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RESEARCH ARTICLE

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Constructing event trees for volcanic crises

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Abstract Event trees are useful frameworks for discussing probabilities of possible outcomes of volcanic unrest. Each branch of the tree leads from a necessary prior event to a more specific outcome, e.g., from an eruption to a pyroclastic flow. Where volcanic processes are poorly understood, probability estimates might be purely empirical – utilizing observations of past and current activity and an assumption that the future will mimic the past or follow a present trend. If processes are better understood, probabilities might be estimated from a theoretical model, either subjectively or by numerical simulations. Use of Bayes' theorem aids in the estimation of how fresh unrest raises (or lowers) the probabilities of eruptions. Use of event trees during volcanic crises can help volcanologists to critically review their analysis of hazard, and help officials and individuals to compare volcanic risks with more familiar risks. Trees also emphasize the inherently probabilistic nature of volcano forecasts, with multiple possible outcomes.

Keywords Acceptable risk · Probability · Bayesian · Event tree · Volcanic hazards · Volcanic risk

Introduction

Most volcanic systems are too complex and our understanding of them too rudimentary for precise, unequivocal predictions of eruptions and their consequences. What are the alternatives? Qualitative statements of hazard and risk, replete with adjectives like “soon,” “high-" or “low-risk,” or “more dangerous than yesterday” are of little value to officials who must make life-and-death decisions about mitigation measures. The best alternatives that we know are quantified estimates of:

- the probabilities of dangerous volcanic events (hazards),
- probable losses of life, limb, or property (risks),
- more familiar risks, for comparison,
- the benefits of mitigation (mainly, avoided risk and loss),
- the costs of mitigation (both direct, such as for evacuations and emergency housing, and indirect, such as economic and social disruption of communities or foregone development).

This paper describes a simplified way to estimate probabilities of specified volcanic events within specified time frames. The same methodology can be extended to judge hazard at specific sites and, though not discussed in this paper, to prepare semiquantitative hazards maps. The product of volcanic hazard and information about an individual's exposure and vulnerability to that hazard, what we call “individual risk,” can be cautiously compared with other, more familiar individual risks in life. A discussion of how to extend these methods to estimate community risk (probable losses of lives and property in a specified area) is beyond the scope of this paper.

We and colleagues have used event trees with mostly positive results at Mount St. Helens, Mount Pinatubo, Soufrière Hills (Montserrat), Popocatépetl, Guagua Pichincha, and Tungurahua (Newhall 1982, 1984; Punongbayan et al. 1996; Aspinall and Cooke 1998; S. de la Cruz written communication, 1996; M. Hall written communication, 1999–2000).

Definitions and time frames

Event tree

A graphical, tree-like representation of events in which branches are logical steps from a general prior event through increasingly specific subsequent events (intermediate outcomes) to final outcomes. We use

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event trees to show possible outcomes of volcanic unrest at progressively higher levels of detail. We also estimate probabilities for each event through the tree. The multiplicative product of probabilities along any one path will yield the probability of the terminal (rightmost) event. For graphical and conceptual simplicity, events at any given level of the tree need not be mutually exclusive or exhaustive.

Probability tree

A graphical, tree-like representation of the probabilities of comprehensive (exhaustive), mutually exclusive events. As above, events are progressively more specific as one moves outward along branches. As above, the multiplicative product of probabilities along any one path will be the probability of the most specific event. However, the requirement that events at any given level of specificity be comprehensive and mutually exclusive means that probabilities of events at that level will sum to 1.0. This sum of 1.0 is required if one wishes to know, for example, the total probability of an outcome (e.g., death) that might be reached along several different possible paths.

Unrest

Anomalous seismicity, geodetic strain, fumarolic activity, or other change above normal background levels, potentially, but not necessarily, precursory to an eruption.

Hazard

Probability of a potentially damaging natural event, such as an earthquake, or pyroclastic flow, within a specified period of time (typically 1 year). (Because this paper deals exclusively with probabilities, we adopt a shorthand that incorporates probabilities into the definitions of hazard and individual risk, and thereby eliminates the need to preface every usage with the words “probability of...” Our estimates of hazards and individual risk are in terms of probabilities per unit time.)

Individual risk

Probability that a specific individual, at known coordinates, will be killed or injured by the volcano within a specified period of time.

Community risk

Probable magnitude of loss in a community, expressed in terms of deaths or economic loss.

Acceptable risk

Risk that an individual is willing to accept, or that a public official is prepared to allow an individual or community in his or her charge to accept, in return for perceived benefits of taking that risk.

Long-term

Pertaining to the coming years, decades, centuries, and longer. For most long-term hazard estimates, the volcano in question is dormant and any seismicity, geodetic change, or fumarolic activity is at background levels.

Intermediate-term

Pertaining to the coming months and, occasionally, years. Intermediate-term hazard is typically estimated when a volcano is restless (or even erupting), but the unrest (or eruption) is not changing rapidly.

Short-term

Pertaining to the coming minutes to weeks. Short-term hazards are typically estimated when unrest (or an eruption) is changing rapidly.

In general, a forecast or risk assessment can look no farther forward than the time span of data on which it is based, nor can it have any greater resolution than that of the data on which it is based. A geologic record of tens of millennia and resolution of centuries applies to coming centuries and millennia, but not necessarily to next week. Similarly, a record of last week’s monitoring applies to next week but not to next year. Note: estimates of hazard and risk over these three timeframes are typically normalized to an annual basis, but can be made for shorter or longer periods as required.

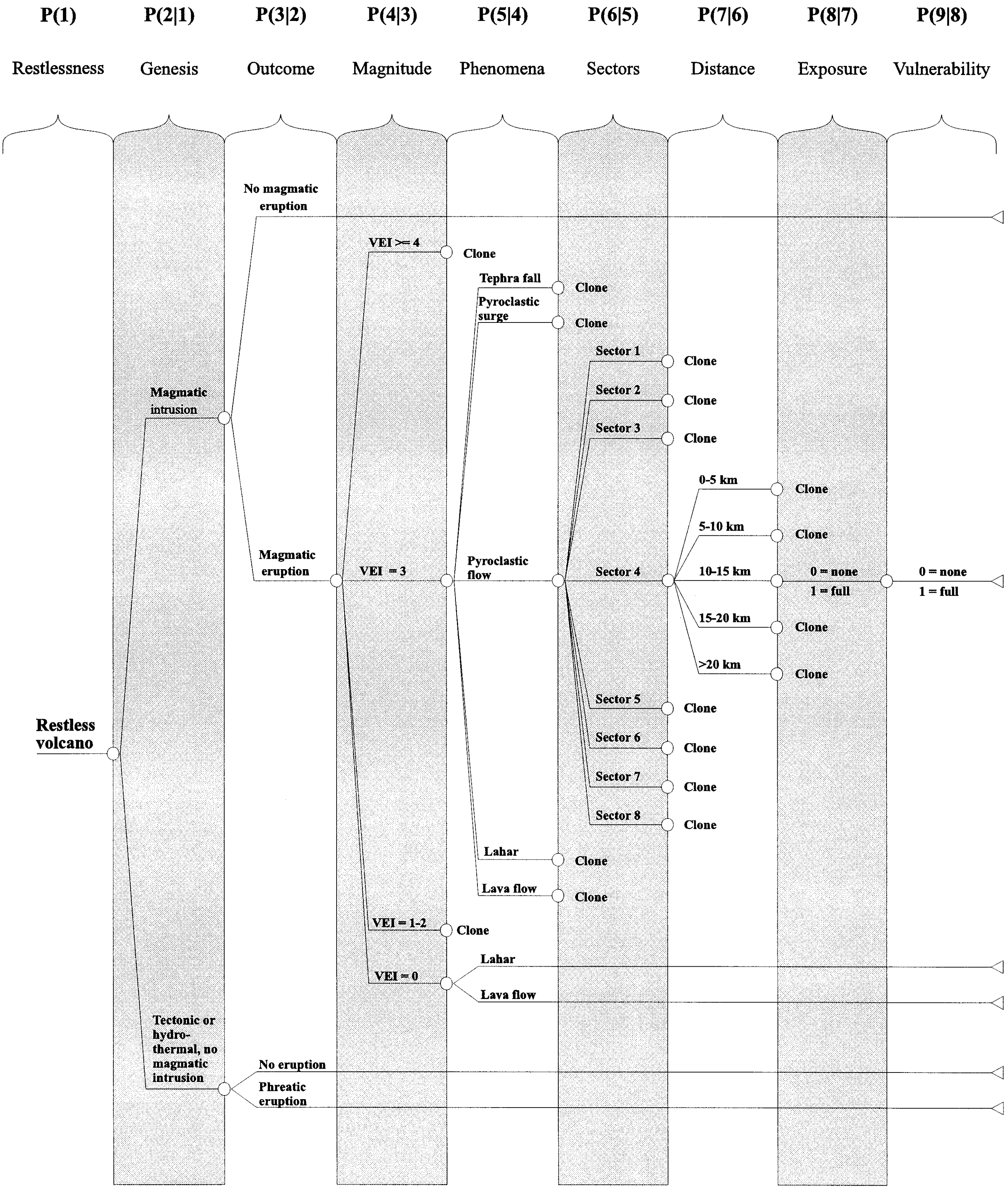
An event tree for estimating volcanic hazard and risk

We have found it useful to organize questions about volcanic hazard and risk into event trees in which the trunk is the most general, initial event and branches lead to increasingly specific, subsequent outcomes (Newhall 1982, 1984; Hoblitt et al. 1987). A conditional probability, written in the form $P(n|n–1)$, is the probability of event n given that event $(n–1)$ has occurred. The probability of any outcome, $P(n)$, is the product of the probability of an initial event, $P(1)$, and all further conditional probabilities, $P(2|1)...P(n|n–1)$, leading to that outcome.

$$\mathrm{P(n) = P(1) \cdot P(2|1) \cdot P(3|2) \cdot \ldots \cdot P(n|n-1)} \qquad (1)$$

In defining events of a generic tree (Fig. 1), we include only the minimum number of branches and “orders” of branches that are needed to describe movement of the system from current conditions through increasingly specific conditions to final outcomes. Unnecessary branches can artificially depress estimates of the key probabilities.

