UNITED STATES DEPARTMENT OF THE INTERIOR
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A METHOD FOR ESTIMATING INTERMEDIATE- AND LONG-TERM RISKS FROM VOLCANIC ACTIVITY, WITH AN EXAMPLE FROM MOUNT ST. HELENS, WASHINGTON

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards or nomenclature.

ABSTRACT

Volcanologists are often asked a question of the form, "What are the chances that a volcano will erupt within a specific time span or display a certain type of eruptive activity?" An answer could address any of three different time spans--short (hours to days), intermediate (weeks to months), and long (years to millenia), and it should describe the chances in terms that will be meaningful even if the questioner is not a volcanologist. This paper describes a method for quantifying intermediate and long-term probabilities of volcanic hazards, and translating these probabilities into estimates of risk comparable with those for more familiar risks. Though the estimates derived by this method include large uncertainties, they may help civil authorities determine whether a particular volcanic risk is acceptable, and what access and land use should be permitted.

The probability of a volcanic hazard (or the risk, where people and property are involved) can be estimated by multiplying the probability (P_1) of an initial volcanic event, E_1, by the conditional probabilities ($P_{2,3...n|1,2,...n-1}$) of increasingly specific derivative events, $E_{2,3,...n}$. Each conditional probability is the probability that event E_n will occur, given that event E_{n-1} has occurred.

The events to be considered for long- and intermediate-term estimates are

E_1 = the beginning of an eruptive period (i.e., a period of frequent eruptions, often extending over a decade or more, preceded and followed by repose periods of a decade or more);

E_2 = the beginning of an eruptive sequence (i.e., a sequence of eruptions without any repose that lasts longer than 6 months);

E_3 = the beginning of an eruption (i.e., days or weeks of explosive or non-explosive ejection of volcanic material onto the earth's surface, without any repose that lasts longer than 1 week);

$E_{4a,b,c}$ = a major-explosive eruption (defined here as producing 0.1 km^3 or more of pyroclastic ejecta), a minor-explosive eruption (producing less than 0.1 km^3 of pyroclastic ejecta), or a non-explosive eruption, respectively, where $E_{4a,b,c,}$ are mutually exclusive events;

E_{5a-g} = pyroclastic flows, mudflows, laterally directed blasts or pyroclastic surges, ballistic fragments, tephra fall, lava flows, and dangerous gas emissions;

E_{6a-g} = events 5_{a-g} that reach specified distances from the vent;

E_{7a-p} = events 6_{a-g} that affect any one of sixteen 22 1/2^o sectors around the volcano;

E_{8a-g} = events 7_{a-p} that affect a specific site; and

E_{9a-g} = events 8_{a-g} that are lethal at that site.

The probabilities of volcanic hazards can be calculated for a general event, e.g., an eruptive period (E_1); for moderately specific events, e.g., a pyroclastic flow anywhere around the volcano (E_{5a}); or for a very specific event, e.g., a pyroclastic flow that will be lethal at a specific location (E_{9a}). In each case,

$$P_n = P_1 \times P_{2|1} \cdots \times P_{n|n-1}.$$

To calculate volcanic risks associated with these events, we can further multiply by the probability of routine exposure to the risks (P_{10}) and the probability that an individual will remain in the area even when an eruption is imminent (P_{11}).

The calculations outlined here have been made for Mount St. Helens, using data from historic and prehistoric eruptions at St. Helens and similar volcanoes. Zones of equal risk have been plotted on a topographic map. Hazards and risks decrease gradationally away from the vent; within a radius of 30 km from the vent, they decrease more abruptly along high terrain than in valleys, and decrease by an average of about one order of magnitude for every 10 km of distance from the vent.

One challenge for future studies is to refine long- and intermediate-term probability estimates through a better understanding of the processes that control the timing and character of eruptions. Another is to use short- to intermediate-term geophysical and geochemical monitoring to re-estimate the probabilities of the same events within shorter time frames, as is often needed during an eruption sequence.

Introduction

Those who live or work near volcanoes, or who must make decisions about public access and land use, require quantitative information about volcanic hazards and risks in order to judge whether those risks are acceptable. This report describes a method for quantifying these hazards and risks. The method (a) identifies factors that determine hazards and risks, (b) allows the probabilities of various hazards to be compared with each other and between areas around a volcano, (c) allows estimates of the net risk from all volcanic hazards to human life, and (d) allows comparisons of volcanic risk with more familiar risks, such as those of selected occupations or everyday activities.

Volcanic hazards are volcanic phenomena (e.g., pyroclastic flows, ashfall) that pose a threat to persons or property. The U.S. Geological Survey has published much information about potential volcanic hazards in the Cascades, but neither the Survey nor others have published much information about probabilities of each type and magnitude of hazard.

Volcanic risks are the expected adverse effects of volcanic hazards on persons or property. For the most part, assessment of these effects is beyond the expertise of volcanologists, but in the interest of making hazard assessments more meaningful, this report will discuss the risk of immediate death from volcanic activity; other risks, to health and property, will not be discussed here.

Hazard and risk assessments can be made along several time scales: long-term (years to millenia), intermediate-term (weeks to months) and short-term (hours to days). Long-term assessments are based mainly on the eruptive history of a volcano, e.g., the report by Crandell and Mullineaux (1978) that presents a long-term hazard assessment for Mount St. Helens. Intermediate-term assessments are long-term assessments modified by information from studies of precursory or eruptive activity of the preceding weeks and months. Intermediate- and long-term assessments discuss the probable frequency and nature of future eruptions, but do not specifically forecast dates or types of eruptions. Specific short-term hazard assessments are based on monitoring data from the preceding hours, days and weeks, and they forecast events that are likely to occur within the next few hours, days or, occasionally, weeks. This report will address long-term and, to some extent, intermediate-term assessments; short- and more precise intermediate-term estimates must make use of geophysical and geochemical monitoring data as well as the known eruptive history of the volcano. Long-term hazard assessments might serve as baselines against which shorter-term assessments may be compared.

The primary purpose of this report is to set forth a method of quantifying intermediate and long-term volcanic hazards and risks; the report also estimates intermediate-term risks to life around Mount St. Helens as of February 1980, early June 1980, August 1981, and February 1982. Unless otherwise indicated, estimates given as examples are for February 1982 (Figures 1-4; Appendices 4-7). There have been significant changes in the estimates of both hazards and risks in the two years between February 1980 and February 1982, and there will be further changes as new events occur and as new discoveries about the volcano are made.

A method for estimating volcanic risks, with an example from Mount St. Helens

In order to calculate the probabilities of volcanic hazards, one can consider the probabilities of the following, increasingly specific events:

1. E_1--the beginning of an eruptive period (i.e., decades to centuries of relatively frequent volcanism that are preceded and followed by repose periods of a decade or more; at Mount St. Helens, recent eruptive periods are (roughly) from 1500 to 1650, 1800 to 1860, and from 1980 to the present)*;
2. E_2--the beginning of an eruptive sequence (i.e., a sequence of eruptions that lasts for a few weeks, months, or years without any pause longer than 6 months; e.g., 1980-81 and continuing);
3. E_3--the beginning of an eruption (i.e., ejection or outpouring of volcanic material that lasts for hours, days, or more without any pause longer than one week; e.g., eruptions of Mount St. Helens on 3/27/80, 5/18/80, 10/16/80-10/19/80, and 12/27/80-1/4/81);
4. E_4--a major-explosive eruption, E_{4a} (defined as one that produces a volume of pyroclastic ejecta equal to or greater than 0.1 km^3), a minor-explosive eruption, E_{4b} (one whose volume of pyroclastic ejecta less than 0.1 km^3), or a non-explosive eruption, E_{4c};
5. E_{5a-g}--a specific kind of eruptive activity (pyroclastic flow, mudflow, lateral blast or pyroclastic surge, ejection of ballistic fragments, tephra fall, lava flow, or dangerous gas emission; the letters a-g here correspond respectively to these phenomena);
6. E_{6a-g}--specified eruptive activity that reaches specified distances;
7. E_{7a-p}--specified eruptive activity that affects specified sectors around the volcano (the letters a-p correspond to sixteen 22 1/2° sectors);
8. E_{8a-g}--specified eruptive activity that affects a certain, relatively small site; and
9. E_{9a-g}--specified eruptive activity that is lethal at that site (recognizing that persons can move out of the way of slowly-moving phenomena).

To estimate volcanic risks, one may also need to consider the following events:

10. E_{10}--a person is routinely present in the hazardous area, and
11. E_{11}--a person will remain in the hazardous area at the time of eruption. If that person has a radio and a vehicle and is willing to leave, the probability of E_{11} is approximately equal to the probability that hazardous eruptions can be predicted more than two hours in advance.

*More complete listings of data for Mount St. Helens appear in Appendices 1 and 2.

Events $E_{2,3,...9}$ are conditional on prior events, i.e., they cannot occur until events $E_{1,2,...8}$ have occurred; events E_1, E_{10} and E_{11} are not conditional on prior events. Events E_6 and E_7 are interchangeable, but will be treated in the indicated order for the sake of convenience.

A conditional probability is the probability that a particular event will occur, given that a necessary prior event has already occurred. In conventional probability notation, the probability of event 2, if event 1 has occurred, is shown as $P_{2|1}$ (= $P\ E_2|E_1$). The probability (P_n) of any volcanic hazard (E_n) can be calculated from the probability (P_1) of an initial volcanic event, multiplied by the conditional probabilities ($P_{2,3...n|1,2,...n-1}$) of increasingly specific volcanic events $E_{2,3,...n}$. P_2 thus becomes the probability of E_1 and E_2, i.e., $P_1 \times P_{2|1}$. For whatever degree of specificity $\underline{n}$ that is required, P_n is the probability of events E_1 and E_2 and ... E_n, i.e., $P_1 \times P_{2|1} \times ... P_{n|n-1}$. P_1 and $P_{2|1, 3|2, ...9|8}$, are estimated from the frequencies of each event, $E_{n|n-1}$, at Mount St. Helens or at similar volcanoes elsewhere in the world.

Any P_n may be multiplied in turn by the probabilities of related events $E_{n+1...m}$, that are not strictly in the chain of volcanic events $E_{1,2...n}$ but that must be considered to calculate risks. For example, the probability that an individual will be killed by a specified kind of eruptive activity is $P_9 \times P_{10} \times P_{11}$. P_{10} is estimated on the basis of the percentage of time an individual routinely spends in the hazardous area, and P_{11} is estimated subjectively on the basis of an assessment of monitoring, warning and evacuation capabilities. Whenever an event E_n is in progress, the current probabilities of that event and those necessarily prior to it, $E_{1,2,...n-1}$, are equal to 1, as for example P_1 and P_2 equal 1 for Mount St. Helens at present.

Some mutually exclusive events can lead to the same result. For example, a pyroclastic flow (E_{5a}) can form during either a major- or a minor-explosive eruption (E_{4a} or E_{4b}). Similarly, a flowage hazard along any one river (e.g., along the Muddy River at Mount St. Helens) might arrive by way of any of several tributaries (e.g., Smith Creek, Pine Creek, Clearwater Creek at Mount St. Helens). As still another example of mutually exclusive events that can lead to the same result, a person might be killed by any of several volcanic hazards. The probabilities of the various mutually exclusive paths are summed so that, in the first example, $P_{5a} = [P_{4a} \times P_{5a|4a}] + [P_{4b} \times P_{5a|4b}]$.

$P_{3,4,...7|2,3,...6}$ and P_{11} depend on the "intermediate-term" state of the volcano -- the prevailing behavior of the volcano over the preceding weeks and months. Intermediate-term values for $P_{3,4,...7|2,3,...6}$ and P_{11} at Mount St. Helens are long-term values for those probabilities modified by the intermediate-term information. Given a range of possible values for each of these probabilities, relatively high or low values can be used, depending on what kind of activity -- major-explosive, minor-explosive or non-explosive --is considered to be the most likely, on the basis of recent eruptive trends, seismicity, deformation and other precursory activity. This is admittedly a crude approximation; additional study of observable and causal relations between eruptions and their precursors is needed before P_{3-7} and P_{11} can be properly quantified for short- and intermediate-term assessments.

As an example of how the values in Appendices 4-7 have been estimated, consider the intermediate-term probability, as of February 1982, that a person will be killed by a pyroclastic flow at the south shore of Spirit Lake. The probability of a pyroclastic flow on any given day from a major-explosive eruption of St. Helens is approximately .02 ($P_{3|2}$) x .05 ($P_{4a|3}$) x .75 ($P_{5a|4a}$) = .00075. The probability of a pyroclastic flow on any given day from a minor-explosive eruption at St. Helens is approximately .02 ($P_{3|2}$) x .20 ($P_{4b|3}$) x .38 ($P_{5a|4b}$) = .0015. The probability that the pyroclastic flow will reach to Spirit Lake (8 km north-northeast of the present vent) is approximately .0022 (P_{5a}) x 0.64 ($P_{6a|5a}$) x 0.3 ($P_{7a|6a}$) = .0004. If a given individual resides on the south shore of Spirit Lake and lacks means of communication and evacuation, his chance of being would be killed on any given day by a pyroclastic flow is approximately .0004 (P_{7a}) x .33 ($P_{8a|7a}$) x 1 ($P_{9a|8a}$) x 1 (P_{10}) x 1 (P_{11}) = .0001. The probability that this person would be killed by a pyroclastic flow within the next year is 1 minus the probability that he will not be killed by a pyroclastic flow in that same year, in 365 "trials", i.e., $1 - (1 - .0001)^{365} = 0.04$. His annual risk at that location from other volcanic events (mudflows, lateral blasts, ballistic fragments, tephra fall, lava flows, and dangerous gas emissions) is about 0.03, for an annual volcanic risk to life from all volcanic events of about 0.07.

If that person is in the area on a working schedule, eight hours per day, 220 days per year, if he has radio communications with the U.S. Geological Survey/University of Washington monitoring operation, and if he has a way to leave the area within about two hours, his average risk per day (from all volcanic activity) would be approximately .0002 (P_9) x .2 (P_{10}) x .01 (P_{11}) = .0000004. This is equivalent to an annual risk of $1 - (1 - .0000004)^{365} = .0002$, or roughly a two-in-one-thousand chance of being killed within the next year by volcanic activity.

