There is consensus that the basic foundation on which any hazard analysis should be undertaken is the establishment of an understanding about a volcano's evolution and previous eruptive behaviour through time, based on combined field geology, dating and geochemical characterisation of the products. However, bringing together experts in modelling and statistical analysis with field scientists is then key. Our ability to achieve tangible advances in probabilistic volcanic hazard analysis hinges on the effective use of advanced modelling and statistical methods, and handling of massive and/or complex data. Dealing with such data requires fundamental advances in mathematical, statistical and computational theory and methodology but also requires training a new generation of scientists that are adapted to cross-disciplinary research environments.

20.5 Glossary of hazard map types

Administrative hazard maps: A type of map used for disaster management that takes into account local infrastructure, land use and populations in addition to information about possible hazard distribution.

Geology-based hazard maps: Indicates hazards based on the distribution of past eruptive products. Can also include information about recurrence rates.

Integrated hazard maps: All available hazard information is amalgamated, resulting in simple, often concentric-type, hazard zones. The information on which these are based can include field distributions as well as modelling. Levels of hazard are usually expressed qualitatively.

Modelling-based hazard maps: Involve scenario-based application of simulation tools often for a single hazard type.

Probabilistic hazard maps: Based on probabilistic application of hazard models (models can be empirical to fully geophysical). Levels of hazard can be expressed quantitatively.

Less common, but also in use are the following terms:

Hazard-specific maps: Considers only one hazard type in one map.

Multi-hazard maps: Considers multiple hazard types in one map.

Nested hazard maps: A type of scenario map indicating the possible distribution of eruptive products of a similar type of event (e.g. lahars), but for scenarios with varying magnitudes or intensities. The distributions are therefore nested within each other.

Rapid-response hazard maps: Generated by ascertaining the distribution of past eruptive products, rapidly (either remotely or in the field) in response to a period of unrest or impending crisis at a volcano where previously eruptive activity is not established or has not previous been well characterised.

Scenario maps: Provide information about the distribution of eruptive products, based on explicit event scenarios that may be considered likely. If levels of hazard are expressed quantitatively they can be considered conditional.

20.6 Summary

The large majority of hazard maps currently in use by government institutions around the globe are geology-based hazard maps, constructed using the distribution of prior erupted products. Such maps are based on the study of the volcano, and provide a wealth of information about its capabilities. An important limitation though, is that the distribution of previous events (even if known in their entirely), does not represent all possible future events. Increasingly, computer simulations of volcanic processes are used to augment the knowledge gained by geology, to gauge potential areas and extents of impact of future events. The hazards of most widespread concern, as indicated by frequency of occurrence on hazards maps are: lahars, pyroclastic density currents, and tephra fall. Currently, tephra hazards (which can have the most wide-spread effects and far-reaching economical impacts) are the best quantified. Lahars and pyroclastic density currents both have more localised impacts but do account for far greater loss of life, infrastructure and livelihoods. These hazard types present greater challenges for modelling, and as a result quantitative hazard analysis for lahar and pyroclastic density currents lags behind that for tephra fall.

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