Fig. 1 A generic event tree for volcanic hazard and risk estimation. The nine steps of estimation progress from general to specific, as described in the text. At step (*6*), our generic framework defines outcomes of hazards into eight 45° sectors; these could be modified as desired for a specific volcano. At step (*7*), our framework defines five distance intervals; in Tables 2 and 3, distance probabilities are smoothed by continuous functions. Readers who need to tally probabilities of a specified outcome that can occur along multiple pathways have two choices. An (overestimated) approximation can be made by summing the probabilities at the ends of paths shown on this tree. A mathematically correct but more tedious approach is to expand this tree so that branches from every node are exhaustive and exclusive. Questions at steps *5–7* must be framed so that they have yes/no answers, e.g., will there be a pyroclastic flow? (yes/no), will the pyroclastic flow travel in the north sector? (yes/no) Will it reach at least 15 km from the vent? (yes/no). These procedures make a much larger, more complicated tree, but are necessary in order to subsequently subtract overlap of probability fields. A computer program could easily handle the expanded tree, but we cannot show the expanded tree graphically on a journal page ▶



Note: Any branch that terminates with "Clone" is identical to the subsequent central branch. For example, in the Magnitude column, the VEI4 and VEI1-2 Clones are identical to the central VEI3 branch.

However, we do include distinct branches for low-probability, high-consequence events. Rare eruptions like those of Mount St. Helens and Mount Pinatubo remind us, painfully, that “low-probability” events can occur within human timeframes and must not be ignored.

In our simplest generic tree, progressively more specific levels or branches of the tree address:

$P(1)$	Probability that the volcano will become restless.
$P(2\|1)$	Probability that, given unrest, the unrest is caused by magmatic intrusion.
$P(3\|2)$	Probability that, given a magmatic intrusion, magma will erupt.
$P(4\|3)$	Probability that, given a magmatic eruption, it will be of specified explosive magnitude.
$P(5\|4)$	Probabilities that, given a specified explosive magnitude, specified volcanic phenomena will occur (e.g., pyroclastic flow, lahar, etc.).
$P(6\|5)$	Probabilities that, given a specified volcanic phenomenon, it will travel into specified azimuthal sectors.
$P(7\|6)$	Probability that, given travel into a specified sector, the given phenomenon will reach at least to a specified distance from the vent.
$P(8\|7)$	Probability that, given all of the above, a specific individual will be present in the same sector at the same or lesser distance from the vent.
$P(9\|8)$	Probability that, given the individual’s presence, (s)he will be killed by that specific hazard.

Before a volcano becomes restless, the long-term prior probability of an eruption, $P(3)$, would be based simply on its known frequency of eruptions. If a magmatic intrusion begins, we will want to estimate $P(3|2)$, a revised probability of eruption. This revised, posterior estimate will be the initial estimate modified by statistics of how often unrest does (and does not) lead to eruptions. $P(3|2)$ will be strongly dependent on the rate of false alarms (unrest that does not lead to eruptions). If that rate is high, new unrest will only minimally increase the probability of eruption.

$P(3|2)$ can be estimated by Bayes theorem:

$$\mathrm{P}(3|2) = \frac{\mathrm{P}(2|3)(\mathrm{P}3)}{\mathrm{P}(2|3)(\mathrm{P}3) + \mathrm{P}(2|3')\,\mathrm{P}(3')}. \tag{2}$$

In words, the probability of an eruption, given unrest

$$\mathrm{P}_{\text{eruption}|\text{unrest}} = \frac{\left(\mathrm{P}_{\text{unrest}|\text{eruption}}\right)\left(\mathrm{P}_{\text{eruption}}\right)}{\left[\left(\mathrm{P}_{\text{unrest}|\text{eruption}}\right)\left(\mathrm{P}_{\text{eruption}}\right) + \left(\mathrm{P}_{\text{unrest}|\text{no eruption}}\right)\left(\mathrm{P}_{\text{no eruption}}\right)\right]}$$

An equivalent formulation for earthquake prediction, couched in terms of mutually exclusive precursory and background earthquakes, is given by Agnew and Jones (1991), and a generic formulation is given in Woo (1999).

Sources of data

For each level (or order of branches) in the event tree of Fig. 1, we will suggest one or more bases for estimating probabilities. Some are purely empirical, based on past history or a present pattern as a guide to the future; others rely on theory and interpretation of magmatic and volcanic process. Both can be used, depending on the available data and how well the particular phenomenon or system is understood. In practice, a partial understanding of current process is sometimes used to guide selection of empirical data.

Historical and geologic data are the principal bases for estimation of long-term probabilities. Because the quality of records deteriorates as one goes back in time, it may be necessary to consider only the most recent *X* years, or just eruptions of larger magnitude, more likely to be preserved in the geologic record and recorded in history. If some data are being drawn from analogous volcanoes or eruptions, the analogues must be chosen carefully. Model-dependent long-term forecasts, e.g., of expected petrologic evolution, or anticipated change in eruption volume, style, repose period, etc., are only as good as the theory behind the models and the calibrations and verifications that have already been made.

For intermediate-term probabilities (coming months), data can be from geologic and historical records of individual episodes of previous unrest, chosen for comparability to the current unrest. Data can also come from models of episodes of unrest, starting, for example, with a magmatic intrusion from depth and ending, with or without eruption, when pressures in the magma or hydrothermal system drop below the level needed to sustain the unrest.

For short-term probabilities, monitoring data are essential (cf. Klein 1984). From them, empirical comparisons can be made with past unrest at the same or similar volcanoes, and an assumption can be made that the current unrest will likely lead to the same outcomes that occurred previously. At the same time, process-oriented interpretation helps us to handle new, previously unobserved patterns, and to spot the pitfalls wherein the same signal can result from two or more possible processes, as, for example, when an increase in SO_2 emission can result from increased exsolution or decreased scrubbing by ground water as some of that water is boiled away.

Hazard estimation

We start to build the event tree here. In each of the following steps, we ask the probability of each event and offer possible empirical and process-oriented data. Later in the paper, we present a simple, hypothetical example.

P*(1)*

Given a young, potentially active volcano in repose, what is the long-term (annual) probability that unrest will begin?

- From historical records and especially from instrumental monitoring records, one can estimate the minimum frequency with which a volcano shows unrest. However, unrest that does not culminate in an eruption is commonly unreported or is buried in files of unpublished data or in obscure historical reports. Compilers need to interview senior scientists and residents, and to examine files in the local observatories and in major libraries.
- In rare instances, non-eruptive unrest can produce a geologic record of its own. Evidence for earlier seismicity might be preserved as fault offsets of young deposits, evidence for past uplift might be preserved in terraces, and evidence of recent magmatic input to a hydrothermal system might be preserved in an unusually acidic hydrothermal fluid.
- Eruptions at some volcanoes – and unrest also, we suspect – fit a Poisson distribution through time (Wickman 1966, 1976; Mulargia et al. 1985). For such volcanoes, the probability of an eruption (or episode of unrest) at any time is independent of the time of the previous eruption and can be estimated directly from the long-term recurrence frequency. At other volcanoes, though, eruptions and unrest show a pattern in which the probability of an eruption (or unrest) depends on the time and volume of the previous eruption (e.g., Carta et al. 1981; Wadge 1982). Empirical estimation of the probability of volcanic unrest must consider any statistical pattern in the recurrence of that unrest, and the attendant uncertainties.
- In principle, detailed knowledge of a volcanic system and the frequency of various triggering stimuli could be used to estimate the probability of renewed unrest at that system. In practice, few if any volcanic systems are understood well enough to improve empirical estimates.

P*(2|1)*

Given unrest, is a magma intrusion in progress?

- Logical and generally reliable indicators of magma involvement in unrest are SO_2 emissions of hundreds of tonnes (or more) per day; rapid, localized inflation of the volcanic edifice (tens of microstrains per day); or uniquely volcanic seismicity such as non-double-couple, low-frequency earthquakes or low-frequency tremor (both with a dominant frequency of <2 Hz).
- Significantly, it is difficult to refute a magmatic origin of unrest. Water-soluble magmatic gas (especially SO_2, HCl, and HF) can be dissolved and then masked (hidden) for months or years in percolating groundwater (Symonds et al. 2001). For example, groundwater masked magmatic gases at Mount St. Helens before its large eruption in 1980 (Casadevall et al. 1981) and at Mount Spurr between eruptions in 1992 (Doukas and Gerlach 1995). An absence of magmatic gas (or highly acidic fluids) in surface samples does not rule out magmatic involvement at depth. Similarly, dike intrusions and pressurization of large magma bodies at depth cause brittle fracturing of rock that, in process and in seismic signature, is indistinguishable from normal tectonic faulting. A swarm of high-frequency, "tectonic" earthquakes might also be "volcano-tectonic," caused by magma intrusion. For example, earthquake swarms at Long Valley caldera, California, reflect a complex interplay of regional tectonic strain and probable intrusion of magma (Hill et al. 1985). Tremor is often but not always of magmatic origin; boiling in a hydrothermal system also generates tremor, with or without magma intrusion (McNutt 1989, 1994; McNutt and Garces 1996). Slow deformation of a volcano, say, mm/year or at most a few cm/year, might be tectonic, magmatic, or hydrothermal; faster deformation is almost always magma-induced (Dvorak and Dzurisin 1997).