The limitations of this approach are discussed in the next section. It is to be emphasized that these probabilities are very rough estimates; the actual probabilities may be at least an order of magnitude higher or lower than the value stated here.

Uncertainties in the estimates of volcanic risk

Several uncertainties are inherent in the probability estimates given here. The most serious point of uncertainty is that nearly all of the component probabilities (P_1, $P_{2,3,\ldots 9|1,2,\ldots 8}$, P_{10} and P_{11}) are calculated on the basis of a very small number of past events. Historical records at most volcanoes are short compared to the recurrence frequencies of volcanic events. Only a few volcanic events have occurred in the short recorded history of Mount St. Helens (limited to the 19th and 20th centuries). Similarly, only a few major volcanic eruptions have occurred at St. Helens in the last 1500 years; many other smaller eruptions probably occurred, but their deposits are either too indistinct to be recognized as products from discrete eruptions, or they have been eroded or buried. Our limited information about eruptions at Mount St. Helens, and even more limited information for many other volcanoes, can be supplemented from our knowledge of worldwide volcanism during historic time (Simkin and others, 1981). Worldwide data is especially useful when we know enough about an individual volcano to know which subsets of worldwide data to use, but not enough about the individual volcano for the known frequencies of its events to be meaningful by themselves. Because of these general limitations in the data, we can infer much about the types of events that have occurred at a volcano, less about their relative frequencies of occurrence, and least about their absolute frequencies.

A related uncertainty in these probability estimates comes from the fact that for steps 1-5 (above and Appendix 1) there are several different sets or subsets of data that might be used. Each different subset of data yields a different probability for that step. There is an element of subjectivity in the choice of an appropriate data set; the size, completeness, and aptness of each possible data set must be considered.

A third basis of uncertainty is that volcanic processes and the deeper structure of most volcanoes, including Mount St. Helens, are not well enough understood for us to know how the observed short- and intermediate-term changes in a given volcano's behavior affect the probabilities of various events. For example, the volumes of volcanic gases rising from St. Helens have decreased since the summer of 1980, apparently because the volatiles in the near-surface melt are becoming depleted (T. Casadevall, oral communication). We have no precise way of estimating the implications for P_3, P_4, and P_5 at St. Helens, and it will be even more difficult to asses the same probabilities at volcanoes that are less well understood than Mount St. Helens.

There are uncertainties affecting other steps, as follow.

1. At steps 2 and 3, if may be difficult to distinguish between "eruptive sequences" and "discrete eruptions". For Mount St. Helens, for example, the historical records of the 19th century are too poor to indicate whether there were 9 eruptive sequences between 1800 and 1857, or a smaller number of eruptive sequences and a larger number of discrete eruptions.

2. At steps 4 and 5, if the worldwide data base is used, an uncertainty results because those data usually refer to eruptive sequences rather than to discrete eruptions.

3. At step 5, it is difficult to distinguish between mudflow and pyroclastic flow deposits, as well as between deposits of discrete flows of the same origin.

4. At step 5, it is difficult to distinguish between surge deposits and deposits from the upper parts of pyroclastic flows ("ash-cloud deposits").

5. At steps 6 and 7, the sector can affect the distance factors. Because Mount St. Helens is breached on its north side, flowage hazards to the north are likely to be more severe and to extend farther than on other sides of the volcano.

6. At step 6, data sets are biased toward larger, better reported eruptions. We need to have separate distance factors for major- and minor-explosive eruptions; in this report, only tephra fall and lateral blasts have been assigned two sets of distance factors. For tephra fall, it is desirable to define thickness-vs.-distance curves for more homogeneous sets of eruptions, e.g. by considering eruptions grouped according to the Volcanic Explosivity Index (VEI) (Newhall and Self, 1982), rather than as simply "major-explosive" or "minor-explosive" eruptions.

7. At step 9, there are uncertainties about the severity of mudflows and heavy ashfall. Most immediate human mortality from ashfall appears to be limited to persons with pre-existing medical problems or to be an indirect effect of the ashfall (e.g., from traffic accidents, overloaded roofs or overloaded tree branches). The long-term health effects of volcanic activity are not addressed in the present discussion.

8. At step 11, an unknown percentage of persons in an area might leave, even without prediction and communication, before a volcanic event would affect their locations.

Because of these uncertainties in both the assumptions and the data base, probability estimates in this report should be regarded as "best guesses" to within about an order of magnitude. Simply by using other subsets of the data, estimates at least 10 times lower or higher than the values shown in Appendices 4-7 could be calculated. If, for example, a person's risk of being killed was estimated to be 0.01/year (1%/year), his actual risk might be as low as 0.001/year (0.1%/year) or even lower, or as high as 0.1/year (10%/year) or even higher. For the purposes of general planning, probabilities like those in Appendix 7 -- plus or minus one order of magnitude -- can be taken as useful best guesses. Where more precision is required, as for firm decisions about acceptable risk or for decisions about where to locate critical facilities, the estimates in this report will have to be refined further. Additional field observations and a better understanding of the volcanic processes will permit more precise probability estimates in the future. Probabilities can also be refined by considering several different probability models, but the current data are inadequate for this purpose. Given better data sets it will be useful to do so (Hewitt, 1969; see also Klein, 1982).

Summary of volcanic risks around Mount St. Helens

Figures 1-4 and Appendices 4-7 show the results of risk calculations for an individual who remains at a site for an entire year without provision for warning and evacuation (Case 1--"full-time hermit case"), and for an individual who works at a site on a typical work-schedule, at a place with provisions for warning and evacuation (Case 2--"typical worker case"). In Appendices 4-7, risks from volcanic hazards at Mount St. Helens are shown for pie-shaped blocks of the area, defined by distance and sector. Risks were calculated for the edge of each block nearest the volcano, resulting in step-like decreases in risk as we move away from the volcano. The decreases across any line are actually gradational, and the steps are only a matter of convenience for the calculations. In general, there is no significant difference in risk between any two nearby points separated by a zone boundary, whereas significant differences exist between the centers or opposite ends of two adjacent blocks.

Risk zone boundaries in figs. 1-4 do not follow the edges of pie-shaped blocks; rather, they have been adjusted for topography. Adjustments for valleys are based on the calculated risks from pyroclastic flows, mudflows, lava flows and volcanic gases, whereas adjustments for ridges are based on risks from lateral blasts or pyroclastic surges, ballistic fragments and tephra falls.

Some important features of Figures 1-4:

-- Volcanic risk varies by several orders of magnitude around the volcano, according to location. Some areas on the north and northwest sides of the volcano are as much as 1000 times riskier than some other areas at comparable distances from the vent. Valleys, especially those heading on Mount St. Helens, are more dangerous than ridges.

-- Risk is by far the highest near the volcano--from 10 to 10,000 times higher on the volcano's flanks than at a distance of about 20 km. There are some areas in which risk decreases abruptly with distance from the volcano, and other areas in which risk decreases more slowly. On the average, risk within 30 km of the vent decreases about one order of magnitude for every 10 km of distance from the vent.

-- There is no area on figs. 1-4 that has zero risk. Every area in those figures stands some volcanic risk, though in many areas that risk is very low.

Figures

Figure 1

Zones of volcanic risk at Mount St. Helens, February 1980. Annual risks of death from volcanic activity are approximately as follow: Zone A = 10^{-1}-10^{0}; Zone B = 10^{-2}-10^{-1}; Zone C = 10^{-3}-10^{-2}; Zone C = 10^{-4}-10^{-3}; Zone E = 10^{-5}-10^{-4}; Zone F = 10^{-6}-10^{-5}; Zone G = 10^{-7}-10^{-6}; Zone H = 10^{-8}-10^{-7}; Zone I = 10^{-9}-10^{-8}; Zone J = 10^{-10}-10^{-9}; Zone K = 10^{-11}-10^{-10}; Zone L = 10^{-12}-10^{-11}. Zones are labelled with two letters; the first represents the risk for Case 1 (full-time resident without radio), and the second, Case 2 (typical worker).

Figure 2

Zones of volcanic risk at Mount St. Helens, June 1980. For an explanation of the letters denoting each zone, see Fig. 1.

Figure 3

Zones of volcanic risk at Mount St. Helens, August 1981. For an explanation of the letters denoting each zone see Fig. 1.

Figure 4

Zones of volcanic risk at Mount St. Helens, February 1982. For an explanation of the letters denoting each zones of risk, see Fig. 1.

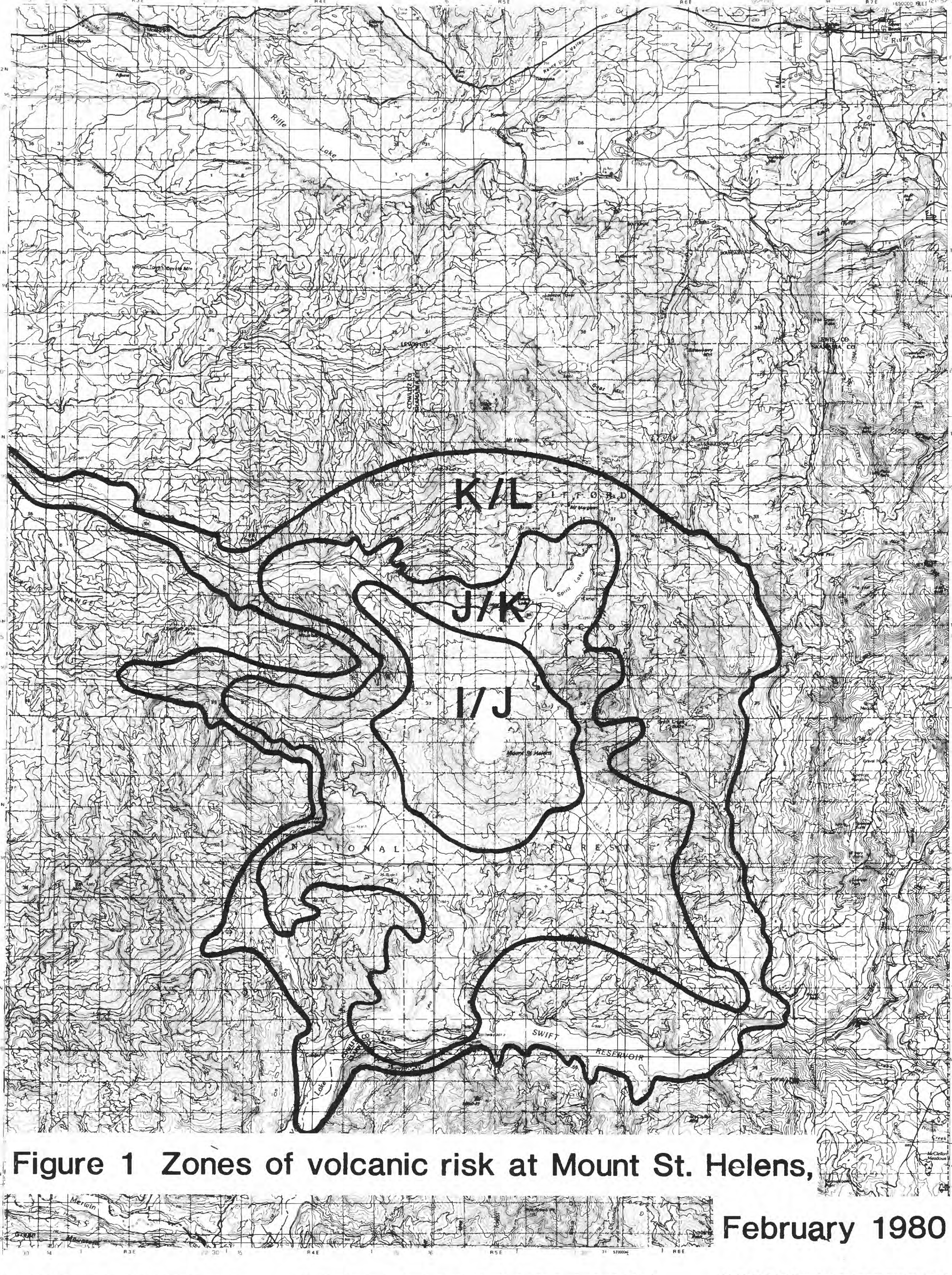

Figure 1 Zones of volcanic risk at Mount St. Helens, February 1980

Produced by the U.S. Geological Survey from 1:100 000-scale quadrangles
Projection and 10 000-meter grid, zone 10, Universal Transverse Mercator
25 000-foot grid ticks based on Washington coordinate system, south zone, and Oregon coordinate system, north zone
Road update furnished by Washington State Department of Natural Resources