Although a small number of phreatic eruptions occur without active magmatic intrusion, only a few of these are large enough to be hazardous. Therefore, all further discussion is of magma-driven unrest.

P*(3|2)*

Given that an intrusion is in progress, what is the probability that magma will erupt?

- Some diagnostic patterns of unrest suggest a high probability that magma will erupt. Such patterns include rapid, exponentially increasing seismic energy release (for example, Tokarev 1971; Malone et al. 1983; Endo et al. 1996), or patterns of visible uplift (e.g., 10's of cm/h at Campi Flegrei and Rabaul in the hours just before magma erupts; del Nero 1538; Dvorak and Mastrolorenzo 1939; Fisher 1939; Blong and McKee 1995). Such changes require little understanding of the underlying processes, although such an understanding is naturally preferable. Two drawbacks to simple pattern recognition are that (1) the most diagnostic signs of an eruption appear only shortly (usually, hours) before that eruption, and (2) any unprecedented or irregular behavior sharply increases the uncertainty of pattern-based forecasts.
- Sometimes, one can observe shoaling of earthquake hypocenters and infer rate of magma ascent, as for example at Kilauea (Eaton and Murata 1960) and at Pinatubo (Harlow et al. 1996). A decrease in the average spectral frequency of seismicity can also suggest magma ascent (Minakami 1960; McNutt 1996). Models of ground deformation can suggest the depth, size, and shape of a pressure source (Mogi 1958; Okada 1985, 1992), and repeated surveys can detect any shoaling of the source (e.g., Aoki et al. 1999). Magma ascent is also indicated if relatively insoluble gases (e.g., CO_2) are released first, followed by progressively more soluble gases (e.g., SO_2, then HCl, etc; Giggenbach 1996;

Martini 1996). In all of the preceding, rate of ascent is important: the faster the ascent, the greater the buoyancy and/or the easier the passage and the higher the likelihood of eruption. In general, rapidly escalating rates suggest a runaway process toward eruption.

- Some diagnostic but counterintuitive changes can also signal an imminent eruption, such as sudden seismic quiescence (Newhall and Endo 1987; McNutt 1996), or sudden shutoff in gas emission while seismicity is shallow and increasing (Fischer et al. 1994; Daag et al. 1996).
- Databases of worldwide unrest and associated eruptions are beginning to help. Databases of volcanic earthquake swarms and volcanic tremor have been compiled by McNutt (1989, 1994), Benoit and McNutt (1996), and McNutt and Garces (1996). Various types of unrest at large calderas are summarized by Newhall and Dzurisin (1988). A list of precursors to phreatic eruptions is given by Barberi et al. (1992).
- We and colleagues are working toward a comprehensive database of unrest but the job is large and it will be years before it is ready. When it is ready, probability estimates can be based on specific characteristics of unrest in specific volcanic and tectonic settings. A few generalizations are possible now. More than half of the intrusions in Kilauea Volcano will lead to magmatic eruption (Klein 1982), and this figure seems to apply to other mafic volcanoes as well. In contrast, at large silicic centers, only one or two of ten episodes of unrest leads to magmatic eruptions (Newhall and Dzurisin 1988, p. 13). Some unrest at large silicic systems is unrelated to intrusions, but even intrusions are often buffered and stop before eruption.
- Although the preceding paragraph treats unrest at Kilauea and silicic systems as if only one parameter was changing, unrest is actually a combination of various forms and rates of seismicity, ground deformation, gas emission, hydrologic change, and other changes. Each of these makes its own contribution to the probability that the composite unrest will lead to a magmatic eruption. Aki (1981) and Cao and Aki (1983) discuss how each potential precursor can be weighted, and how probability gain can be estimated for combinations of independent and dependent forms of unrest. These methods will be especially useful upon completion of a large, unified database of unrest from the world's volcanoes.
- In this paper, we consider initial phreatic eruptions to be a form of unrest that can lead to magmatic eruptions. From Simkin and Siebert (1994), approximately 40% of explicitly distinguished phreatic eruptions are associated with magmatic eruptions and most but not all preceded the magmatic phase (e.g., those of Mount St. Helens in March–early May 1980, or that at Pinatubo in April 1991). This is surely an underestimate of how often phreatic eruptions are followed by magmatic eruptions because phreatic onsets of magmatic eruptions are often ignored. It is difficult for magma to "sneak past" shallow groundwater without causing at least minor phreatic explosions.
- With simple conceptual models of a volcanic system, volcanologists can offer subjective judgments of the likelihood of eruption and its likely type and magnitude. Eventually, given enough input data and development of numerical models, these subjective estimates may be compared with objective probability distributions for various combinations of magma state and triggering mechanisms.

P*(4|3)*

Given a magmatic eruption, what is the probability that it will be of VEI 0 (non-explosive), 1–2 (weakly explosive), 3 (moderately explosive), or ≥4 (strongly explosive)? VEI is the volcanic explosivity index (Newhall and Self 1982) defined from the (1) bulk volume of pyroclastic deposits (modified from Tsuya 1955, who used the volume of all magma erupted, explosively or not), (2) mass discharge rate, usually reflected in column height, (3) fragmentation vs. dispersal classification of eruptions (hawaiian, strombolian, vulcanian, subplinian, plinian, etc.; Walker 1973; Wright et al. 1980), or (4) combinations of the above.

- A starting point for estimating $P(4|3)$ is the historical record of the particular volcano of concern. If that record is insufficient, turn to the geologic record. Be aware that both records grow progressively less complete as one moves back in time, especially for small eruptions because of vagaries of human reporting and erosion and burial in the geologic record. A common practice is to use data from the longest period for which records are judged to be reasonably complete for the eruption magnitudes of concern. An alternative is to calculate a weighted Gamma distribution of activity rates (Woo 1999, p. 85).
- The global record of Holocene explosive eruptions reveals a magnitude–frequency relationship (Fig. 2; Decker 1990; Simkin 1993; Simkin and Siebert 1994; Pyle 1998) that is analogous to the familiar Gutenberg–Richter relationship for earthquakes. Over the range VEI 2–7, the probability of VEI_n is about six times that of VEI_{n+1}. Subsets of data from similar volcanoes can be plotted in the same manner. From such plots, one can interpolate the relative likelihoods of various types and magnitudes of eruption. Most individual volcanoes have too few known eruptions for magnitude–frequency relationships to be meaningful.
- At volcanoes for which there is a statistically apparent relationship between repose times and volume of the preceding and succeeding eruptions (simplest case, steady-state volcanism of Wadge 1982; Kuntz et al. 1986; Swanson and Holcomb 1990), probabilities of the likely magnitude (volume) of an impending eruption would be adjusted for time elapsed since the previous eruption and the volume of that previous eruption. An example from Kilauea and Mauna Loa is described by King (1989).

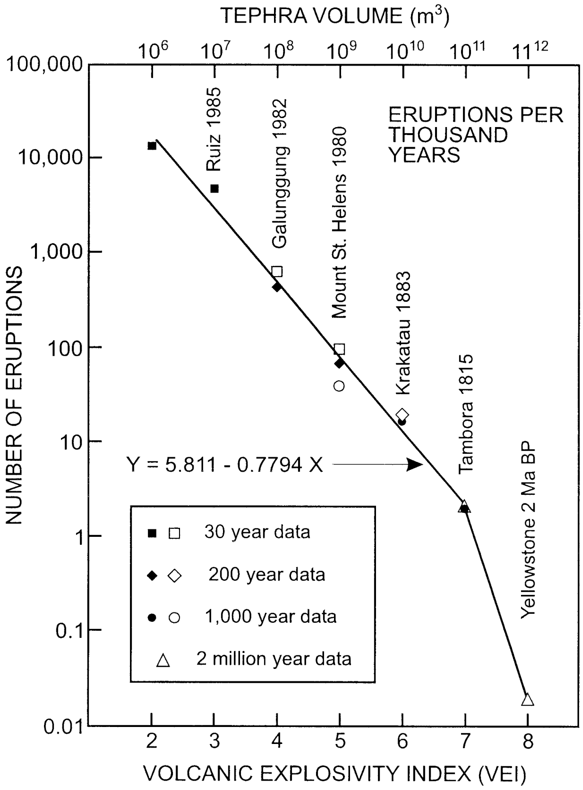


Fig. 2 Explosive magnitude vs. frequency of Holocene eruptions, worldwide (Simkin and Siebert 1994). Best-fit line is determined by an exponential regression model for VEI 2–7 using data points that are filled. In the regression equation, Y=log (Number of eruptions/1000 yrs) and X=VEI

- Evidence of overpressures (and hence explosive potential), include:
  - seismic indicators of a pressurized conduit, e.g., deep and shallow low-frequency or hybrid events and strong low-frequency tremor; or
  - rapid acceleration of unrest (e.g., of seismic energy release, extrusion rate, ground deformation, or gas emission), suggesting rapid, accelerating magma ascent and probable buildup of gas overpressures.
- A large volume of uplift, and thus, by inference a large intrusion, might also increase the probability of a large eruption.
- Cautionary note: unusually strong seismicity (e.g., high M_{max} or cumulative energy of earthquakes) does not by itself indicate a large volume or notable pressurization of magma. The relationship between seismicity and intrusive volume is especially complicated if there is concurrent release of regional tectonic strain. A similar caution should be noted for high SO_2 emission: some of the highest known levels of SO_2 emission have been followed by disproportionately small eruptions, perhaps because rapid degassing prevented buildup of gas concentrations and overpressures.