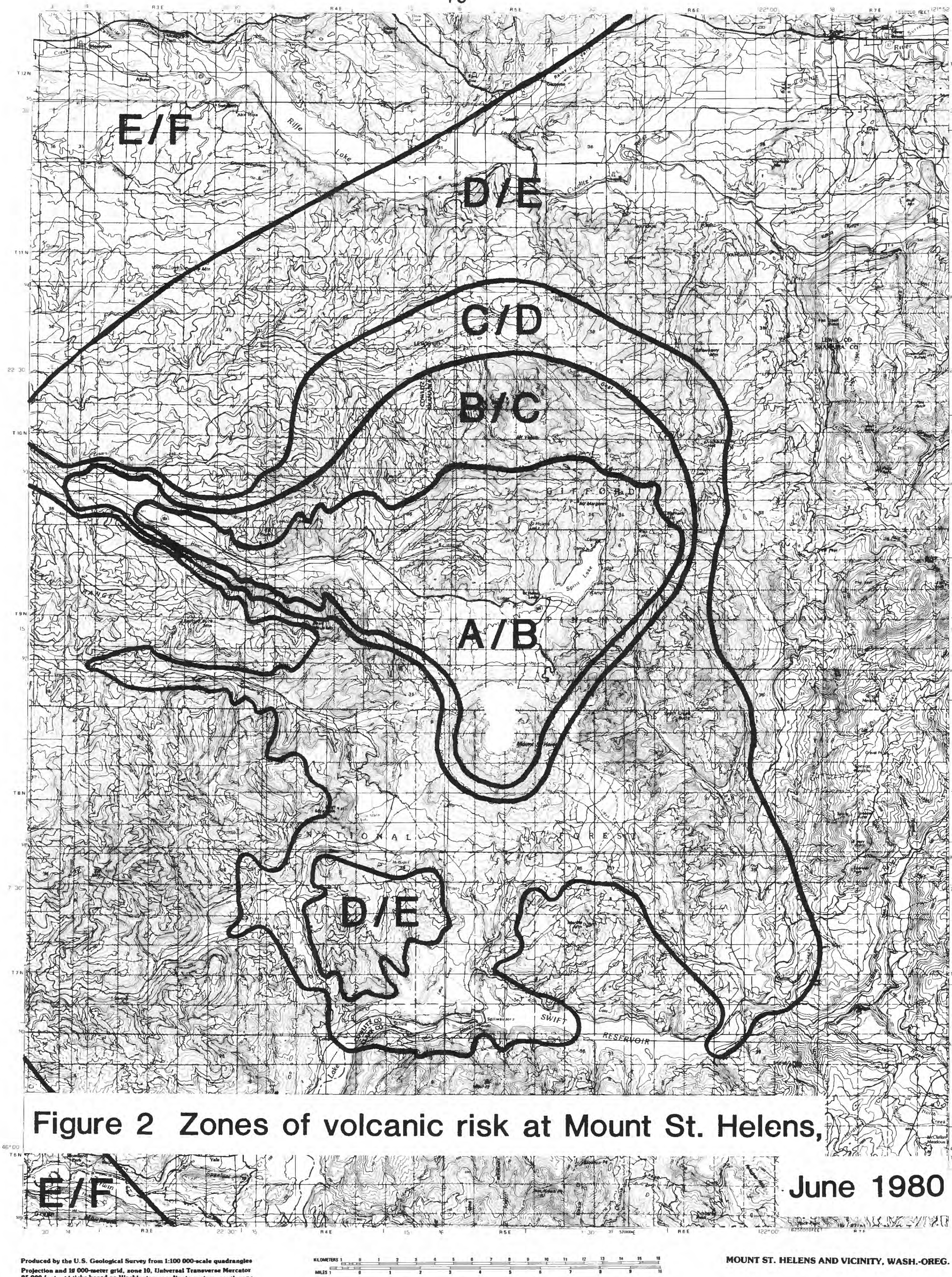

Figure 2 Zones of volcanic risk at Mount St. Helens, June 1980

Produced by the U.S. Geological Survey from 1:100 000-scale quadrangles
Projection and 10 000-meter grid, zone 10, Universal Transverse Mercator
25 000-foot grid ticks based on Washington coordinate system, south zone, and Oregon coordinate system, north zone
Road update furnished by Washington State Department of Natural Resources

MOUNT ST. HELENS AND VICINITY, WASH.-OREG.

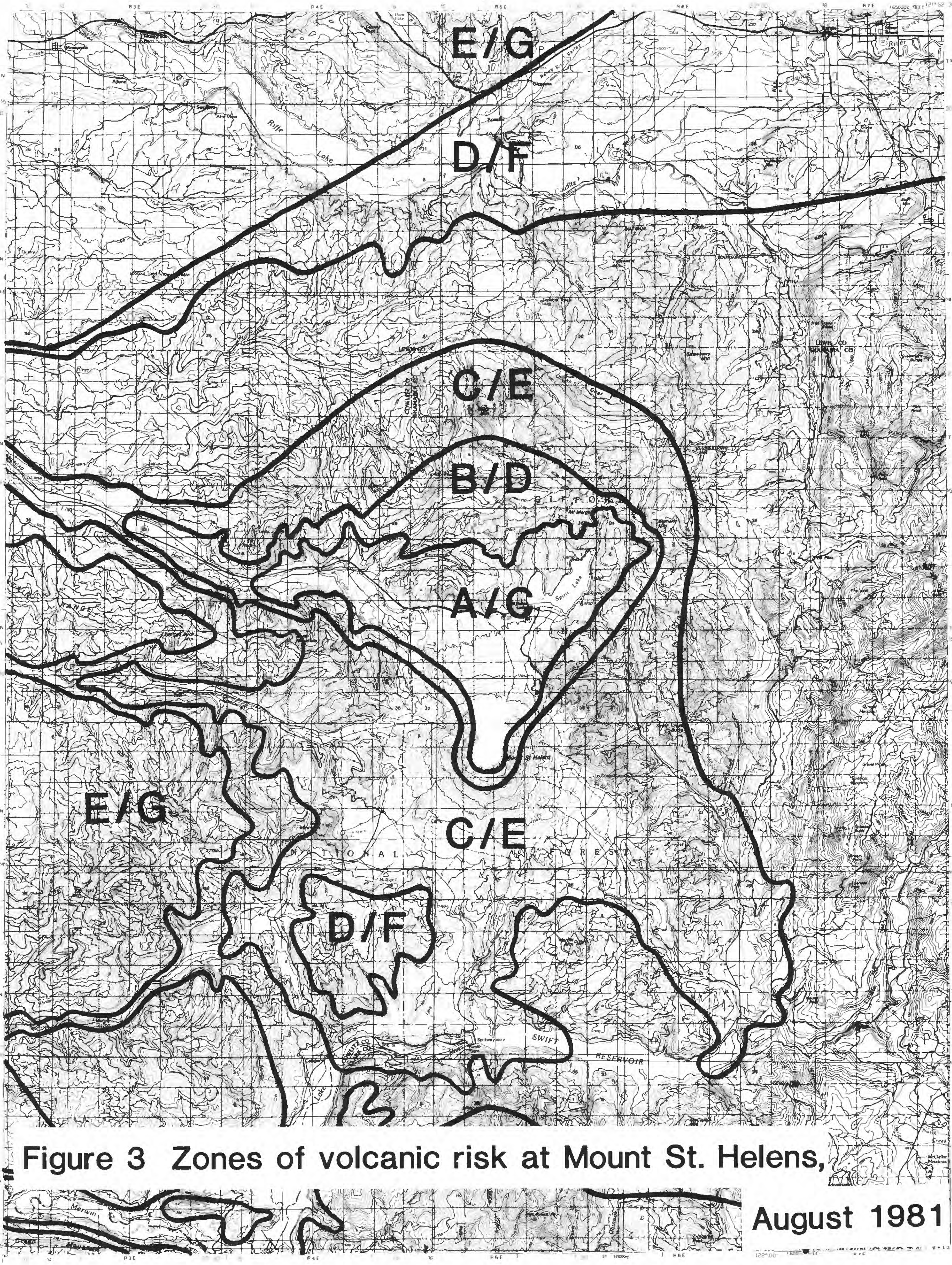

Figure 3 Zones of volcanic risk at Mount St. Helens, August 1981

Produced by the U.S. Geological Survey from 1:100 000-scale quadrangles
Projection and 10 000-meter grid, zone 10, Universal Transverse Mercator
25 000-foot grid ticks based on Washington coordinate system, south zone, and Oregon coordinate system, north zone
Road update furnished by Washington State Department of Natural Resources

MOUNT ST. HELENS AND VICINITY, WASH.-OREG.

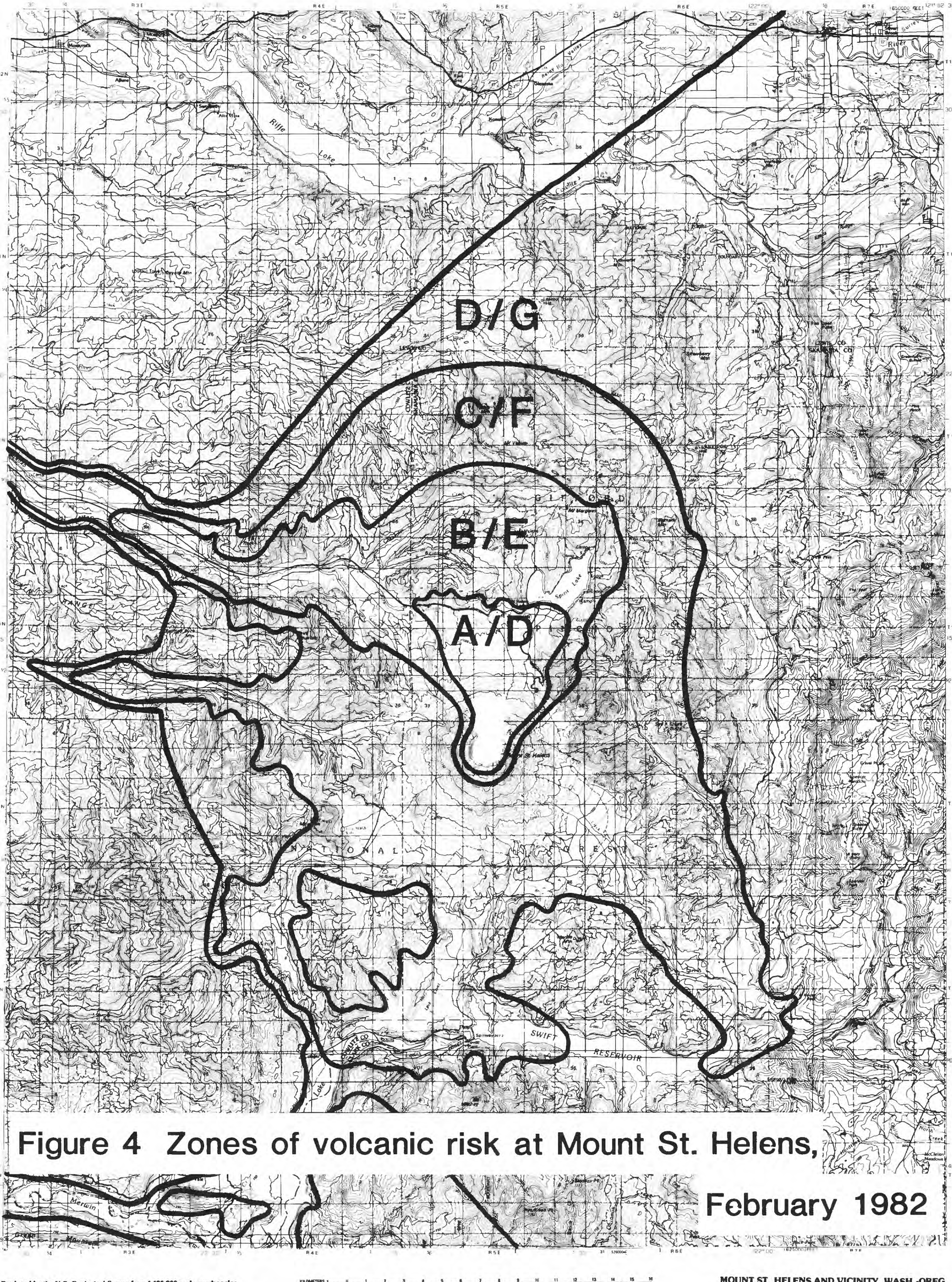

Figure 4 Zones of volcanic risk at Mount St. Helens, February 1982

Produced by the U.S. Geological Survey from 1:100 000-scale quadrangles
Projection and 10 000-meter grid, zone 10, Universal Transverse Mercator
25 000-foot grid ticks based on Washington coordinate system, south zone, and Oregon coordinate system, north zone

-- As of February 1982 at Mount St. Helens, risks in Case 2 are approximately 3 orders of magnitude lower than those in Case 1. Since June 1980, risks in Case 2 have decreased faster than those in Case 1; this is due in large part to improvements in predictive capability.

The risk assessments presented in figs. 1-4 and Appendices 4-7 are subject to constant change. P_{1-3} will change with time even if nothing changes at the volcano; P_{1-8} will change with any new volcanic activity, and with the discovery of any new information about St. Helens' eruptive history. The best values for P_{3-8} and P_{11} will certainly change as the short- and intermediate-term behavior of Mount St. Helens becomes better understood, or if that behavior changes. Volcanism is a dynamic phenomenon, so volcanic risks will be constantly changing and they must be reassessed periodically.

Table 1 presents some familiar risks. Because this report expresses volcanic risks in the same terms as more familiar risks, it is possible to (a) determine the level of risk at a given site near Mount St. Helens, and compare that with more familiar risks, and (b) locate those areas around St. Helens that are subject to any familiar level of risk. A word of caution: most familiar risks are known more precisely than an order-of-magnitude estimate, but since volcanic risks are not, one should not read more detail into risk comparisons than the volcanic data permit.

The volcanic risk shown in figs. 1-4 is additive to all other (nonvolcanic) risks, e.g., occupational or traffic risks. Just as the mutually exclusive risks of being killed by various volcanic events must be summed to estimate a total risk from volcanic activity, so must the risks from volcanic activity and all other hazards be summed to estimate total risk from all causes. If a person is in an area where volcanic risk roughly equals his "background" level of risk, then he is more or less doubling his normal risks.

Other risks in the Mount St. Helens area are not strictly volcanic and are not discussed in this report. They include non-volcanic flood risks, risks of aircraft accidents, risks of encounters between logging trucks and other vehicles, and risks of traffic accidents in the event of a hasty retreat from the volcano.

Table 1: Volcanic risks at Mount St. Helens compared to familiar risks. Values shown are annual probabilities of death for "average" participating individuals. Except where otherwise noted, all statistics pertain to the population of the U.S.

The statistics in Table 1 are from Bailey (1980), Bullock, R. (oral communication), Follmann (1978), Hewitt and Sheehan (1969), Insurance Information Institute (1965), Levett, S. (oral communication), Pfeffer and Klock (1974), Pochin (1975), Rainey, W. (oral communication), and Starr (1969).

TABLE 1 VOLCANIC RISKS AT MOUNT ST. HELENS, COMPARED TO FAMILIAR RISKS (expressed as annual probabilities of death).

Risk Zones A-G, Mount St. Helens (solid line=best guess; dashed line=possible range)	Risk of death from any cause, (based on mortality tables	Risk of death in various occupations	Risk of death from miscellaneous causes
1.0 (10^{-0}) —			
Zone A			
	Age 90 ($2.3x10^{-1}$)		
0.1 (10^{-1}) —	Age 80 ($0.9-1.1x10^{-1}$)	U.S. Forces in WWII, Korea, Vietnam ($2-5x10^{-2}$)	
Zone B			
0.01 (10^{-2})	— Age 60 ($1.8-2.1x10^{-2}$)		Drug abuse($8x10^{-3}$)
		Helicopter pilots($6x10^{-3}$)	Smoking($5x10^{-3}$)(?)
		Deep sea fishing($3x10^{-3}$)	Cardiovascular disease ($2.9x10^{-3}$)
Zone C	Avg, age-weighted($6.4x10^{-3}$)	Logging($2.5x10^{-3}$)	
	Avg,all workers($4.4x10^{-3}$)	Avg 33 hazardous occuptions($1.2x10^{-3}$)	Cancer($1.3x10^{-3}$)
	Age 40, ($3x10^{-3}$)	Mining & quarrying ($1x10^{-3}$)	
	Age 20, ($1.1-1.8x10^{-3}$)		
0.001 (10^{-3})	—	Construction($7.2x10^{-4}$)	
		Agriculture($6.3x10^{-4}$)	
		Transportation & utilities($3.8x10^{-4}$)	Accidents--all types ($4.5x10^{-4}$)
Zone D		Law enforcement($2x10^{-4}$)	Car accidents($2.5x10^{-4}$)
		Government,civilian($1.3x10^{-4}$)	
		All workers($1.2x10^{-4}$)	
		Manufacturing($1.0x10^{-4}$)	
0.0001 (10^{-4})	—	Trades($8x10^{-5}$)	Accidental falls($8x10^{-5}$)
Zone E			Drowning, ($4x10^{-5}$)
			Firearm accidents($1.4x10^{-5}$)
0.00001 (10^{-5}) —			
Zone F			Floods,world($2x10^{-6}$)
			Tornadoes,U.S.($1x10^{-6}$)
0.000001 —			Earthquakes, world($8x10^{-7}$)
			Hurricanes,U.S.($5x10^{-7}$)
			Volcanic eruptions, world($1x10^{-7}$)

Distinction between risk to individuals and risk to a population

The risks discussed above are for an individual. Although the risks are expressed as a chance that a given individual will be killed, they are calculated as 1-q, where q equals the probability that in 365 successive "trials," that individual will be killed 0 times (i.e., will not be killed).

The probability that an individual will be killed two or more times is nonsensical. In a large population, though, an individual who is killed might be replaced by another, just as bowling pins can be reset. In practical fact, individuals move into locations where others have been killed, and therefore land managers and public safety officials must consider the probability of two or more deaths per "member" of a population.

To estimate the expected number of eruption-caused deaths for a population, one must consider the probability P(1) of one eruption, the probability P(i) of i eruptions in the same time span, the average size of a population (N), the rate at which that population moves back into a hazardous area after a death has occurred (assumed here, for simplicity of calculation, to be instantaneous), and the fraction (X) of the population that will be killed in each eruption.

If the daily probability of an eruption that would be lethal at a specific site is P_9, the probability P(1) of one such eruption within the next year is $1-(1-P_9)^{365}$. If such eruptions are randomly distributed throughout the year but cannot occur within less than one week of one another, the probability P(2) of having two such eruptions in a year is $[1-(1-P_9)^{365}][1-(1-P_9)^{358}]$, and the probability of having i such eruptions in a year is $[P(i-1)][1-(1-P_9)^{(372-7i)}]$. The probability of having one or more such eruptions in a year is the sum of P(1) + P(2) + P(3) ... + P(52). When the value of P_9 is .0001 or smaller, as it typically is, this sum is approximately equal to P(1) + P(2) + P(3); when P_9 is small, the probabilities of four or more fatal eruptions in a single year are negligible.

The expected number of deaths E(N) in a single event is N x X, where N and X are defined as they were above. If those who are killed are replaced, the expected number of deaths in i events, $E(N|i)$, is N x X x i. The expected number of deaths over the next year, then, is

N x X x [P(1) + P(2) + P(3)...+ P(52)].

For example, consider a population of 100 persons working 40 hours/week, with provisions for warning and evacuation, between 10 and 15 km due north of Mount St. Helens. If lethal eruptive activity affects their work site), the fraction expected to be killed, (X), is P_{10} x P_{11}, or approximately .002. The probability that lethal volcanic activity will affect this site on any given day in the next year is $P_{9c}+P_{9e}$, or approximately .00008; the probability P(1) that such activity will affect the site in the next year is approximately .029. The probability P(2) that lethal activity will affect the site twice in the same period is approximately .0008, and the probability P(3) that it will affect the site three times in the same period is approximately .00002. It follows, then, that the expected number of deaths from eruptions in the next year, for this specific population and area, is

$$N \times X \times P(1,2,3) = E(N|3)$$
$$100 \times .002 \times .03 = .006 \text{ persons.}$$

Statistical estimates of the expected number of deaths are most reliable when death is an infrequent result of many repeated events. For example, the number of automobile accidents in the U.S. is large, but the number of fatal accidents is relatively small, so the expected number of deaths can be estimated quite reliably. Volcanic eruptions, however, are relatively infrequent events that, for the most part, either are fatal to all the people at a location or do not cause injury at all. As a result, the expected numbers of deaths may be a deceptive value; the actual numbers are more likely to be nearly zero or nearly the size of the population at risk at a given time.

Possible uses of this report

The principal purpose of this report has been to introduce a method of analyzing intermediate- and long-term volcanic hazards and risks. This analytical framework can help land managers, officials responsible for public safety, and the general public to understand better what are the various factors that determine volcanic risks, and how those risks might be reduced. Intermediate- and long-term risk assessments can be useful in planning land use and emergency responses to volcanic activity, in determining the design and location of critical facilities, in resolving insurance questions, and in a variety of other, familiar activities. Land-use plans for recreation, reforestation and other purposes might be affected by the prospects of further volcanic activity. Limitations of land use and access have been part of the emergency response at Mount St. Helens during the last two years, and the probabilities described in this report may help public officials as they balance the risks and benefits of various future closures.

The estimated probabilities in this report are preliminary and approximate; special note should be made of the wide range of possible risk values for any particular point around the volcano (Table 1, Figs. 1-4). This report does not designate any areas as "safe," because the definition of the word "safe" depends on the level(s) of risk and uncertainty one is willing to accept. Decisions about acceptable risk involve not only the volcanic risks but a variety of social and economic costs and benefits (Lowrance, 1976); such decisions must be made by the public, their elected representatives, and the land managers, not by geologists.

Another possible use of the method described here is to define baseline probabilities for various events, against which any future changes in activity can be compared. Many advances in science result from recognizing the usual and the unusual, and asking why each is so. Knowledge of the usual (baseline probabilities) will certainly help in recognizing the unusual.

Finally, the method described here can be adapted to utilize short-term monitoring data, and thus permit short-term hazard assessments. Short-term assessments are much needed as geologists and civil authorities attempt to mitigate the results of imminent or ongoing eruptions.

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Appendix 1: Steps in the estimation of volcanic hazards and risks at Mount St. Helens

Note 1: Values used in the examples are current as of February 1982.
Note 2: For some steps there are several subsets of data that could be used. All are shown; the subset that was used in calculations for risks as of February 1982 (Fig. 4, Appendix 7) is marked with an asterisk. Source data is presented in Appendix 2; a complete listing of input data used for calculating values in appendices 4-7 is given in Appendix 3.

STEP 1. Calculate the probability P_1 of entering an ERUPTIVE PERIOD (i.e., decades to centuries of relatively frequent volcanism, following and followed by repose periods of a decade or more; e.g., Kalama, Goat Rocks, and the current eruptive period).

*A. Using the last 500 years at Mount St. Helens,

$$\frac{\text{Number of eruptive periods in past 500 years}}{\text{no. of years (500) less no. of yrs. in eruptive periods (150)}}$$

$$= \frac{3}{350} = .009/\text{year} \qquad (= .00002/\text{day}).$$

B. Using the last 1500 years at Mount St. Helens,

$$\frac{\text{No. of eruptive periods in past 1500 yrs.}}{\text{no. of yrs. (1500) less no. of yrs in eruptive periods (200)}}$$

$$= \frac{4}{1300} = .003/\text{yr}. \qquad (= .000008/\text{day})$$

Note: If the volcano is already in an eruptive period, P_1 becomes 1.

STEP 2. Calculate $P_{2|1}$, the probability of entering an ERUPTIVE SEQUENCE (i.e., a sequence of eruptions in which no repose period exceeds 6 months; e.g., 1831, 1835, ...1980-), given that an eruptive period has begun.

A. Using past 1500 yrs. at Mount St. Helens,

$$\frac{\text{number of eruptive sequences}}{\text{number of yrs. in those eruptive periods (200) less \# of yrs. in eruptive sequences (50)}}$$

$$= \frac{\text{approx. } 20}{150} = 0.1/\text{year} \quad (=.0004/\text{day}).$$

B. Using 1800-present at Mount St. Helens, and counting that as one eruptive period, 180 yrs. long

$$\frac{\text{approx. 12 eruptive sequences}}{\text{160 yrs.}} = .075/\text{yr} \; (= .0002/\text{day}).$$

*C. Using 1800-present at Mount St. Helens, as above, but counting two periods, 1800-1857 and 1980-?

$$\text{approx. } \frac{\text{12 eruptive sequences}}{\text{40 yrs.}} = .3/\text{yr} \; (= .0008/\text{day}).$$

Note--If the volcano is already in an eruptive sequence, $P_{2\ 1}$ becomes 1.

STEP 3. Calculate $P_{3|2}$, the probability of an ERUPTION (i.e., more or less continuous ejection of volcanic material, without any pause longer than one week; e.g., 5/18/80), given that an eruptive sequence has begun.

A. Using 1800-present at Mount St. Helens,

$$\frac{\text{No. of eruptions}}{\text{No. of years in eruptive sequences (17) less the no. of years of actual eruptions (0.1)}}$$

$$= \frac{33 \text{ eruptions}}{17 \text{ years}} \quad \text{or 2 eruptions/yr.} \quad (= .003/\text{day}).$$

B. Using post-3/20/80 activity at Mount St. Helens,

13 eruptions/1.8 yr or 7 eruptions/year (= .02/day)
(counts phreatic activity 3/27/80-5/14/80 as 1 eruption).

*C. Using post-5/18/80 activity at Mount St. Helens,

11 eruptions/1.7 yr or 6 eruptions/year (= .02/day).

STEP 4. Calculate $P_{4a-c|3}$, the probabilities of various <u>TYPES OF ERUPTIONS</u> (major-explosive, minor-explosive, or non-explosive), given that an eruption has begun.

"Major explosive eruption" -- produces 0.1 km^3 of pyroclastic ejecta or more
"minor explosive eruption" -- produces less than 0.1 km^3 of pyroclastic ejecta
"non-explosive eruption" -- essentially no pyroclastic ejecta.

(Each fraction listed below represents the number of major-, minor- or non-explosive eruptions divided by the total number of known eruptions during that period.)

A. Using past 1500 yrs. at Mount St. Helens

Major-explosive	4/54	=.1 ($P_{4a|3}$)
Minor-explosive (includes dome building eruptions when accompanied by minor-explosive activity)	40/54	=.8 ($P_{4b|3}$)
Non-explosive	6/54	=.1 ($P_{4c|3}$).

B. Using 1800-present at Mount St. Helens

Major-explosive	2/33	= .05
Minor-explosive	24/33	= .75
Non-explosive	7/33	= .20.

C. Using 1980-present at Mount St. Helens (counts activity between 3/27/80 and 5/17/80 as 1 minor-explosive eruption),

Major-explosive	1/13	= .1
Minor-explosive	6/13	= .45
Non-explosive	3/13	= .45.

D. Using post-5/18/80 activity at Mount St. Helens,

Major-explosive	0/11	= 0
Minor-explosive	5/11	= .45
Non-explosive	6/11	= .55.

*E. Using post-5/18/80 activity but giving a subjective weighting to the most recent activity and to intermediate-term monitoring data,

Major-explosive		= .05
Minor-explosive		= .20
Non-explosive		= .75.

F. Using activity at other subduction-zone volcanoes (post-1900, old island arcs and continental crust only, with good historical records--New Zealand, Indonesia, Philippines, Honshu, Kyushu, Hokkaido, Kuriles, Kamchatka, Mexico, Guatemala, El Salvador),

Major-explosive	19/780	= .02
Minor-explosive	740/780	= .95
Non-explosive	21/780	= .03.

G. Using all historic eruptions at subduction zone volcanoes in which dome building is reported to have occurred (the data do not permit distinction between activity preceding or following dome growth),

Major-explosive	15/470	=	.03
Minor-explosive	415/470	=	.88
Non-explosive	40/470	=	.09.

STEP 5. Calculate $P_{5a|4a-c}$, the probabilities of SPECIFIC VOLCANIC HAZARDS (pyroclastic flows, mudflows, lateral blasts or pyroclastic surges, ballistic fragments, tephra fall, lava flows, and dangerous concentrations of volcanic gases), given a general type of eruption.

*A. Using past 1500 yrs. at Mount St. Helens,

	(no. of eruptions with this event/total no. of eruptions)		
	if Major-expl.	Minor-expl.	Non-expl.
Pyroclastic flow (all types)	3/4 ($P_{5a\|4a}$)	15/40 ($P_{5a\|4b}$)	0/10 ($P_{5a\|4c}$)
Mudflow	1/2:2/2** ($P_{5b\|4a}$)	2/20:4/20** ($P_{5b\|4b}$)	0/10 ($P_{5b\|4c}$)
Lateral blast or pyroclastic surge	1/4 ($P_{5c\|4a}$)	1/40 ($P_{5c\|4b}$)	0/10 ($P_{5c\|4c}$)
Ballistic fragments	4/4*** ($P_{5d\|4a}$)	40/40*** ($P_{5d\|4b}$)	0/10 ($P_{5d\|4c}$)
Tephra fall	4/4 ($P_{5e\|4a}$)	40/40*** ($P_{5e\|4b}$)	0/10 ($P_{5e\|4c}$)
Lava flow	0/4 ($P_{5f\|4a}$)	5/40? ($P_{5f\|4b}$)	4/10? ($P_{5f\|4c}$)
Dangerous concentration of volcanic gases****	0/4? ($P_{5g\|4a}$)	0/40? ($P_{5g\|4b}$)	0/10? ($P_{5g\|4c}$).