Table 1 Probabilities of various eruptive phenomena, as a function of the volcanic explosivity index (VEI). Data are from Simkin and Siebert (1994) for subaerial eruptions in all regions of the world, during the period 1900–present. Counts courtesy of Lee Siebert, Smithsonian Institute. *n* Number of eruptions in each VEI category. *Pf* Pyroclastic flow; *lf* lava flow; *mf* mudflow (lahar)

	n	Tephra[a]	pf	lf	mf
VEI 0	145	0.0	0.0	0.95	0.05
VEI 1–2	2,049	0.95	0.05	0.25	0.05
VEI 3	329	1.0	0.35	0.6	0.25
VEI ≥4	62	1.0	0.7	0.45	0.55

[a] Assumed to equal the number of entries in Simkin and Siebert (1994) for “explosions”. By definition, events with VEI≥1 will produce tephra. The only explosive eruptions not counted as producing tephra are a few VEI 1 eruptions that produced less than 10^{-4} m^3 of pyroclastic debris and column heights <100 m

P*(5|4)*

Given an eruption of specified type or magnitude, what is the likelihood that specific volcanic phenomena (lava flows, lava domes, pyroclastic flows, pyroclastic surges, lahars, tephra fall and other hazards) will occur?

- From the geologic record, determine the relative frequencies of various flows, tephra fall of a given volume, and other hazards. If the geological record of the restless volcano is not known in detail, refer to Volcanoes of the World (Simkin and Siebert 1994) to estimate the historical frequency of each phenomenon in association with this type and magnitude of eruption, or the frequency for all historical volcanism (Table 1). To refine estimates, look for historical associations between particular patterns of unrest and specific eruptive phenomena (e.g., a correlation between banded tremor and base surge) to infer the probabilities of various volcanic phenomena.
- The probabilities of various phenomena will be no greater than the probabilities of logical requisites for each phenomenon, e.g., a high eruption column necessary for high-energy column collapse. Similarly, active dome growth is necessary for most dome collapse; rapid snowmelt, crater lake ejection, or heavy rainfall is needed for lahar generation; a sizeable sector collapse or dome collapse is needed for a laterally directed blast, and so on. Monitoring data can suggest specific processes, e.g., banded tremor suggests the possibility of boiling groundwater that can lead to phreatic or phreatomagmatic eruptions.
- For vertically directed explosive eruptions, gas content of the magma, vent diameter, and exit velocity (and thus mass-discharge rate) control most of the volcanic phenomena that will result (Sparks and Wilson 1976; Carey and Sigurdsson 1989; Neri and Dobran 1994). Up to a point, increasing magma discharge rate promotes a buoyant column. A further increase in magma discharge rate or an increase in vent radius will push a buoyant column towards column collapse, as will a de-

crease in water or exit velocity. Because the interior of an eruption column can be rising while an outer ring is collapsing, tephra fall and pyroclastic flows can occur simultaneously.

P*(6|5)*

Given a specific phenomenon, what is the likelihood that it will move into a specified radial sector around the volcano?

- For flowage phenomena (lavas, pyroclastic flows and surges, debris avalanches, lahars, dense CO_2 gas), use the sector distribution attained by past flows. Because CO_2 flows leave no permanent deposit, their prior paths will be recorded only in historical data. Provided that topography has not changed substantially, the azimuthal or sector distribution of past flows will indicate the likely effect of local topography on future flow direction(s). Other controls on flow direction include microtopography of the crater rim, location of the vent relative to the rim, whether the crater fills to the point of sending flows in multiple directions, and downslope topography.
- Tephra will be carried by winds at the time of the eruption, sometimes in different directions at different elevations. Although wind rose diagrams and climatologic data for a particular area define the statistically likely directions of tephra transport, the actual transport will depend solely on wind pattern at the time of eruption. This last point was emphasized when ash blew in statistically unlikely directions and caused damage at Mount St. Helens on 25 May 1980 (Sarna-Wojcicki et al. 1981) and at Mount Pinatubo on 15 June 1991 (Paladio-Melosantos et al. 1996).
- Volcanic phenomena can affect multiple sectors around a volcano simultaneously. In this paper, though, we limit discussion to the probabilities of death for individuals in single locations.

P*(7|6)*

Given occurrence of a phenomenon in the specified sector, what is the likelihood that it will reach to a specified distance? For example, given a (pyroclastic flow) in sector (A), what is the probability that it will travel 0–5, 5–10, 10–15, 15–20, and >20 km?

- Turn first to the past history of the specific volcano. However, be aware that thin, fine-grained (sandy or finer) deposits are easily eroded or bioturbated, so the actual distances traveled might be greater than are now discernible in the geologic record. Historical records may have better resolution, though, regrettably, few historical descriptions contain enough geographic landmarks for judging distance.
- The distance (L) reached by a pyroclastic flow or surge depends on the height (H) from which that flow originates, the volume (V) of that flow, duration or sustenance of flow, and the intervening topography (Hayashi and Self 1992; Sheridan and Macías 1995; Dade and Huppert 1998; Woods et al. 1998; Calder et al. 1999). H and V are influenced in turn by mass discharge rate and eruption duration. Table 2 A shows dependence of 159 pyroclastic flows on H, which, for this table, is the vertical distance from the summit to the toe of a flow. Flows that drop more than 2 km vertically reach about twice as far as flows with lesser vertical drops. Most small-volume pyroclastic flows (<0.1 km^3) have H/L ratios between 0.2 and 0.4; larger-volume flows have lower H/L ratios. In larger explosive eruptions, collapse occurs from heights above vents and thus L is longer than predicted from the height of the cone. Walker et al. (1995) caution that some pyroclastic flows may travel in waves and also override topography beyond predictions of simple H/L ratios.
- Where H is roughly constant, as at a dome that is shedding pyroclastic flows, V is the main determinant of L.
- Our approach for pyroclastic flows takes advantage of how flow mobility depends strongly on VEI (in turn reflecting mass discharge rate, the height of an eruption column, and V). Because we use VEI earlier in the event tree, for $P(4|3)$ and $P(5|4)$, we use it again here as the independent variable, from which L can be estimated. Based on 191 pyroclastic flows from eruptions of various VEI, Table 2 B gives empirical probabilities that flows from eruptions of various VEI will reach or exceed specified distances. Data were ranked from shortest to longest. Then, the probability of each cumulative rank m was calculated as $P(m)=m/(n+1)$, where n is the number of data points (Haan 1979). Curves were fit to the ranked data with a smoothing spline.
- Eventually, numerical modeling of pyroclastic flows and surges over specific topographic paths may give an independent, process-based estimate of likely flow reach (e.g., Sparks et al. 1978; Valentine and Wohletz 1989; Valentine et al. 1992; Dobran et al. 1994; Woods and Bursik 1994; Bursik and Woods 1996; Neri and Macedonio 1996; Freundt and Bursik 1998; Woods et al. 1998). Until such models are fully tested and available in an easy-to-use form, our admittedly simplistic empirical estimates will suffice.
- The run-out of debris avalanches depends strongly on H and to a lesser degree on V. Siebert (1996) reported that for volcanic debris avalanches of volume 0.1–1 km^3, H/L ranges from 0.09 to 0.18 and averages 0.13. For volcanic debris avalanches with V>1 km^3, H/L ranges from 0.04 to 0.13 and averages 0.09. Siebert's (1996) empirical regression line of H/L vs. volume can be used to forecast L when H and volume are assumed.
- The run-out distance of lahars varies greatly from a few kilometers to more than a hundred kilometers. Run-out is influenced by flow volume, clay content,

Table 2 Pyroclastic flow run-out exceedance probabilities as a function of **A** vertical drop, *H*, and flow type; **B** volcanic explosivity index (*VEI*) and vertical drop, *H*. *n*, number of pyroclastic flows in each *H*, flow type, and VEI group. The probabilities across the top of each table are exceedance probabilities, calculated using a Weibull procedure as described in Haan (1979). Values within the tables are distances from the vent, rounded to nearest 0.1 km. If *H* and flow type are known or assumed, use **A**; if VEI and *H* are known or assumed, use **B**. Whichever part of the table you use, find the distance of the town from the vent in the appropriate row. The probability that a flow will reach or exceed this distance is at the top of that column. Interpolate as needed. For example, if a block and ash flow drops 1.5 km, the probability that it will reach or exceed 8 km from the vent is 0.10. If a VEI 3 eruption (*H* unspecified) produces a pyroclastic flow, the probability that the flow will reach or exceed 8 km from the summit is about 0.28 (interpolated). A spreadsheet list of individual flows is available upon request

A Flows arranged according to vertical drop (primary sort), and type of flow (secondary sort, *in italics*). Other includes pumice flows, scoria flows, surges, blasts, and unspecified. Eruptions of VEI 6 and higher excluded

Vertical drop (*H*, in km)	*n*	Exceedance probability										
		0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.05
0<*H*≤1.0, all types	44	1.1 Km	1.5	2.1	2.8	3.5	4.2	5	5.9	7.4	15.1	19.4
Block and ash	*14*	*1.7*	*2.1*	*2.8*	*3.2*	*3.6*	*4*	*4.4*	*4.8*	*5.4*	*6.2*	*6.9*
Other	*30*	*1.1*	*1.4*	*1.8*	*2.5*	*3.3*	*4.3*	*5.5*	*7.1*	*12.6*	*18.3*	*27.0*
1.0<*H*≤1.9, all types	51	1.1	2.0	2.7	3.3	4.6	5.5	6.6	8.2	10.4	14.0	17.3
Block and ash	*18*	*0.9*	*1.3*	*1.9*	*2.5*	*3.0*	*3.6*	*4.3*	*5.1*	*6.2*	*8.0*	*10.0*
Other	*33*	*1.4*	*2.2*	*3.5*	*5.0*	*5.8*	*7.2*	*8.4*	*9.9*	*13.0*	*15.6*	*25.2*
H≥2.0, all types	63	4.3	4.7	5.6	6.4	7.3	8.3	9.5	11.0	12.8	16.2	21.9
Block and ash	*33*	*4.1*	*4.5*	*5.4*	*6.5*	*7.1*	*7.7*	*8.9*	*10.5*	*11.5*	*13.8*	*14.7*
Other	*30*	*4.3*	*4.8*	*5.8*	*6.7*	*7.6*	*8.9*	*10.5*	*12.3*	*16.1*	*21.9*	*29.1*

B Flows arranged according to VEI (primary sort) and vertical drop (secondary sort, *in italics*)

	n	Exceedance probability										
		0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.05
VEI 1–2, all *H*	78	1.1	1.5	2.3	3.0	3.7	4.4	5.3	6.3	7.3	9.9	11.8
H=0–1.0 km	*23*	*1.1*	*1.3*	*1.5*	*1.6*	*2.3*	*3.0*	*3.5*	*4.1*	*5.0*	*6.3*	
H=1.1–1.9 km	*24*	*0.9*	*1.1*	*2.0*	*2.4*	*2.8*	*3.1*	*3.4*	*4.6*	*5.2*	*5.9*	*9.0*
H≥2 km	*31*	*4.1*	*4.4*	*4.9*	*6.5*	*6.9*	*7.2*	*7.4*	*8.2*	*10.5*	*11.9*	*13.5*
VEI 3, all *H*	31	3.0	3.9	4.7	5.2	5.6	6.0	6.6	7.6	9.5	13.1	16.9
H=0–1.0	*8*			*3.6*	*3.9*	*4.6*	*5.2*	*5.4*	*5.6*	*5.8*		
H=1.1–1.9	*7*			*3.9*	*5.5*	*6.0*	*6.5*	*6.9*	*7.3*	*7.7*		
H≥2 km	*16*	*4.6*	*4.8*	*5.2*	*5.8*	*6.5*	*7.6*	*9.0*	*10.9*	*12.8*	*14.5*	*15.2*
VEI 4–5, all *H*	49	2.7	4.4	7.2	8.6	9.9	11.1	12.5	14.5	17.7	24.9	31.3
H=0–1.0	*13*		*2.2*	*3.1*	*6.0*	*8.7*	*11.5*	*13.6*	*15.5*	*18.6*	*28.0*	
H=1.1–1.9	*20*	*3.1*	*4.1*	*6.5*	*8.2*	*8.6*	*9.5*	*11.8*	*13.3*	*14.8*	*21.0*	*34.2*
H≥2	*15*	*7.3*	*7.7*	*8.1*	*8.5*	*9.6*	*12.5*	*14.6*	*17.4*	*21.6*	*28.1*	*33.0*
VEI 6–8, *H* assumed >>2	33	11.0	16.1	22.7	30.4	40.0	47.0	52.6	58.6	67.2	95.9	122.9
All VEI 4 and higher, all *H*	82	3.7	6.2	8.8	10.8	13.3	16.8	21.1	32.5	49.3	63.0	88.8

degree of channelization, longitudinal profile, and perhaps temperature. Lahar hazard can actually increase for some distance away from a vent, if water and (or) sediment are still being added, but it then diminishes with further distance, especially if the peak discharge can be contained within existing channels (Pierson et al. 1990). Lahars that remain in their channels are of little immediate threat; those that overflow their banks are of great concern. Iverson et al. (1998) show how the (assumed) volume of a lahar (*V*) can be used to empirically forecast both cross-sectional area (*A*) and planimetric area (*B*) of inundation, according to the formulae $A=0.05V^{2/3}$ and $B=200V^{2/3}$. Figure 3 shows scatter plots of *A* and *B* vs. volume (Iverson et al. 1998). By assuming a volume, *A* and *B* and a digital elevation model can be used to predict the inundation area and hence run-out distance in a specific drainage.

- Numerical models (see Pareschi 1996; Costa 1997; Denlinger and Iverson 2001; Iverson and Denlinger 2001) can also route a lahar down rivers with known slopes and cross sections, but cannot adequately predict addition or subtraction of sediment enroute, and the corresponding influence on run-out distance.
- The distance reached by a lava flow is a function of slope, viscosity, supply rate(s), and supply duration. Numerical models for lava flows allow estimates of maximum potential flow length and reductions in that length in the event of loss of channelization of the lava (Ishihara et al. 1990; Wadge et al 1994; Kilburn 1996). Hallworth et al. (1987) and Griffiths and Fink (1992a, 1992b) offer laboratory models of lava flows.
- At some volcanoes, including frequently active Kilauea Volcano, vent locations vary with time so our event tree scheme is less useful than a direct measure of the frequency with which a particular site has been

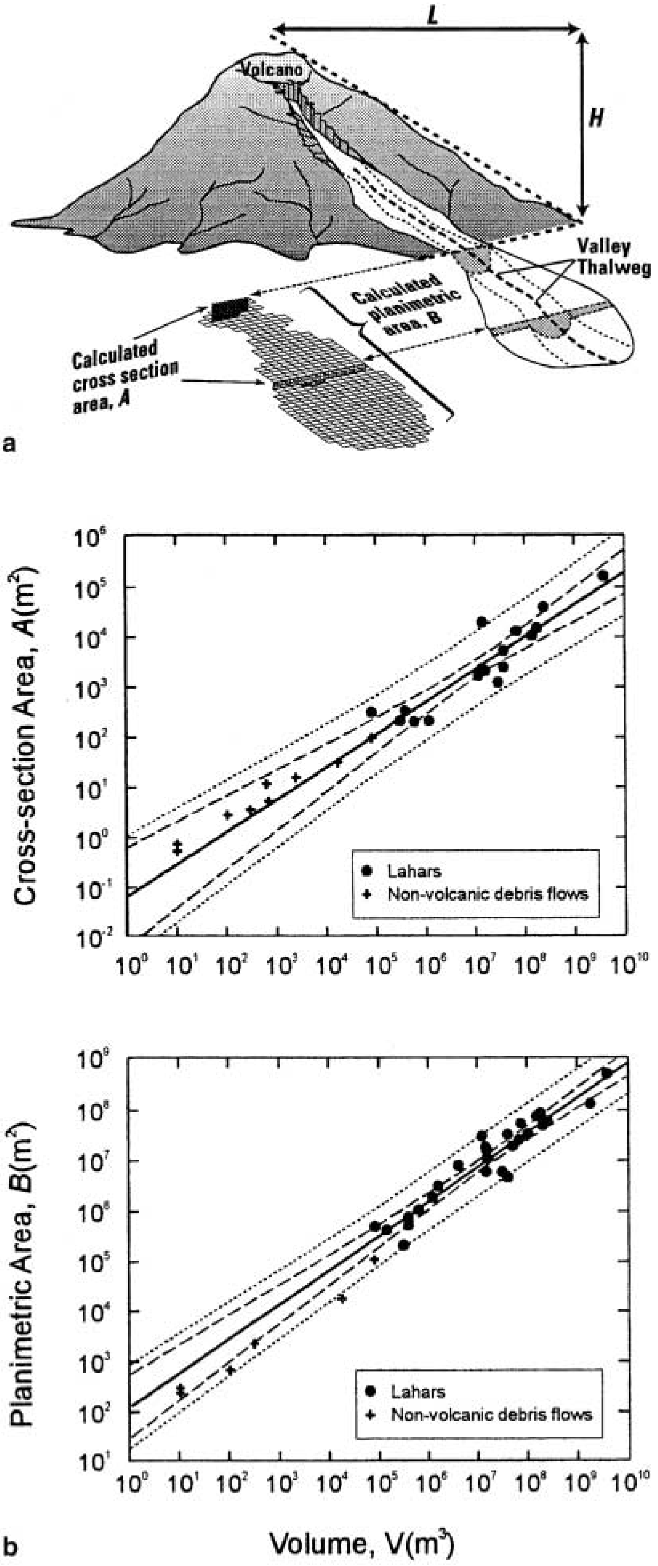


Fig. 3 Empirical method for estimating lahar inundation area and thus run-out distance in a specific drainage for which digital topography is available (from Iverson et al. 1998). **a** Parameters *L*, *H*, *A*, and *B* defined; **b** scatter plots of *A* and *B* vs. *V*, with 95% confidence intervals for regression (*dashed lines*) and prediction (*dotted lines*; Devore and Peck 1996). In practical usage, volume will be assumed; the cross-sectional area (*A*) and planimetric area (*B*) of inundation are functions of volume (*V*), as described in the text

inundated with lava. Long-term inundation probabilities can be updated by monitoring of seismicity and other indicators of where lava might be erupted, and by modeling of lava from a new vent across digital topography (Kauahikaua et al. 1998).

- Tephra fall usually thins downwind and becomes correspondingly less lethal, so concern for public safety is tied to the thickness vs. distance curve, and the distance over which fall deposits accumulate to thicknesses great enough to cause roof collapse. Probabilities that tephra fall will exceed a specified or critical thickness can be estimated statistically from isopach data on eruptions of various magnitudes (e.g., Hoblitt et al. 1987; Connor et al. 2001). Table 3, based on a worldwide sample and the same statistical method used for pyroclastic flows, shows tephra fall thicknesses that are exceeded in 5, 10... 95% of the instances of eruptions of the three explosive magnitudes we introduced in $P(4|3)$, namely VEI 1–2, VEI 3, and VEI 4. Within each part of Table 3, thickness–probability relations are given as a function of distance from the vent. Most deaths from tephra are from roof collapse, and >5 cm of wet ash or >10 cm of dry ash can cause some roofs to collapse, so users might want to check exceedance probabilities of those thicknesses at the distance(s) and VEI's of concern. The tendency for large eruptions to be better reported than small eruptions biases the data of Table 3 toward larger eruptions within each VEI group. Estimates of thicknesses and probabilities err conservatively, therefore, on the side of safety.
- Predictions of the probable time, thickness, and grain sizes of fallout can also be modeled if there is information about column height, wind speed, initial grain-size distribution, and particle densities (e.g., Carey 1996; Carey et al. 1996; Sparks et al. 1997; Hill et al. 1998; Hurst and Turner 1999). The Ashfall model of Hurst and Turner (1999) can be interfaced with real-time meteorological and eruption data to re-estimate tephra fall probabilities during eruptions.
- Tephra that rises into flight paths and remains there threatens aircraft. The advancing geographic footprint of an ash plume, and concentrations of ash in that plume, can be modeled by one of a number of programs, e.g., the VAFTAD program of Heffter and Stunder (1993), and measured in near real-time by remote sensing techniques. In this paper, we do not estimate probabilities for ash in flight lines, or resulting damage, but the general event tree approach of this paper could be applied to ash-aircraft hazards as well.