B. Using 1800-present at Mount St. Helens

	(no. of eruptions with this event/total no. of eruptions)		
Pyroclastic flow (all types)	1/2 ($P_{5a\|4a}$)	8/24 (etc.)	0/7
Mudflow	1/2	3/24	0/7
Lateral blast or pyroclastic surge	1/2	0/24	0/7
Ballistic fragments	2/2***		24/24***
0/7			
Tephra fall	2/2	24/24***	0/7
Lava flow	0/2	1/24	1/7
Dangerous conc. of volc. gas	0/2	0/24	0/7.

C. Using post-1900 activity at other subduction-zone volcanoes in similar climates (Japan, Kamchatka, Kuriles),

	(no. of eruptions with this event/total no. of eruptions)		
Pyroclastic flow (all types)	9/13	18/400	0/4
Mudflow	0/10:3/3**	10/ 200:18/ 200**	0/2:0/2**
Lateral blast or pyroclastic surge	2/13	? 0/4	
Ballistic fragments	13/13***	400/400***	0/4
Tephra fall	13/13	400/400	0/4
Lava flow	6/13	36/400	1/4
Dangerous conc. of volc. gas	0/13?	1/400?	0/4?.

Notes for Step 5 (A-C):

* Preferred assumption

** June-Nov. : Dec.-May; in case A, the 1/3:2/3 ratio from data set C has been used.

*** Assumed, rather than observed.

**** Dangerous concentrations of volcanic gases can also develop during non-eruptive, fumarolic activity; such cases are not considered here.

Dome growth <u>per se</u> is not included here as a hazard; lithic pyroclastic flows and associated mudflows, lateral blasts, ballistic fragments and tephra fall from growing domes are included. Although domes related to Mount St. Helens are found as far as 13 km away from the summit, further dome growth in the present eruptive sequence is expected to be confined to the present crater.

STEP 6. Calculate $P_{6a-g|5a-g}$, i.e., the probabilities that each hazardous event $E_{5a,b,...g}$ will reach specified distances from the vent (DISTANCE FACTORS).

The probability that a hazardous event will reach to a specified distance from a vent can be estimated on the basis of the proportions of past instances of that kind of event that have reached that distance. All proportions are cumulative, i.e., the proportion of those reaching at least as far as the specified distance or, for tephra fall, of those attaining at least a specified thickness at the specified distance. The data on which these proportions are based are presented in Appendix 2.

Distance (km from the vent) / Hazard	5	10	15	20	30	40	50	100	200
Pyroclastic flow[1]	.75	.1	.01	.001	0	0	0	0	0
Lahar[2]	.93	.44	.28	.21	.13	.10	.08	.04	.01
Lateral blast or pyroclastic surge[3]									
(major-expl.)	.5	.3	.1	.05	.01	0	0	0	0
(minor-expl.)	.5	.1	.01	0	0	0	0	0	0
Ballistic fragments[4]	.01	.001	0	0	0	0	0	0	0
Tephra fall, 10 cm.[5]									
(major-expl.)	.99	.98	.96	.93	.9	.8	.7	.5	.1
(minor-expl.)	.3	.2	.1	.05	.01	0	0	0	0
Lava flow[6]	.5	.1	.02	0	0	0	0	0	0
Dangerous concentr. of volcanic gases[7]	.01	0	0	0	0	0	0	0	0

1 based on lengths of 23 pyroclastic flows that have occurred at Mount St. Helens since the height of the cone was reduced on 5/18/80 ($P_{6a|5a}$).

2 based on the lengths of 35 Mount St. Helens mudflows ($P_{6b|5b}$).

3 based on a small number of lateral blasts and pyroclastic surges at St. Helens and other circum-Pacific volcanoes. The data are insufficient to define a probability distribution, so some additional values were assumed. ($P_{6c|5c}$)

4 based on the observed distribution of ballistic fragments at Mount St. Helens (1980), Asama, Agung and Arenal, and on calculated ranges for ballistic fragments given assumed sizes, shapes, initial velocities and initial angles of ejection ($P_{6d|5d}$).

5 based on thickness-vs.-distance relations (out to 200 km only) for 36 major-explosive eruptions, and 15 minor-explosive eruptions, at St. Helens and other subduction-zone volcanoes. See additional discussion below. ($P_{6e|5e}$)

6 based on lengths of 44 Mount St. Helens lava flows ($P_{6f|5f}$).

7 Available data are inadequate to define a probability distribution. The values shown here are assumed values. Small concentrations of volcanic gases may extend for many km from the vent, but the gases will be sufficiently diluted with air so as not to be fatal to humans. ($P_{6g|5g}$)

STEP 6 (Continued). Tephra fall

The calculation of distance factors for tephra fall is more complicated than for other volcanic events because it is, in its simplest form, a two-variable problem. Probabilities must be determined for different thicknesses of tephra at different distances. Explosive eruptions were classified as either major or minor (Step 4); then, using isopach maps for 36 major-explosive eruptions and 15 minor-explosive eruptions (from records of worldwide volcanism), log (maximum thickness (t_{max})) was plotted against distance down the plume axis (Appendix 2).

From the plots, probabilities of a given tephra thickness at a given distance from a volcano can be estimated from the percentage of eruptions for which that thickness of tephra (or greater) has been observed at that distance from a vent. For example, at 5 km from a vent, nearly all (approximately 99%) of the major explosive eruptions have deposited at least 10 cm of tephra, 90% have deposited at least 30 cm, 80% at least 50 cm, and so on. Thus, given a major explosive eruption, there is a .99 probability that at least 10 cm of tephra will fall at a point 5 km downwind from the vent, a .9 probability that at least 30 cm will fall at the same point, a .8 probability that at least 50 cm will fall at the same point, and so on. Looking at the problem from a different angle, there is a .99 probability that at least 10 cm will fall at a point 5 km downwind, that at least 7 cm will fall at a point 10 km downwind, that at least 5 cm will fall at a point 15 km downwind, and so on. Probabilities for other thicknesses and distances can be estimated from the tables below, or directly from the thickness-vs.-distance curves in Appendix 2.

There are some gaps in reporting, particularly of the distal thicknesses of tephra falls. Where original data was incomplete, the writer visually extrapolated the known parts of each thickness-vs.-distance curve out to 200 km. This reduces the bias toward larger, better-reported eruptions. Curves extrapolated in this manner were used in preparing the tables below.
This is a subjective procedure that still needs improvement. The problems also go beyond a paucity of reported data. Compaction and erosion of deposits before they are measured will lead to an underestimation of tephra probabilities; these factors are not considered here but should be considered in future work.

The probabilities of various tephra thicknesses at various distances, shown in the tables below, are useful for long-term planning. Probabilities will actually vary from day to day, depending on wind speeds and directions. The probable tephra thicknesses on a given day may be estimated from the height and duration of an eruption column and from wind information, if these parameters can be calibrated against the thickness-vs.-distance curves shown below. Still other parameters, such as the concentration and sizes of particles in the plume, will also need to be considered in the development of more precise estimates of probable thicknesses at varying distances.

Step 6. continued

Relationship between tephra thickness (along the axis of a plume) and distance (from the vent), for major-explosive eruptions

(based on a sample of 36 eruptions, roughly corrected to balance a balance a reporting bias toward larger eruptions):

Downwind distance from the vent <u>Km</u>	<u>Percentage of tephra deposits with thickness greater than or equal to the value given</u> (thicknesses in cm)									
	99%	90	80	70	60	50	40	30	20	10	1%
5 km	10cm	30 cm	50	70	100	200	300	400	500	800	1000
10	7cm	25	35	50	70	100	200	300	400	600	800
15	5	20	25	30	40	60	100	200	300	400	600
20	4	15	20	25	35	50	70	100	150	250	400
30	3	10	15	20	30	40	50	70	100	150	250
40	2	5	10	15	20	30	40	50	70	100	150
50	1	4	7	10	15	20	30	40	50	80	120
100	.5	1	2	3	5	10	15	20	30	60	100
200	.1	.3	.5	.7	1	2	3	5	7	10	50

Step 6. (continued)

Relationship between tephra thickness (along the axis of a plume) and distance (from the vent), for minor-explosive eruptions (based on a sample of 15 eruptions, roughly corrected to balance a reporting bias toward larger eruptions):

Distance from the vent, along plume axis Km	Percentage of tephra deposits with thicknesses equal to or greater than the value given (thicknesses in cm)										
	99%	90	80	70	60	50	40	30	20	10	1%
5	tr	.1cm	.2	.4	1	2	5	10	15	30	45
10	tr	.1	.2	.3	.5	1	2	5	10	20	30
15	tr	tr	.1	.3	.4	.8	1	2	5	10	20
20	tr	tr	.1	.2	.3	.5	.8	1	2	5	15
30	tr	tr	tr	.1	.2	.3	.5	.8	1	2	10
40	tr	tr	tr	.1	.2	.2	.3	.5	.8	1	5
50	tr	tr	tr	tr	.1	.2	.2	.3	.5	.8	3
100	tr	tr	tr	tr	tr	.1	.1	.2	.3	.5	1
200	tr	tr	tr	tr	tr	tr	tr	tr	.1	.2	.4

tr = trace, less than 0.1 cm

STEP 7. Calculate $P_{7a-p|6a-g}$, the probabilities that a hazardous event reaching a specified distance will be in a specific 22.5° sector (SECTOR FACTORS). These probabilities are a function of initial direction of travel, topography, and wind directions.

For pyroclastic flows (based crudely on 1980 activity at Mount St. Helens; strong topographic control)($P_{7a-p|6a}$):

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.6	.3	.0067	.0067	.0067	.0133	.0067	(.0067 for all other sectors)								

For mudflows (dependent on likely vectors of pyroclastic flows and on the availability of water, snow, or glacial ice)($P_{7a-p|6b}$):

winter & spring:

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.4	.2	.01	.03	.05	.01	.08	.03	.05	.03	.01	.01	.01	.03	.05	.01

summer & fall:

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.01	.05	.01	.1	.15	.25	.05	.05	.1	.05	.01	.01	.01	.05	.1	.01

For lateral blasts, surges (given strong topographic control near the vent, crude topographic control away from the volcano)($P_{7a-p|6c}$)

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.9	.5	.02	.015	.01	.015	.02	.015	.01	.01	.01	.01	.01	.01	.015	.4

(assuming that each blast covers a 45° sector, an area much smaller than the 1980 blast at Mount St. Helens but a reasonable estimate for any future blast at Mount St. Helens, given that no unstable flank remains and that the walls of the amphitheater will tend to focus any future blast)

For ballistics ($P_{7a-p|6d}$)

1.0 for any given sector

For tephra fall ($P_{7a-p|6e}$):

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.04	.08	.14	.16	.16	.13	.10	.06	.04	.02	.01	.01	.01	.01	.01	.02

(assuming that each plume covers a 22.5° sector; sector factors will vary slightly with season)

For lava flows (given strong topographic control; low but non-zero probabilities on the W, S and E are for flank flows)($P_{7a-p|6f}$):

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.9	.05	.004	(.004 for all other sectors)												

For dangerous concentrations of volcanic gases (moderate topographic control near the vent; strong topographic control away from the vent area)($P_{7a-p|6g}$):

N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
.6	.3	.01	.01	.01	.01	--	--	--	--	--	--	--	--	.01	.05

(-- = too small to estimate)

Directional probabilities for flowage hazards are for the initial direction of transport from the mountain; probabilities for points downvalley will be the sum of probabilities for all their tributaries. The list below summarizes the probabilities that have been summed to account for topographic controls on flowage hazards:

Adjustments made in the sector probabilities of flowage hazards in order to account for topographic barriers and diversions. Subscripts indicate distances from the vent (in km).

Along North and South Toutle:

NW_{10} (new) = $N_{10} + NNW_{10} + NW_{10}$ (original)
$WNW_{15} = N_{15} + NNW_{15} + NW_{15} + WNW_{15}$
$WNW_{20} = N_{20} + NNW_{20} + NW_{20} + WNW_{20}$
$WNW_{30} = N_{30} + NNW_{30} + NW_{30} + WNW_{30} + W_{30}$
(S. Fork and N. Fork both in WNW)
$WNW_{40} = N_{40} + NNW_{40} + NW_{40} + WNW_{40} + W_{40}$
$WNW_{50} = N_{50} + NNW_{50} + NW_{50} + WNW_{50} + W_{50}$

Along Smith Creek, Muddy River:

$E_{5} = NE_{10} + ENE_{10} + E_{5}$
$ESE_{10} = NE_{15} + ENE_{15} + E_{10} + ESE_{10}$
$SE_{15} = NE_{20} + ENE_{20} + E_{15} + ESE_{15} + SE_{15}$
$SE_{20} = NE_{30} + ENE_{30} + E_{20} + ESE_{20} + SE_{20}$

Along Lewis River:

$SSW_{15} = S_{15} + SSW_{15} + SSE_{30} + SE_{30} + E_{30} + ESE_{30} + NE_{40} + ENE_{40}$
$SSW_{20} = S_{20} + SSW_{20} + SSE_{40} + SE_{40} + E_{40} + ESE_{40} + NE_{50} + ENE_{50}$
$SW_{30} = SSW_{30} + S_{30} + SSE_{50} + SE_{50} + SW_{30} + E_{50} + ESE_{50}$
$SW_{40} = SW_{40} + SSW_{40} + S_{40} + SSE_{50} + SE_{50}$
$SW_{50} = SW_{50} + SSW_{50} + S_{50} + SSE_{50}$

Step 8. Calculate $P_{8a-g|7a-p}$, the probabilities that a hazardous event will affect a specified small area (e.g., a cabin site), given that the event has generally affected a larger, pie-shaped area defined by distance and sector (COVERAGE FACTORS). The exact proportion of a pie-shaped block that flowage hazards will affect will depend on details of the topography, and a correction was made for this fact when zone boundaries on Figs. 1-4 were drawn.

Volcanic Hazard	$P_{8a-g|7}$	
Pyroclastic flow	.33	any sector and distance ($P_{8a|7}$)
Mudflow	.20	any sector and distance ($P_{8b|7}$)
Lateral blast, pyroclastic surge	1.0	any sector and distance ($P_{8c|7}$)
Ballistic fragments	.01	any sector, between 0-5 kms ($P_{8d|7}$)
	.001	any sector, between 5-10 kms (")
	.0001	any sector, between 10-15 kms (")
Tephra fall	1.0	any sector and distance ($P_{8e|7}$)
Lava flow	.20	any sector and distance ($P_{8f|7}$)
Dangerous conc. of volc. gases	.50?	any sector and distance ($P_{8g|7}$)

Step. 9 Calculate $P_{9a-g|8a-g}$, the probabilities that a person who is caught unawares by the event will be killed (SEVERITY FACTORS).

Volcanic Hazard		Probability that the event will be lethal	
Pyroclastic flow		1	$(P_{9a|8a})$
Mudflow		1/10	$(P_{9b|8b})$
Lateral blast, pyroclastic surge		1	$(P_{9c|8c})$
Ballistic fragments		1	$(P_{9d|8d})$
Tephra fall	(for 10 cm)	1/1000 (or 1/10,000?)	$(P_{9e|8e})$
	(for 1 m)	1/100 (or 1/1000?)	$(P_{9e|8e})$
Lava flow		1/1000 (or 1/10,000?)	$(P_{9f|8f})$
Dangerous concentration of volcanic gases		1/2........................	$(P_{9g|8g})$

These estimates are based on mortality data for the 1980 eruptions of Mount St. Helens and for eruptions at other volcanoes. The values for slow-moving events (mudflows and lava flows) are based on the assumption that most persons are able to move out of the flow path. Deaths from tephra fall are primarily due to secondary causes--e.g., collapsing roofs, falling tree branches, lightning from the drifting ash cloud, or impaired visibility on highways. Deaths from lava flows are those of overly curious sightseers. Values indicated as 1 are in fact slightly less than 1; all the values are rough estimates and are subject to revision as more and better data is compiled.

One meter of tephra will have effects roughly ten times as severe as the effects of 10 cm of tephra, judging by records of historic volcanism around the world; but accumulation of the former is also about ten times less likely than accumulation of the latter. To calculate the risk to human life, then, we can simply consider one thickness (10 cm).

A similar simplification is employed for calculating volcanic-gas risks: the probability of any concentration that could cause illness or death is, in a broad way, inversely proportional to the severity of that concentration. For this analysis, therefore, we consider only the event that at least one volcanic gas is sufficiently concentrated to cause death. There are so few documented cases of dangerous gas concentrations that estimates regarding gases in Steps 6, 7, 8 and 9 are very crude.

Step 10. Calculate P_{10}, the probability that an individual will routinely be in the hazardous area.

$$\frac{\text{Percentage of time that the individual is routinely in the area}}{100}$$

This can vary from nearly 1.0 for a full-time resident, through approximately .2 for full-time work in the area, to less than .01 for occasional visits.

Step 11. Calculate P_{11}, the probability that -- even with our present predictive capability -- a given individual will still be in the hazardous area when an eruption occurs.

If the individual can receive a warning, has a means to leave the area within an hour or two, and does so, P_{11} becomes 1.0 minus the probability that we can forecast hazardous eruptions two hours or more in advance. We currently estimate the probable long-term success rate of forecasting hazardous eruptions at Mount St. Helens to be 99% (0.99); this value would be higher under ideal, quiet conditions and lower if equipment failure or bad weather occurs. The long-term average failure rate for average conditions, then, is approximately 1% (P_{11} = 0.01). The chances of failure have been decreasing as more and more data are collected at Mount St. Helens, and as new eruptions are successfully predicted.

During extended periods of strong precursory activity (e.g., prior to May 18, 1980) and during eruptions (e.g., between pulses on October 16, 17 and 18, 1980) the chances of forecasting the exact timing of hazardous activity are still very low; for most purposes, P_{11} during such activity is approximately 1.

If the individual does not receive or heed a warning, P_{11} is approximately 1.

Appendix 2 Data for Steps 1-5: Eruptions of Mount St. Helens during the last 1500 years (480 A.D.--present). Names of eruptive periods are from Hoblitt et al. (1980); tephra layers W, X and T and the Floating Island lava flow are described in Crandell and Mullineaux (1978).

Abbreviations: "Ma" = major-explosive, "Mi" = minor-explosive, "Non" = non-explosive, "pf" = pyroclastic flow, "mf" = mudflow, "bal" = ballistic fragments, "lb" = lateral blast or pyroclastic surge, "tf" = tephra fall, "lf" = lava flow, "dm" = dome growth.
Abbreviations in table body: "M" = Multiple, "?" = Possible.

Date	Eruptive Periods (Step 1)	Eruptive Sequences (Step 2)	Eruptions (Step 3)	Main types of eruptions (Step 4)			Types of eruptive activity (Step 5)						
				Ma	Mi	Non	pf	mf	lb	bal	tf	lf	dm
700-870 A.D. (lower lim.= 600 A.D.)	1 (Sugar Bowl)	1?	M?	--	M?	--	M	M	1	M?	M?	--	1 or more
1500-1650	1 (Kalama)	1	5(set W)	2	3	--	M	?	--	5	5	--	1?
		1	5(set X)	--	5	?	M	M	--	5	5	M	--
		1	M	--	M	--	M	M	--	M	M	--	M
ca. 1800	1 (Goat Rocks)	1	1 (layer T)	1	--	--	?	?	--	1	1	--	--
1831 (August)	(Goat Rocks, cont.)	1 (including first lobe of Floating Island flow?)	2?	--	1	--	--	--	--	1	1	1	--
1835 (March)		1	1	--	1	--	--	--	--	1	1	--	--
1842-1845 (Nov. 22-25, Dec. 5 & Dec. 13, 1842; Oct. 1843; Feb. 16, May 3 & Dec. 28(?), 1844; Feb. 15, Sept. 13 and one unspecified date, 1845)		1	10	--	10	?	M	?	--	10	10	?	M

Appendix 2, continued

Date	Eruptive Periods (Step 1)	Eruptive Sequences (Step 2)	Eruptions (Step 3)	Main types of eruptions (Step 4) Ma	Mi	Non	pf	Types of eruptive activity (Step 5) mf	lb	bal	tf	lf	dm
1847 (March 26)	(Goat Rocks, cont.)	1	1	--	1	--	?	?	--	1	1	?	--
1850 (ca. March 21, May 10)		1	2	--	2	--	?	?	--	2	2	?	--
1853 (April 10?)	(Goat Rocks, cont.)	1	1	--	1	--	?	?	--	1	1	?	--
1854 (Feb-April)		1	1?	--	1	--	?	?	--	1	1	?	--
1857 (April)		1	1	--	1	--	?	?	--	1	1	?	--

Minor explosions, probably hydrothermal or phreatic, noted in 1889, 1903 and 1921.

1980-81	1(Current)	1	13	1	6	6	6	1	1	7	7	--	8

(March 27-May 14, May 18, May 25, June 12-13, July 22, Aug. 7, Oct. 16-19, Dec. 27, 1980--Jan. 4, 1981, Feb. 4-7, April 10-12, June 18-20, Sept. 6-11, Oct. 30-Nov. 1, 1981, and continuing.

Sources:

Crandell, Mullineaux and Rubin (1975), Crandell and others (1981), Harris (1980), Hoblitt, Crandell and Mullineaux (1980), Holmes (1980), Hopson and Melson (1980), Mullineaux and Crandell (1981), Mullineaux, Hyde and Rubin (1975), Williams (1980).

Appendix 2, continued: Data for Step 6

Lava flows (n = 45), lengths in km:
2, 2.8 (2)*, 3.2 (2), 3.6, 4 (8), 4.4 (5), 4.8 (6), 5.2 (2), 5.6 (4), 6 (5), 6.8 (2), 7.6, 8, 8.8, 9.6, 11.6, 13.6, 16.4

Pyroclastic flows, pre-May 18, 1980 (n = 35); lengths in km:
3.6, 4 (2), 5.5 (3), 6, 6.5, 7, 7.2, 7.5 (7), 8, 8.5, 8.8, 9.2, 9.5, 9.6, 11 (2), 13 (2), 14 (3), 15.5 (3), 18 (2)

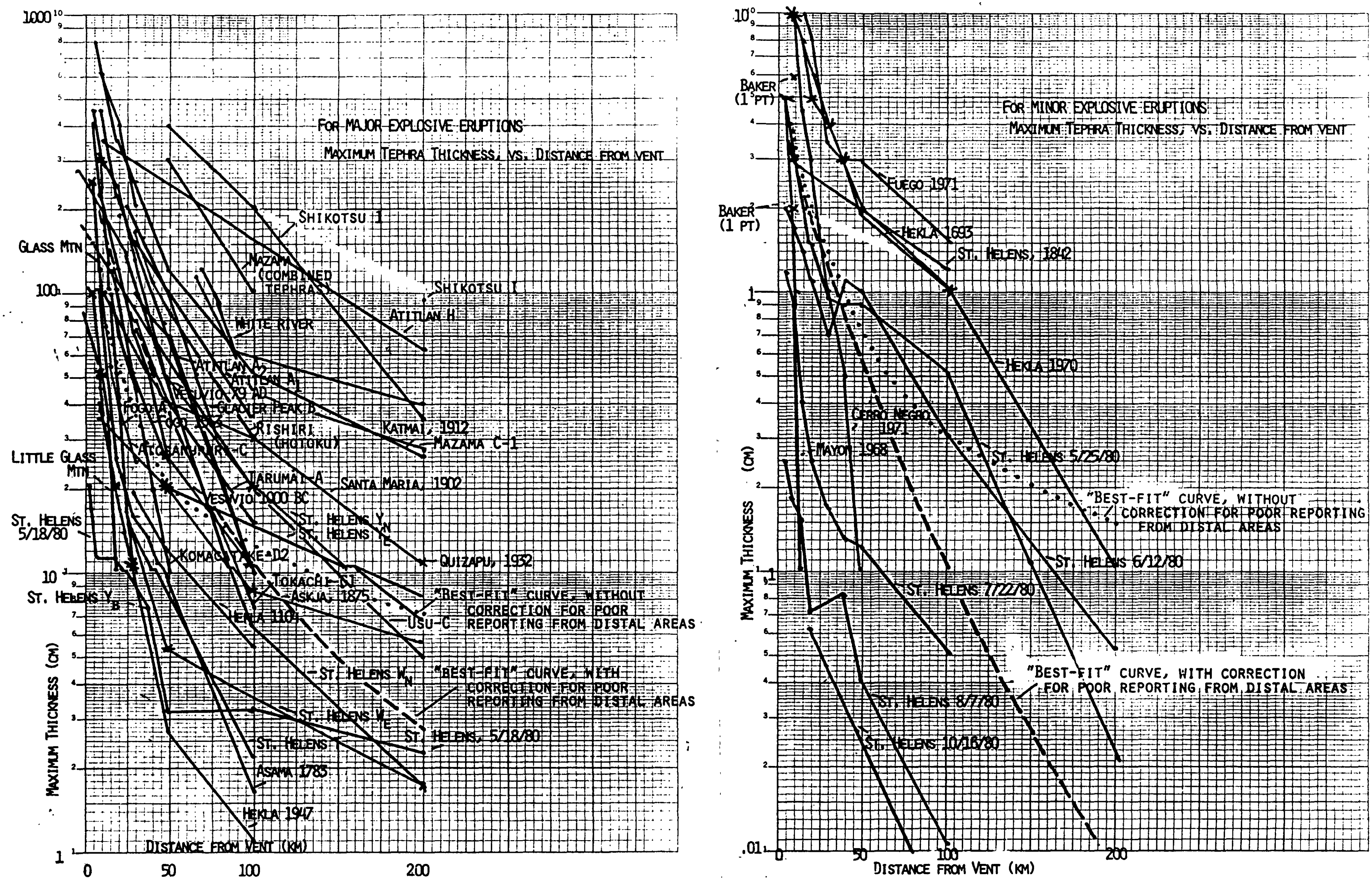
Pyroclastic flows, May 18, 1980 and subsequent (n = 23); lengths in km:
3 (2), 4 (3), 5 (3), 7 (3), 8 (12) (approximate)

Mudflows (n = 35), lengths in km:
4 (2), 4.4, 4.8, 5.6 (2), 6, 6.4 (2), 6.8, 7.2 (2), 7.6, 8.4, 8.8, 9.6, 11 (2), 12, 13 (4), 14, 16, 19, 22, 33, 50, 65 (4), 100 (2)

Tephra falls (n = 41):
Data are presented graphically on page 42.

Sources: D.R. Crandell (written communication), Crandell and Mullineaux (1973, 1978), Hahn and others (1979), Heiken (1981), Hopson (1980), Hyde (1975), Hyde and Crandell (1978), Janda and others (1981), Lirer and others (1973), Mullineaux (1974 and written communication), Rose and others (1973), Rowley and others (1981), Sarna-Wojcicki and others (1981), Sasaki and others (1974), Self and Sparks (1978), Walker and Croasdale (1970), Wilcox (1959), Williams and McBirney (1979), and S.N. Williams (written communication).

Numbers in parentheses indicate the number of flows of that length.



Appendix 2, continued. Thickness vs. distance data for tephra fall deposits.

Appendix 3: Input data for the probability calculations.
Abbreviations: pf=pyroclastic flow; mf=mudflow; lb=lateral blast; bf=ballistic fragments; tf=tephra fall; lf=lava flow; vg=volcanic gases
Note: many of these data are approximate. In some calculations, zero was used as an approximation of probabilities that are slightly greater than zero.