Individual risk estimation

P*(8|7): exposure*

Given that phenomenon *X* affects a specified site (sector and distance), what is the likelihood that an individual will be present? Within this general question we consider

Table 3 Exceedance probabilities of tephra fall thickness (cm) along axis, as a function of VEI and distance (km) from the vent. Number of tephra falls within each VEI group is shown in parenthesis. For each VEI and distance down axis (in km), thicknesses are shown within the table and their probabilities of exceedance are shown across the top of each column. To estimate the probability that as much or more than *X* cm of tephra will fall at a specified distance, assume a VEI. Then, for the specified distance and VEI, find *X* cm in the appropriate part of the table. The probability of exceedance is at the top of that column. For example, the probability that at least 6 cm of tephra would fall 30 km down axis from a VEI 3 eruption is 0.2, and the probability that at least 0.2 cm of tephra would fall 5 km downwind from a VEI 1-2 eruption is 0.8. A spreadsheet list of individual tephra layers is available upon request

For eruptions of VEI ≥4 (*n*=86, including 32 VEI=4, 29 VEI=5, 22 VEI=6, 2 VEI=7, and 1 VEI=8)

Distance (km)	Exceedance Probability										
	0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.05
5	11.5	18.9	34.4	52.8	76.2	107.2	150.9	217.6	333.8	604.3	986.4
10	6.2	12.0	28.0	35.7	41.6	55.3	99.1	159.7	235.1	416.7	619.7
15	5.6	9.6	18.3	24.0	29.8	34.2	49.1	114.0	162.0	296.3	392.9
20	3.0	5.5	11.0	17.4	22.9	29.5	71.9	118.3	199.5	262.6	326.8
30	2.8	5.2	9.4	15.3	18.4	39.8	76.6	102.0	153.4	210.8	374.9
40	1.6	2.4	5.4	11.6	15.4	26.7	58.7	95.8	114.1	231.4	440.3
50	1.3	3.2	7.3	11.6	17.0	28.1	45.9	70.0	108.8	199.8	372.5
100	0.4	1.6	3.9	6.4	9.1	12.4	16.7	23.3	35.6	70.9	140.2
200	0.1	0.4	2.2	3.7	5.4	6.8	8.5	14.1	32.6	59.1	87.1

For eruptions of VEI 3 (*n*=39)

Distance (km)	Exceedance Probability										
	0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.05
5	0.7	1.9	3.1	4.9	8.6	11.2	15.2	36.4	49.5	81.6	123.5
10	0.2	0.7	1.8	3.1	4.8	7.1	10.4	15.3	23.6	40.8	58.6
15	0.1	0.2	0.9	1.4	2.4	4.4	8.3	10.7	14.4	33.5	51.3
20	0.1	0.1	0.5	1.0	1.2	2.5	4.0	6.8	11.9	19.4	28.2
30	0.1	0.2	0.4	0.6	1.0	1.5	2.2	3.5	6.0	13.5	28.4
40	0.1	0.1	0.3	0.4	0.6	0.9	1.3	2.2	5.3	10.1	
50	0.0	0.1	0.1	0.2	0.4	0.5	0.8	1.3	2.3	5.9	
100	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5	0.8	1.9	
200				0.0	0.1	0.1	0.1	0.1			

For eruptions of VEI 1–2 (*n*=29, including 10 VEI=1 and 19 VEI=2)

Distance (km)	Exceedance Probability										
	0.95	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.05
5	0.0	0.1	0.2	0.3	0.4	0.7	1.2	2.6	4.7	9.0	17.5
10	0.1	0.1	0.2	0.3	0.5	0.8	1.3	2.0	3.0	4.5	5.4
15	0.1	0.1	0.2	0.4	0.6	0.8	1.0	1.4	2.0	4.2	
20	0.0	0.1	0.1	0.2	0.3	0.4	0.5	0.8	1.2	2.3	
30	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.7	2.2	
40	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.7	
50											
100											
200	Insufficient data										

two end member cases: (1) that no precautions will have been taken, regardless of warnings; and (2) that a warning and evacuation system is in place and will, in principle, be used.

- In case (1), which we call the “Harry Truman” case in honor of the late Harry Truman of Mount St. Helens, an individual’s exposure will depend solely on time that (s)he routinely spends in the hazardous area. We assume 1.0 for a fulltime resident, 0.25 for someone who works in the area but resides elsewhere, and much less for a tourist.
- In case (2), we start with the same routine occupancy as above but multiply by the probability of unsuccessful warning and evacuation. The latter can be estimated from past performance of the scientific team and past experience with other volcano-induced evacuations in the same culture and political setting. Research into the controls on successful forecasts and on individuals’ and community reactions to warnings might also be used. With good warnings and both readiness and willingness to evacuate, the probability of exposure of people and mobile property may drop almost to 0.

P*(9|8): vulnerability*

Given that an individual is present when the hazard arrives, what is the probability that (s)he would be killed by that hazard?

- Much is known about impacts of various volcanic phenomena (Blong 1984, 1996; Baxter 1990). Some simple rules of thumb include: (1) people and structures reached by pyroclastic flows or surges almost never survive, i.e., their vulnerability is nearly 1.0 except perhaps in the distal few tens of meters of a flow or in exceptionally good shelter; (2) vulnerability to lahars is nearly 1.0 in an active channel, but can decrease outside that channel if sturdy, multistory buildings are present and if the lahar does not completely bury those buildings; (3) people can escape from all but the fastest lava flows; and (4) people are rarely killed directly by tephra fall, but are vulnerable if they take shelter in buildings and the load of tephra fall on the roofs exceeds the bearing strength of the roof (sometimes as low as 100 kg/m^2, or as little as 10 cm of dry ash or 5 cm of wet ash).
- Short-term individual risk from tephra fall decreases sharply if one stays away from roofs and tree branches that can collapse; cars are good shelters from tephra fall. Long-term individual risk from fine ash is still the subject of research (Buist and Bernstein 1986; Baxter et al. 1999).

With *P*(9|8), we finish estimation of individual risk, the probability that an individual would be killed at a specific point around the volcano. Estimation of community risk, the amount of probable loss, requires an additional factor called “value,” for the equation: *risk*=*hazard*×*value*×*vulnerability* (Fournier d’Albe 1979).

For a community, “value” would be the number of people or the cost of property at risk. Calculation of community risk is beyond the scope of this paper.

An illustrative example

A common question that volcanologists face is, “How much danger would I face if I were to stay in my town?” The answer will depend greatly on the state of the volcano, location of the town, and existence and use of a warning system. Here is how we would answer this question for a hypothetical 3,100-m-high andesitic stratovolcano Montaña, a hypothetical town Población (Fig. 4), and a hypothetical resident, Juan, with reference to steps in the event tree (Fig. 1). Consider a case in which Montaña has just begun to show unrest, so *P*(1)=1.

To estimate *P*(2|1), the conditional probability that a magmatic intrusion is causing this unrest, we rely mainly on monitoring data. The strongest evidence for magma would be high SO$_2$ emission, localized high rates of inflation, and occurrence of distinctive low-frequency earthquakes. In this early stage of unrest at Montaña, there might be no truly diagnostic evidence yet, so we might consider less reliable evidence such as the spatial and temporal patterns of seismicity. Let us assume that seismicity consists of high-frequency events at shallow depth beneath the summit of the cone, occurring in swarms rather than as a mainshock–aftershock sequence. This is certainly consistent with a magma intrusion, although not diagnostic of one, so we will guess that *P*(2|1) is roughly 0.5.

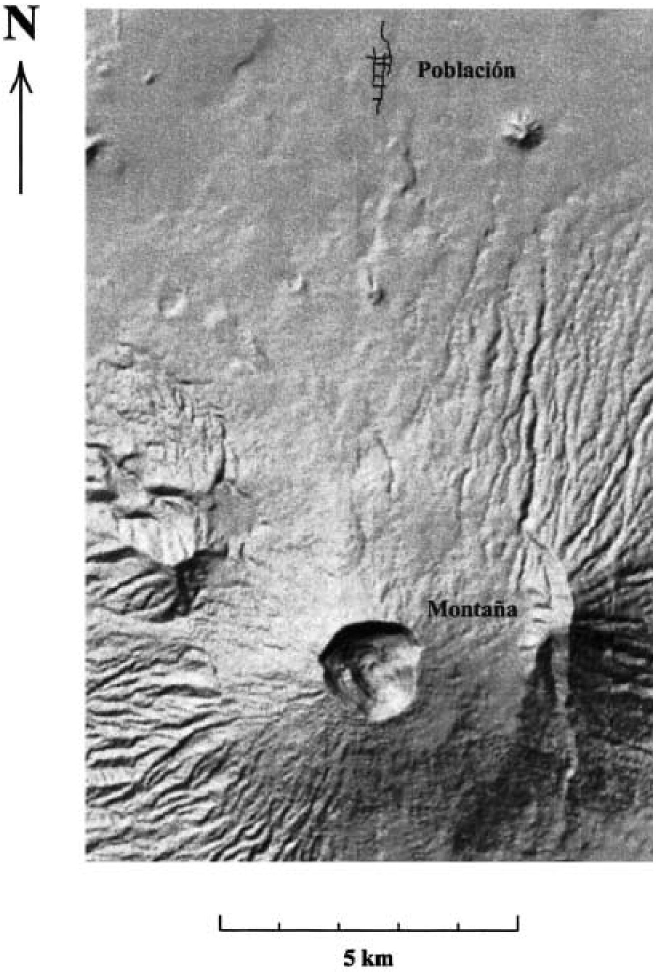


Fig. 4 Reference map for hypothetical Montaña Volcano and Población town (see section An illustrative example)