Step	Date	2/1/80	6/1/80	8/1/81	2/1/82
1		.00001	.00002	.00002	.00002
2		.0004	.0008	.0008	.0008
3		.02	.03	.02	.02
4a		.07	.09	.05	.05
4b		.85	.87	.35	.20
4c		.08	.04	.60	.75
5a	(if major-expl.)	.67	.75	.75	.75
	(if minor-expl.)	.29	.31	.38	.38
	(if non-expl.)	.05	.05	.05	.05
5b	(if major expl.)	1	.5	.5	1
	(if minor expl.)	.24	.11	.1	.2
	(if non-expl.)	.05	0	0	.05
5c	(if major-expl.)	0	.25	.25	.25
	(if minor-expl.)	.03	.03	.025	.025
	(if non-expl.)	0	0	0	0
5d	(if major-expl.)	1	1	1	1
	(if minor-expl.)	1	1	1	1
	(if non-expl.)	0	0	0	0
5e	(if major-expl.)	1	1	1	1
	(if minor-expl.)	1	1	1	1
	(if non-expl.)	0	0	0	0
5f	(if major-expl.)	0	0	0	0
	(if minor expl.)	.15	.14	.125	.125
	(if non-expl.)	.8	.8	.8	.57
5g	(if major-expl.)	0	0	0	0
	(if minor-expl.)	0	0	0	0
	(if non-expl.)	0	0	0	0

6a (pf, 5km)	.85	.75	.75	.75
(pf, 10km)	.5	.1	.1	.1
(pf, 15km)	.15	.01	.01	.01
(pf, 20km)	.01	.001	.001	.001
(pf, 30+ km)	0	0	0	0
6b (mf, 5km)	.93	.93	.93	.93
(mf, 10km)	.44	.44	.44	.44
(mf, 15km)	.28	.28	.28	.28
(mf, 20km)	.21	.21	.21	.21
(mf, 30km)	.13	.13	.13	.13
(mf, 40km)	.10	.10	.10	.10
(mf, 50km)	.08	.08	.08	.08
(mf, 100km)	0	0	0	0
(mf, 200km)	0	0	0	0
6c (lb, 5km, maj.)	.5	.5	.5	.5
(lb, 10km, maj.)	.3	.3	.3	.3
(lb, 15km, maj.)	.1	.1	.1	.1
(lb, 20km, maj.)	.05	.05	.05	.05
(lb, 30km, maj.)	.01	.01	.01	.01
(lb, 40+ km, maj)	0	0	0	0
(lb, 5km, min.)	.5	.5	.5	.5
(lb, 10km, min.)	.1	.1	.1	.1
(lb, 15km, min.)	.01	.01	.01	.01
(lb, 20+ km, min)	0	0	0	0
6d (bf, 5km)	.01	.01	.01	.01
(bf, 10km)	.001	.001	.001	.001
(bf, 15+ km)	0	0	0	0
6e (10 cm tephra at 5km, maj.)	.99	.99	.99	.99
(", 10km, maj.)	.98	.98	.98	.98
(", 15km, maj.)	.96	.96	.96	.96
(", 20km, maj.)	.93	.93	.93	.93
(", 30km, maj.)	.9	.9	.9	.9
(", 40km, maj.)	.8	.8	.8	.8
(", 50km, maj.)	.7	.7	.7	.7
(", 100km, maj.)	.5	.5	.5	.5
(", 200km, maj.)	.1	.1	.1	.1
(", 5km, min.)	.3	.3	.3	.3
(", 10km, min.)	.2	.2	.2	.2
(", 15km, min.)	.1	.1	.1	.1
(", 20km, min.)	.05	.05	.05	.05
(", 30km, min.)	.01	.01	.01	.01
(", 40+km, min.)	0	0	0	0
6f (lf, 5km)	.5	.5	.5	.5
(lf, 10km)	.1	.1	.1	.1
(lf, 15km)	.02	.02	.02	.02
(lf, 20+ km)	0	0	0	0
6g (vg, 5km)	.01	.01	.01	.01
(vg, 10+ km)	0	0	0	0

7a	(pf, N)	.1	.6	.6	.6
	(pf, NNE)	.06	.3	.3	.3
	(pf, NE)	.06	.0067	.0067	.0067
	(pf, ENE)	.06	.0067	.0067	.0067
	(pf, E)	.06	.0067	.0067	.0067
	(pf, ESE)	.06	.0133	.0133	.0133
	(pf, SE)	.06	.0067	.0067	.0067
	(pf, SSE)	.06	.0067	.0067	.0067
	(pf, S)	.06	.0067	.0067	.0067
	(pf, SSW)	.06	.0067	.0067	.0067
	(pf, SW)	.06	.0067	.0067	.0067
	(pf, WSW)	.06	.0067	.0067	.0067
	(pf, W)	.06	.0067	.0067	.0067
	(pf, WNW)	.06	.0067	.0067	.0067
	(pf, NW)	.06	.0067	.0067	.0067
	(pf, NNW)	.06	.3	.3	.3
7b	(mf, N)	.1	.01	.01	.4
	(mf, NNE)	.06	.05	.05	.2
	(mf, NE)	.06	.01	.01	.01
	(mf, ENE)	.06	.1	.1	.03
	(mf, E)	.06	.15	.15	.05
	(mf, ESE)	.06	.25	.25	.01
	(mf, SE)	.06	.05	.05	.08
	(mf, SSE)	.06	.05	.05	.03
	(mf, S)	.06	.1	.1	.05
	(mf, SSW)	.06	.05	.05	.03
	(mf, SW)	.06	.01	.01	.01
	(mf, WSW)	.06	.01	.01	.01
	(mf, W)	.06	.01	.01	.01
	(mf, WNW)	.06	.05	.05	.03
	(mf, NW)	.06	.1	.1	.05
	(mf, NNW)	.06	.01	.01	.01
7c	(lb, N)	.2	.9	.9	.9
	(lb, NNE)	.12	.5	.5	.5
	(lb, NE)	.12	.02	.02	.02
	(lb, ENE)	.12	.015	.015	.015
	(lb, E)	.12	.01	.01	.01
	(lb, ESE)	.12	.015	.015	.015
	(lb, SE)	.12	.02	.02	.02
	(lb, SSE)	.12	.015	.015	.015
	(lb, S)	.12	.01	.01	.01
	(lb, SSW)	.12	.01	.01	.01
	(lb, SW)	.12	.01	.01	.01
	(lb, WSW)	.12	.01	.01	.01
	(lb, W)	.12	.01	.01	.01
	(lb, WNW)	.12	.01	.01	.01
	(lb, NW)	.12	.015	.015	.015
	(lb, NNW)	.12	.4	.4	.4

7d (bf, all sectors)	1	1	1	1
7e (tf, N)	.04	.04	.04	.04
(tf, NNE)	.08	.08	.08	.08
(tf, NE)	.14	.14	.14	.14
(tf, ENE)	.16	.16	.16	.16
(tf, E)	.16	.16	.16	.16
(tf, ESE)	.13	.13	.13	.13
(tf, SE)	.10	.10	.10	.10
(tf, SSE)	.06	.06	.06	.06
(tf, S)	.04	.04	.04	.04
(tf, SSW)	.02	.02	.02	.02
(tf, SW)	.01	.01	.01	.01
(tf, WSW)	.01	.01	.01	.01
(tf, W)	.01	.01	.01	.01
(tf, WNW)	.01	.01	.01	.01
(tf, NW)	.01	.01	.01	.01
(tf, NNW)	.02	.02	.02	.02
7f (lf, N)	.1	.9	.9	.9
(lf, NNE)	.06	.05	.05	.05
(lf, NE)	.06	.004	.004	.004
(lf, ENE)	.06	.004	.004	.004
(lf, E)	.06	.004	.004	.004
(lf, ESE)	.06	.004	.004	.004
(lf, SE)	.06	.004	.004	.004
(lf, SSE)	.06	.004	.004	.004
(lf, S)	.06	.004	.004	.004
(lf, SSW)	.06	.004	.004	.004
(lf, SW)	.06	.004	.004	.004
(lf, WSW)	.06	.004	.004	.004
(lf, W)	.06	.004	.004	.004
(lf, WNW)	.06	.004	.004	.004
(lf, NW)	.06	.004	.004	.004
(lf, NNW)	.06	.05	.05	.05
7g (vg, N)	.1	.6	.6	.6
(vg, NNE)	.06	.3	.3	.3
(vg, NE)	.06	.01	.01	.01
(vg, ENE)	.06	.01	.01	.01
(vg, E)	.06	.01	.01	.01
(vg, ESE)	.06	.01	.01	.01
(vg, SE)	.06	.01	.01	.01
(vg, SSE)	.06	0	0	0
(vg, S)	.06	0	0	0
(vg, SSW)	.06	0	0	0
(vg, SW)	.06	0	0	0
(vg, WSW)	.06	0	0	0
(vg, W)	.06	0	0	0
(vg, WNW)	.06	0	0	0
(vg, NW)	.06	.01	.01	.01
(vg, NNW)	.06	.05	.05	.05

8a (pf)	.33	.33	.33	.33
8b (mf)	.2	.2.	.2	.2
8c (lb)	1	1	1	1
8d (bf, 0-5 km)	.01	.01	.01	.01
(bf, 5-10 km)	.001	.001	.001	.001
(bf, 10-15 km)	.0001	.0001	.0001	.0001
8e (tf)	1	1	1	1
8f (lf)	.2	.2	.2	.2
8g (vg)	.5	.5	.5	.5
9a (pf)	1	1	1	1
9b (mf)	.1	.1	.1	.1
9c (lb)	1	1	1	1
9d (bf)	1	1	1	1
9e (tf, 10 cm)	.001	.001	.001	.001
9f (lf)	.001	.001	.001	.001
9g (vg)	.5	.5	.5	.5
10 (Case 1)	1	1	1	1
(Case 2)	.2	.2	.2	.2
11	.8	.5	.9	.99

Appendices 4-7: Volcanic risks to human life at Mount St. Helens

Appendices 4-7 give approximate probabilities that a given individual, at various distances and directions from Mount St. Helens, will be killed by volcanic activity in the year following a specified date. Appendix 4 gives values as of February 1980; appendix 5, as of June 1, 1980; appendix 6, as of August 1981, and appendix 7, as of February 1982. Two cases are considered: a "full-time hermit" case in which the individual remains in the area 24 hours/day, 365 days/year, without provision for warning or evacuation; and a "typical worker" case in which an individual is in the area 8 hours/day, 220 days/year, and is able to receive warnings and evacuate.

Values are given as logarithms, to the base 10, of the calculated order of magnitude of risk. A value of -1 means that the individual has a roughly 10^{-1} or 0.1 (10%) chance of being killed at some time in the next year. When an eruption is deemed imminent, the short-term risks are, of course, much higher (perhaps 100-1000 times higher) than the annual risks shown here. When monitoring indicates that the volcano is quiet, the short-term risks are perhaps 10-100 times lower than those shown here. Values presented in this table are approximate; actual values are probably within plus or minus one order of magnitude. No rigorous error analysis is possible. No significance should be attached to any small differences in probability shown here; rather, the table is intended to indicate which are the most serious volcanic risks at each location. Appendices 4-7 form the basis, prior to final topographic corrections, of Figures 1-4, respectively.

Appendix 4. Volcanic risks at St. Helens, as of February 1980

Case 1: Full-time hermit, without radio.

(Values are the logarithms, base 10, of the annual risks of death from volcanic events, e.g., "-1" indicates a risk of 10^{-1} = 0.1; "-2" indicates a risk of 10^{-2} = 0.01, etc.)

Abbreviations: "pf" = pyroclastic flow, "mf" = mudflow, "lb" = lateral blast or pyroclastic surge; "x" = diverted topography into another sector; "--" = risk greater than 0 but less than 10^{-12}/yr.

Km from vent		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
	mf	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11
	lb	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
(risks from other volcanic hazards are less than 10-12/yr.)																	
	tot	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
10	pf	x	-10	x	x	x	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	x
	mf	x	-12	x	x	x	-11	-12	-12	-12	-12	-12	-12	-12	-12	-11	x
	lb	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11
	tot	-11	-10	-11	-11	-11	-10	-10	-10	-10	-10	-10	-10	-10	-10	-9	-11
15	pf	x	--	x	x	x	x	-10	-11	x	-10	-11	-11	-11	-10	x	x
	mf	x	--	x	x	x	x	-11	-12	x	-11	-12	-12	-12	-11	x	x
	tot	x	--	x	x	x	x	-10	-11	x	-10	-11	-11	-11	-10	x	x
20	pf	x	--	x	x	x	x	-12	x	x	-12	x	x	x	-11	x	x
	mf	x	--	x	x	x	x	-11	--	x	-11	--	--	--	-11	x	x
	tot	x	x	x	x	x	x	-11	x	x	-11	x	x	x	-11	x	x
30	mf	x	--	x	x	x	x	x	x	x	x	-11	--	x	-11	x	x
40	mf	x	--	x	x	x	x	x	x	x	x	-12	--	x	-11	x	x
50	mf	x	--	x	x	x	x	x	x	x	x	--	x	x	-12	x	x

Risks at 100 and 200 km are less than 10^{-12}/yr.

Appendix 4. Case 2: Typical Worker (same abbreviations as Case 1)

Km	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	
5	pf	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11
10	pf	x	-12	x	x	x	-11	-12	-12	-12	-12	-12	-12	-12	-12	-11	x
15	pf	x	--	x	x	x	x	-12	x	x	x	x	x	x	-12	x	x

Risks at 20, 30, 40, 50, 100 and 200 km are less than 10^{-12}/yr

Appendix 5. Volcanic risks at Mount St. Helens, as of June 1, 1980

Case 1: Full-time hermit, without radio.

(Values are the logarithms, base 10, of the annual risks of death from volcanic events, e.g., "-1" indicates a risk of 10^{-1} = 0.1; "-2" indicates a risk of 10^{-2} = 0.01, etc.) Abbreviations: "pf" = pyroclastic flow, "mf" = mudflow, "bal" = ballistic fragments, "lb" = lateral blast or pyroclastic surge, "tf" = tephra fall, "lf" = lava flow, "vg" = volcanic gases, "x" = diverted topography into another sector; "--" = risk greater than 0 but less than 10^{-12}/yr.

Km from vent		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-0	-1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-1
	mf	-4	-3	-4	-3	-2	-2	-3	-3	-3	-3	-4	-4	-4	-3	-3	-3
	lb	-1	-1	-2	-2	-3	-2	-2	-2	-3	-3	-3	-3	-3	-3	-2	-1
	bal	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4
	tf	-4	-4	-3	-3	-3	-3	-3	-4	-4	-4	-4	-4	-4	-4	-4	-4
	lf	-4	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-5
	vg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tot	-0	-0	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-0
10	pf	x	-1	x	x	x	-3	-3	-3	-3	-3	-3	-3	-3	-3	-1	x
	mf	x	-3	x	x	x	-2	-3	-3	-3	-3	-4	-4	-4	-3	-3	x
	lb	-1	-1	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-2
	bal	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
	tf	-4	-4	-3	-3	-3	-3	-4	-4	-4	-4	-5	-5	-5	-5	-5	-4
	lf	x	-6	x	x	x	-6	-7	-7	-7	-7	-7	-7	-7	-7	-4	x
	tot	-1	-1	-3	-3	-3	-2	-2	-3	-3	-3	-3	-3	-3	-3	-1	-2
15	pf	x	--	x	x	x	x	-3	-4	x	-4	-4	-4	-4	-2	x	x
	mf	x	--	x	x	x	x	-2	-3	x	-2	-4	-4	-4	-3	x	x
	lb	-2	-2	-3	-3	-4	-3	-3	-3	-4	-4	-4	-4	-4	-4	-3	-2
	bal	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-4
	lf	x	--	x	x	x	x	-7	-8	x	-7	-8	-8	-8	-5	x	x
	tot	-2	-2	-4	-4	-4	-4	-3	-3	-4	-3	-4	-4	-4	-2	-4	-2

Appendix 5. Case 1: Full time hermit, without radio (continued).