P(3|2), the probability that magmatic unrest will culminate in a magmatic eruption, is estimated by use of Eq. 2,

$$\mathrm{P}(3|2) = \frac{\mathrm{P}(2|3)(\mathrm{P}3)}{\mathrm{P}(2|3)(\mathrm{P}3) + \mathrm{P}(2|3')\mathrm{P}(3')}.$$

P(3) is the long-term eruption rate for Montaña. If eight magmatic eruptions have occurred in 400 years of recorded history (Table 4), the prior estimate of *P*(3)=0.02/year. *P*(2|3) is ~1.0 because it is virtually impossible for a magmatic eruption to occur without being preceded by some measure of magmatic unrest. *P*(2|3′),

Table 4 Incidence matrix for eruptions of hypothetical volcano, Montaña, based on its long-term eruptive history. Eight magmatic eruptions occurred in 400 years of recorded history; another eight episodes of magmatic unrest did not lead to eruptions

	Unrest (2)	No unrest (2′)	Total
Eruption (3)	8	0	8
No eruption (3′)	8	384	392
Total	16	384	400

the probability of unrest given no eruption, can be estimated from the particular volcano in question or from a large set of similar volcanoes. As noted earlier in discussion of data sources, roughly two in ten episodes of unrest at silicic centers and perhaps six in ten episodes of unrest at basaltic centers lead to eruptions. If Montaña is a typical andesitic stratocone, we might guess that its magmatic unrest will lead to eruptions or not with equal frequency. Thus, alongside the eight magmatic eruptions in 400 years, there might have been another eight episodes of magmatic unrest that did not lead to eruptions (Table 4). $P(2|3')$, the probability of unrest given no eruption, is thus 8/392. The probability of no eruption, $P(3')$, is 392/400.

Thus, $P(3|2)=(0.02\times1.0)/(0.02\times1.0+0.02)=0.02/0.04=0.5$. Note that this is 25 times the prior estimate of $P(3)$. Had the false alarm rate been higher or had eruptions of Montaña been less frequent, the increase in $P(3|2)$ over $P(3)$ would have been much smaller.

$P(4|3)$, the probability that an eruption will be of a certain magnitude, will be judged from the historical record, from the latest repose period, and from monitoring (especially, if there is any evidence of rapid magma ascent). Let us say for this example that most eruptions of Montaña are of VEI 2, with a known range from VEI 1–5, and that the long-term probabilities of $P(4|3)$ were 0.1 for VEI 0, 0.1 for VEI 1, 0.6 for VEI 2, 0.15 for VEI 3, and 0.05 for VEI ≥4. Current unrest is not old enough to suggest any deviation from typical behavior of Montaña. If, over the next few weeks, SO_2 emission were to double, low-frequency seismicity were to extend from 1–6 km below the surface, and deformation were to suggest a strong pressure source at 3 km depth, we would adjust the probabilities of VEI 3 and VEI ≥4 upward to reflect VEIs that follow rapidly developing unrest at other, similar stratovolcanoes.

$P(5|4)$, the probability of a specific eruptive phenomenon, will depend on the VEI. Because there are many non-exclusive possibilities here and in the next two steps, we will illustrate with just one scenario – of a VEI 3 eruption and a pyroclastic flow reaching Población, 10 km north of the summit. Nearly every VEI 3 eruption of Montaña produces pyroclastics flows, so $P(5|4_{\mathrm{VEI\ 3}})$ will be high, say 0.9.

$P(6_N|5_{pf})$, the probability that a pyroclastic flow will travel north toward Población, will be determined largely by the macro- and microtopography of the crater rim. Let's say that the rim is 50 m lower on its west side than on all other sides. $P(6_N|5_{pf})$ will be relatively low, perhaps 0.3. If this were a VEI 2 eruption, the chance of a pyroclastic flow reaching over the north rim would be even smaller; if it were a VEI 4 eruption, the small difference in crater rim topography probably would not prevent flows to the north, so $P(6_N|5_{pf})$ would be large, perhaps 0.8 or 0.9. Direction of flow is further influenced by macrotopography of the flanks, especially the course of deep valleys.

$P(7_{10}|6_N)$ will be the probability that the pyroclastic flow will travel ≥10 km, and thus reach Población. From Table 2 A, based mainly on H, we could estimate a probability of 0.3 to 0.4. A better estimate can be made by combining VEI and H (Table 2 B). If the eruption is of VEI 1–2, there is a ~0.1 probability that a northward-bound pyroclastic flow would reach Población. If the eruption is of VEI 3 that probability rises slightly, to about 0.2. And if the eruption is of VEI ≥4 that probability rises to 0.7 or higher.

$P(8|7_{10})$ is the probability that Juan will be present in Población in the event that a pyroclastic flow reaches the town. This probability depends on his normal schedule, the warning system, and his willingness to heed warnings. Let us assume that Juan is normally present in Población 100% of the time but is willing to move if warned, and that there is a 50% chance that a warning would reach him early enough for him to move to safety. Thus, his exposure $P(8|7)$ is 0.5. If he were to evacuate before an eruption, his exposure would be near zero.

$P(9|8)$, vulnerability, is the probability that if Juan is caught in Población by a pyroclastic flow, he will be killed. For pyroclastic flows this number is high, typically >0.9. Here, let's assume 0.95.

Now, let us answer Juan's original question of how much risk he faces by staying in Población if unrest continues and if we are concerned only about the possibility of a moderately large VEI 3 eruption that produces a pyroclastic flow.

$P(1)$ is 1.0 and does not affect the calculation, so we start with $P(2|1)$ and multiply through to $P(9|8)$:

$$\begin{aligned}\mathrm{P}\left(\mathrm{death}_{\mathrm{VEI3,pf}}\right) &= \mathrm{P}(2|1)\cdot\mathrm{P}(3|2)\cdot\mathrm{P}(4|3)\cdot\mathrm{P}(5|4_{\mathrm{VEI3}})\\ &\quad\cdot\mathrm{P}\left(6_{\mathrm{N}}|5_{\mathrm{pf}}\right)\cdot\mathrm{P}(7_{10}|6_{\mathrm{N}})\\ &\quad\cdot\mathrm{P}(8|7)\cdot\mathrm{P}(9|8)\\ &= 0.5\cdot0.5\cdot0.15\cdot0.9\\ &\quad\cdot0.3\cdot0.2\cdot0.5\cdot0.95\approx0.001/\mathrm{year}\end{aligned}$$

$P(death,_{\mathrm{VEI\ 3},pf})$ is Juan's chance of being killed in Población by a pyroclastic flow from a VEI 3 eruption. To be complete, we should include risks from pyroclastic flows during VEI 2 and VEI ≥4 eruptions, $P(death_{\mathrm{VEI\ 2},pf})$ and $P(death_{\mathrm{VEI\ 4+},pf})$. Those can be summed, because the VEI categories are mutually exclusive. Call the collective probability of being killed by a pyroclastic flow $P(A)$. We should also include risks from other eruptive phenomena, e.g., lahars and tephra fall, which we might symbolize as $P(B)$ and $P(C)$, respectively. Here, because the various eruptive phenomena are not mutually exclusive and because Juan cannot be killed twice, we must subtract out overlap. The general equation for estimating the probability of *A* or *B* or *C* is

$$\begin{aligned}\mathrm{P}(\mathrm{A}\cup\mathrm{B}\cup\mathrm{C}) &= [\mathrm{P}(\mathrm{A})+\mathrm{P}(\mathrm{B})+\mathrm{P}(\mathrm{C})-\mathrm{P}(\mathrm{A}\cap\mathrm{B})\\ &\quad -\mathrm{P}(\mathrm{A}\cap\mathrm{C})-\mathrm{P}(\mathrm{B}\cap\mathrm{C})+\mathrm{P}(\mathrm{A}\cap\mathrm{B}\cap\mathrm{C})]\\ &= \mathrm{P}(\mathrm{A})+\mathrm{P}(\mathrm{B})+\mathrm{P}(\mathrm{C})-\mathrm{P}(\mathrm{A})\mathrm{P}(\mathrm{B})\\ &\quad -\mathrm{P}(\mathrm{A})\mathrm{P}(\mathrm{C})-\mathrm{P}(\mathrm{B})\mathrm{P}(\mathrm{C})\\ &\quad +\mathrm{P}(\mathrm{A})\mathrm{P}(\mathrm{B})\mathrm{P}(\mathrm{C})\,. \end{aligned} \tag{3}$$

In practice, if these probabilities are small and/or approximate, one can ignore the unions ($\cap$'s) and still retain the right order of magnitude, i.e.,

$$\mathrm{P}(\mathrm{A}\cup\mathrm{B}\cup\mathrm{C}) \cong \mathrm{P}(\mathrm{A})+\mathrm{P}(\mathrm{B})+\mathrm{P}(\mathrm{C}). \tag{4}$$

Because we carried the calculation all the way through to individual risk, $P(A)$ or $P(A\cup B\cup C)$ can be compared with actuarial data on more familiar occupational or lifestyle related risks (Table 5). In our example, $P(death_{\mathrm{VEI}\ 3,pf})$ during unrest is of the same order of magnitude as risks of working in a high-risk occupation such as logging (US Bureau of Labor Statistics, annual reports). Potential uses and limitations of this information are discussed below, under the section Acceptable risk.

Table 5 Annual risks of death, listed by age group, occupation, disease, and accidents

	Risk of death, any cause, by age[a]	Risk of death in various occupations[b]	Risk of death by disease[c]	Risk of death, accidents[d]
10^{-0}				
	Age 90 (2×10^{-1})			
10^{-1}				
	Age 80 (6×10^{-2})			
		US Forces in WWII, Korea, Vietnam ($2\text{-}5\times10^{-2}$)		
10^{-2}	Age 60 (1×10^{-2})		Drug abuse (8×10^{-3})	
	Age 50 (5×10^{-3})	Helicopter pilots (6×10^{-3})	Smoking (5×10^{-3})	
		Deep sea fishing (3×10^{-3})	Cardiovascular disease (3.5×10^{-3})	
	Age 40 (2×10^{-3})		Cancer (2×10^{-3})	
			AIDS in sub-Saharan Africa (1.5×10^{-3})	
		Logging (1.3×10^{-3})		
10^{-3}	Age 20 (1×10^{-3})			
		Mining and quarrying (2.5×10^{-4})		All accidents, US (3.4×10^{-4})
		Agriculture (2.1×10^{-4})		All accidents Australia (2.5×10^{-4})
		Law enforcement (2×10^{-4})		
		Construction (1.5×10^{-4})		Car accidents (1.5×10^{-4})
		Transport & utilities (1.2×10^{-4})		
10^{-4}			AIDS in industrial countries (1×10^{-4})	
		All workers (4.5×10^{-5})		Accidental falls (6.1×10^{-5})
		Retail&wholesale trade (3.0×10^{-5})		
		Manufacturing (3.0×10^{-5})		
		Government (3.0×10^{-5})		
				Drowning (1.5×10^{-5})
10^{-5}				
				Firearm accidents (3×10^{-6})
				Floods, world (2×10^{-6})
10^{-6}				Tornadoes, U.S. (1×10^{-6})
				Hurricanes, U.S. (5×10^{-7})
10^{-7}				Eruptions (world) (1×10^{-7})

[a] For U.S., 1979-1997, from http://wonder.cdc.gov/mortJ.shtml

[b] Most data from U.S. Dept. of Labor, Bureau of Labor Statistics, Fatal occupational injuries by occupation and major event or exposure, 1998 (U.S.) Values for WWI, helicopter pilots, and logging are as of 1985. Deep-sea fishing statistic is from Pochin (1975)

[c] Most data from Centers for Disease Control, Atlanta. Deaths, Crude Death Rates, and Percent of Deaths for 72 Selected Causes, United States, 1995-1997. Value for smoking from Starr (1969). Values for AIDS from World Health Organization

[d] Most data from National Safety Council, Injury Facts, 1999 edition (U.S.)

Uncertainty in estimates of probability

Scientific honesty and our ethical responsibility to those at risk demand that uncertainties in probability estimates be acknowledged and, if possible, quantified. Here are three possible approaches.

The first is to use different but equally applicable subsets of data to estimate probabilities. Data could be from multiple events at the volcano in question, or from a global sample, or both. Because the number of data sets and thus different estimates of probability is usually small, a standard deviation of estimates may be unreliable but the range of plausible values will be seen.

The second method is for one or a few scientists to estimate approximate uncertainty using their own sense of process and history. This is a subjective estimate, but, if the scientists are experienced and question their own estimates, the result may be as good as any other.

The third method is similar except that it uses a larger set of expert estimates of the mean probability. Uncertainty is defined by the 2σ range of expert estimates. Two variants of this approach are discussed by Coppersmith and Youngs (1990), Aspinall and Woo (1994), and Aspinall and Cooke (1998). Aspinall and co-workers also asked experts to estimate their own uncertainty by indicating the lowest and highest values they deemed reasonable.

Each of the preceding methods can give the uncertainty of probability estimate at single levels in the tree, $P(1)$, $P(2|1)...P(n|n–1)$. Assuming that error at each level is independent of error at previous and later levels, the composite uncertainty from a string of uncertain conditional probabilities is calculated by the formula (Bevington and Robinson 1992, p. 46):

$$\sigma_{\mathrm{P}}^2 = \mathrm{P}^2 \left[\frac{\sigma^2_{\mathrm{P}(1)}}{\mathrm{P}(1)^2} + \frac{\sigma^2_{\mathrm{P}(2|1)}}{\mathrm{P}(2|1)^2} + \cdots + \frac{\sigma^2_{\mathrm{P}(n|n-1)}}{\mathrm{P}(n|n-1)^2} \right], \qquad (5)$$

where P is the composite probability and σ_P is the composite uncertainty in that estimate.

In our experience, when we intentionally play devil's advocate and bias estimates up or down, we can change final results by more than an order of magnitude. However, when we limit our assumptions to those that we think are really likely, the final results are usually within a single order of magnitude, which, we think, is about the same resolution as most individual's decisions about acceptable risk.

Estimated vs. acceptable individual risk

Individual volcanic risk can be compared with other more familiar risks. Table 5, from actuarial and other databases, quantifies familiar risks. The most reliable comparisons are between similar risks, e.g., between risks from various natural hazards. Be very careful if comparing dissimilar risks (Covello et al. 1988; Finkel 1996): Covello et al. warn that "use of (risk comparisons)... can severely damage your credibility." Many problems in the past have arisen from comparison of involuntary vs. voluntary risks, particularly when a business or government is proposing to impose a risk that it has compared with voluntary risks. Volcanic events are rather different, and not subject to human control. In our experience, comparisons between volcanic and more familiar risks are welcomed for reference by officials and by residents, provided that the necessary cautions are given.

Tolerance for risk varies widely. In the UK, individuals commonly accept risks of death of up to 1 in 1,000 per year if there are benefits to taking that risk, but generally avoid risks of 1 in 100 per year or higher (Chief Medical Officer 1996). Some individuals will conclude that if their personal risk from the volcano is no higher than another acceptable risk, then the volcanic risk is also acceptable. Others might prefer to add the volcanic risk to their other risks, and then decide whether the new cumulative risk is acceptable. One of the major determinants of tolerance is the personal value of accepting that risk. Often, there is a tradeoff between possible loss of life or limb and the costs of mitigation steps. For example, someone whose job requires work near a volcano might be willing to accept a high level of risk because, if (s)he chose to avoid that risk, (s)he would lose pay or even a job. Volcanologists are sometimes willing to accept high personal risk, if it means that others' lives may be saved. Almost always, people attach high value to being able to remain in their homes and communities, and are thus reluctant to evacuate. Indeed, some elderly residents have taken the position that "I'm going to die soon anyway, and I prefer to die in a place I love, that I've known all my life." On the other hand, a tourist might choose a low threshold of personal risk because any expected gain would not, for him or her, justify the added risk.

Because most judgments about acceptable risk (especially, of risk to life) are themselves imprecise, even order-of-magnitude uncertainty in estimating hazard and risk may be tolerable. This point was impressed upon the authors by public safety officials and loggers at Mount St. Helens. Geologists were initially reluctant to "put numbers" on hazards and risks because the data were sparse and uncertainties would be much higher than are normally acceptable in scientific argument. Practically none of our estimates would be statistically defensible. However, officials and loggers said that they were comfortable with high uncertainty and that any numbers that we geologists could provide would be better than any that they would estimate by themselves. Many other decisions they make involve equally high uncertainty.

In principle, if citizens or officials would define the level of individual risk that they will accept, volcanologists could then inform them when that level is met or exceeded. Clear definition of acceptable risk also lets volcanologists widen or narrow the time and (or) spatial windows of forecasts. Higher tolerance for risk of death gives volcanologists time to watch the volcano for a little longer, to gather more data, and thus to narrow eruption forecast window(s).

A common preference of public officials and some citizens (especially, businessmen), and indeed of some volcanologists too, is to defer any evacuation until an eruption is quite certain and imminent (i.e., until the forecast window is narrow). They prefer to wait until “the last minute” to evacuate, or to evacuate just beyond an optimistic, proximal line of safety. In this way political objections to evacuation are minimized, as are the chances of false alarms, but risk of death naturally increases. One reason that volcanologists and officials are reluctant to risk false alarms, aside from pride and legal challenges, is that citizens have a short tolerance for evacuations. If no eruption occurs immediately, citizens will return home and be unlikely to evacuate again even if warnings signs from the volcano increase. This awkward situation exists at this time of writing at Tungurahua Volcano, Ecuador.

Application to your volcano

Our generic tree is designed to be applicable at most volcanoes. However, some questions (levels of events) may need to be reformulated and some branches may need to be added at one or more levels to address the behavior of a specific volcano. As a rule, a tree should contain only those levels and branches that are needed to analyze and describe plausible pathways that the volcanic unrest might follow, and that public officials need for decisions about mitigation measures.

Much can be learned by sharing experiences from different situations. We invite IAVCEI’s Commission on the Mitigation of Volcanic Disasters to open a World-Wide Web site on which a variety of event trees could be examined, and from which one could link to helpful data sets.

Summary

An event tree can help volcanologists, individually or in teams, to think logically through all of the components of any hazard or risk assessment. The same framework is a useful tool for conveying hazards information to non-scientists, especially to officials responsible for public safety. Although probabilities and the tracking of probabilities through an event tree can on occasion seem complicated, officials who have studied them soon come to understand the components of hazards assessments better than they otherwise might, and understand the uncertainties in those estimates much better than they otherwise might.

Semi-quantitative estimates of hazard and risk allow individual citizens and their public officials to compare what are often unfamiliar volcanic risks with more familiar risks and to make calculated decisions about which risks to accept and which to actively mitigate.

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