Km		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
20	pf	x	--	x	x	x	x	-4	-5	x	-5	-5	-5	-5	-3	x	x
	mf	x	--	x	x	x	x	-2	-3	x	-3	-4	-4	-4	-3	x	x
	lb	-2	-2	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-2
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5
	lf	x	--	x	x	x	x	--	--	x	--	--	--	--	--	x	x
	tot	-2	-2	-3	-3	-3	-3	-2	-3	-4	-3	-4	-4	-4	-3	-4	-2
30	pf	x	--	x	x	x	x	x	x	x	--	--	--	--	--	x	x
	mf	x	--	x	x	x	x	x	x	x	--	-3	-4	--	-3	x	x
	lb	-3	-3	-4	-4	-5	-4	-4	-4	-5	-5	-5	-5	-5	-5	-4	-3
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5
	tot	-3	-3	-4	-4	-4	-4	-4	-4	-4	-4	-3	-4	-4	-3	-4	-3
40	pf	x	--	x	x	x	x	x	x	x	x	--	--	x	--	x	x
	mf	x	--	x	x	x	x	x	x	x	x	-3	-5	x	-3	x	x
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5
	tot	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-3	-4	-5	-3	-5	-5
50	pf	x	--	x	x	x	x	x	x	x	x	--	--	x	--	x	x
	mf	x	--	x	x	x	x	x	x	x	x	-3	-5	x	-3	x	x
	tf	-5	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5
	tot	-5	-4	-4	-4	-4	-4	-4	-4	-5	-5	-3	-5	-5	-3	-5	-5
100	tf	-5	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5
200	tf	-5	-5	-5	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-6

Appendix 5.(continued) Case 2: Typical Worker (same abbreviations as Case 1)

Km		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-1	-2	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-2
	mf	-5	-4	-5	-4	-3	-3	-4	-4	-4	-4	-5	-5	-5	-4	-4	-4
	lb	-2	-2	-3	-3	-4	-3	-3	-3	-4	-4	-4	-4	-4	-4	-3	-2
	bal	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
	tf	-5	-5	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5
	lf	-5	-6	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-6
	vg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tot	-1	-1	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-1
10	pf	x	-2	x	x	x	-4	-4	-4	-4	-4	-4	-4	-4	-4	-2	x
	mf	x	-4	x	x	x	-3	-4	-4	-4	-4	-5	-5	-5	-4	-4	x
	lb	-2	-2	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3
	bal	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
	tf	-5	-5	-4	-4	-4	-4	-5	-5	-5	-5	-6	-6	-6	-6	-6	-5
	lf	x	-7	x	x	x	-7	-8	-8	-8	-8	-8	-8	-8	-8	-5	x
	tot	-2	-2	-4	-4	-4	-3	-3	-4	-4	-4	-4	-4	-4	-4	-2	-3
15	pf	x	--	x	x	x	x	-4	-5	x	-5	-5	-5	-5	-3	x	x
	mf	x	--	x	x	x	x	-3	-4	x	-3	-5	-5	-5	-4	x	x
	lb	-3	-3	-4	-4	-5	-4	-4	-4	-5	-5	-5	-5	-5	-5	-4	-3
	bal	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tf	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
	lf	x	--	x	x	x	x	-8	-9	x	-8	-9	-9	-9	-6	x	x
	tot	-3	-3	-4	-4	-4	-4	-3	-4	-4	-3	-4	-4	-4	-3	-4	-3
20	pf	x	--	x	x	x	x	-5	-6	x	-6	-6	-6	-6	-4	x	x
	mf	x	--	x	x	x	x	-3	-4	--	-4	-5	-5	-5	-4	--	--
	lb	-3	-3	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-3
	tf	-5	-5	-5	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-7	-7
	tot	-3	-3	-4	-4	-4	-4	-3	-4	-5	-4	-5	-5	-5	-4	-5	-3
30	mf	--	--	--	--	--	--	--	--	--	--	-4	-5	--	-4	--	--
	lb	-4	-4	-5	-5	-6	-5	-5	-5	-6	-6	-6	-6	-6	-6	-5	-4
	tf	-5	-5	-5	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-6
	tot	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5	-4	-5	-5	-4	-5	-4
40	mf	x	--	x	x	x	x	x	x	x	x	-4	-6	x	-4	x	x
	tf	-5	-5	-5	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-6
	tot	-5	-5	-5	-5	-5	-5	-5	-5	-5	-6	-4	-6	-6	-4	-6	-6
50	mf	x	--	x	x	x	x	x	x	x	x	-4	-6	x	-4	x	x
	tf	-6	-5	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-6	-6
	tot	-6	-5	-5	-5	-5	-5	-5	-5	-6	-6	-4	-6	-6	-4	-6	-6
100	tf	-6	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6
200	tf	-6	-6	-6	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7

Appendix 6. Volcanic risks at Mount St. Helens, as of August 1981:
Case 1: Full-time hermit, without radio.
(Values are the logarithms, base 10, of the annual risks of death from volcanic events, e.g., "-1" indicates a risk of 10^{-1} = 0.1; "-2" indicates a risk of 10^{-2} = 0.01, etc.)
Abbreviations: "pf" = pyroclastic flow, "mf" = mudflow, "bal" = ballistic fragments, "lb" = lateral blast or pyroclastic surge, "tf" = tephra fall, "lf" = lava flow, "vg" = volcanic gases, "x" = diverted topography into another sector; "-" = risk greater than 0 but too small to estimate.

Km from vent		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-1	-1	-3	-3	-3	-2	-3	-3	-3	-3	-3	-3	-3	-3	-3	-1
	mf	-4	-3	-4	-3	-3	-3	-3	-3	-3	-3	-4	-4	-4	-3	-3	-3
	lb	-1	-1	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-2
	bal	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5
	lf	-3	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-5
	vg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tot	-1	-1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-1
10	pf	x	-2	x	x	x	-3	-3	-3	-3	-3	-3	-3	-3	-3	-1	x
	mf	x	-4	x	x	x	-3	-4	-4	-3	-4	-4	-4	-4	-4	-3	x
	lb	-2	-2	-3	-3	-4	-3	-3	-3	-4	-4	-4	-4	-4	-4	-3	-2
	bal	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5
	lf	x	-5	x	x	x	-6	-7	-7	-7	-7	-7	-7	-7	-7	-4	x
	tot	-2	-2	-3	-3	-3	-2	-3	-3	-3	-3	-3	-3	-3	-3	-1	-2
15	pf	x	--	x	x	x	x	-4	-4	x	-4	-4	-4	-4	-2	x	x
	mf	x	--	x	x	x	x	-3	-4	x	-3	-5	-5	-5	-3	x	x
	lb	-2	-2	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-2
	bal	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tf	-5	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5
	lf	x	--	x	x	x	x	-7	-7	x	-7	-7	-7	-7	-5	x	x
	tot	-2	-2	-4	-4	-4	-4	-3	-3	-4	-3	-4	-4	-4	-2	-4	-2

Appendix 6. Case 1: Full time hermit, without radio (continued).

Km		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
20	pf	x	--	x	x	x	x	−5	−5	x	−5	−5	−5	−5	−3	x	x
	mf	x	--	x	x	x	x	−3	−4	x	−3	−5	−5	−5	−3	x	x
	lb	−2	−3	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−3
	tf	−5	−4	−4	−4	−4	−4	−4	−5	−5	−5	−5	−5	−5	−5	−5	−5
	lf	x	--	x	x	x	x	--	--	x	--	--	--	--	--	x	x
	tot	−2	−3	−4	−4	−4	−4	−3	−4	−4	−3	−4	−4	−4	−3	−4	−3
30	pf	x	--	x	x	x	x	x	x	x	--	--	--	--	--	x	x
	mf	x	--	x	x	x	x	x	x	x	--	−3	−5	--	−4	x	x
	lb	−3	−3	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5	−3
	tf	−5	−5	−4	−4	−4	−4	−4	−5	−5	−5	−5	−5	−5	−5	−5	−5
	tot	−3	−3	−4	−4	−4	−4	−4	−4	−5	−5	−3	−5	−5	−4	−5	−3
40	pf	x	--	x	x	x	x	x	x	x	x	--	--	x	--	x	x
	mf	x	--	x	x	x	x	x	x	x	x	−4	−5	x	−4	x	x
	tf	−5	−5	−4	−4	−4	−4	−5	−5	−5	−5	−6	−6	−6	−6	−6	−5
	tot	−5	−5	−4	−4	−4	−4	−5	−5	−5	−5	−4	−5	−6	−4	−6	−5
50	pf	x	--	x	x	x	x	x	x	x	x	--	--	x	--	x	x
	mf	x	--	x	x	x	x	x	x	x	x	−4	−5	x	−4	x	x
	tf	−5	−5	−4	−4	−4	−4	−5	−5	−5	−5	−6	−6	−6	−6	−6	−5
	tot	−5	−5	−4	−4	−4	−4	−5	−5	−5	−5	−4	−5	−6	−4	−6	−5
100	tf	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5	−6	−6	−6	−6	−6	−5
200	tf	−6	−6	−5	−5	−5	−5	−5	−6	−6	−6	−6	−6	−6	−6	−6	−6

Appendix 6. Case 2: Typical Worker (same abbreviations as Case 1)

Km		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-2	-3	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3
	mf	-6	-5	-6	-5	-4	-4	-5	-5	-5	-5	-6	-6	-6	-5	-5	-5
	lb	-3	-3	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-3
	bal	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
	tf	-6	-6	-5	-5	-5	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-6
	lf	-5	-6	-8	-8	-7	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-6
	vg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tot	-2	-3	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3
10	pf	x	-4	x	x	x	-5	-5	-5	-5	-5	-5	-5	-5	-5	-3	x
	mf	x	-5	x	x	x	-4	-5	-5	-5	-5	-6	-6	-6	-5	-5	x
	lb	-3	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-4
	bal	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8	-8
	tf	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-6
	lf	x	-7	x	x	x	-8	-8	-8	-8	-8	-8	-8	-8	-8	-6	x
	tot	-3	-3	-5	-5	-5	-4	-5	-5	-5	-5	-5	-5	-5	-5	-3	-4
15	pf	x	--	x	x	x	x	-6	-6	x	-6	-6	-6	-6	-4	x	x
	mf	x	--	x	x	x	x	-5	-6	x	-5	-6	-6	-6	-5	x	x
	lb	-4	-4	-5	-6	-6	-6	-5	-6	-6	-6	-6	-6	-6	-6	-6	-4
	bal	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tf	-6	-6	-6	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7
	lf	x	--	x	x	x	x	-8	-9	x	-9	-9	-9	-9	-7	x	x
	tot	-4	-4	-5	-5	-5	-5	-4	-5	-6	-5	-5	-5	-5	-4	-6	-4
20	pf	x	--	--	--	--	--	-7	-7	--	-7	-7	-7	-7	-5	--	--
	mf	x	--	--	--	--	--	-5	-6	--	-5	-6	-6	-6	-5	--	--
	lb	-4	-4	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-4
	tf	-6	-6	-6	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7
	tot	-4	-4	-6	-6	-6	-6	-5	-5	-6	-5	-6	-6	-6	-5	-6	-4
30	mf	--	--	--	--	--	--	--	--	--	--	-5	-7	--	-5	--	--
	lb	-5	-5	-6	-7	-7	-7	-6	-7	-7	-7	-7	-7	-7	-7	-7	-5
	tf	-7	-6	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7	-7
	tot	-5	-5	-6	-6	-6	-6	-6	-6	-6	-6	-5	-6	-7	-5	-6	-5
40	mf	x	--	x	x	x	x	x	x	x	x	-5	-7	x	-5	x	x
	tf	-7	-6	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7	-7
	tot	-7	-6	-6	-6	-6	-6	-6	-6	-7	-7	-5	-7	-7	-5	-7	-7
50	mf	x	--	x	x	x	x	x	x	x	x	-6	-7	x	-6	x	x
	tf	-7	-6	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7	-7	-7
	tot	-7	-6	-6	-6	-6	-6	-6	-7	-7	-7	-6	-7	-7	-6	-7	-7
100	tf	-7	-7	-6	-6	-6	-6	-6	-7	-7	-7	-7	-7	-7	-7	-7	-7
200	tf	-8	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8	-8

Appendix 7. Volcanic risks at Mount St. Helens, as of February 1982:
Case 1: Full-time hermit, without radio.
(Values are the logarithms, base 10, of the annual risks of death from volcanic events, e.g., "-1" indicates a risk of $10^{-1} = 0.1$; "-2" indicates a risk of $10^{-2} = 0.01$, etc.)
Abbreviations: "pf" = pyroclastic flow, "mf" = mudflow, "bal" = ballistic fragments, "lb" = lateral blast or pyroclastic surge, "tf" = tephra fall, "lf" = lava flow, "vg" = volcanic gases, "x" = diverted topography into another sector; "-" = risk greater than 0 but too small to estimate.

Km from vent		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-1	-1	-3	-3	-3	-2	-3	-3	-3	-3	-3	-3	-3	-3	-3	-1
	mf	-2	-2	-4	-3	-3	-4	-3	-3	-3	-3	-4	-4	-4	-3	-3	-2
	lb	-1	-2	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-2
	bal	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
	tf	-4	-4	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5
	lf	-4	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-5
	vg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tot	-1	-1	-2	-2	-2	-2	-2	-2	-2	-3	-3	-3	-3	-3	-2	-1
10	pf	x	-2	x	x	x	-3	-4	-4	-4	-4	-4	-4	-4	-4	-1	x
	mf	x	-3	x	x	x	-3	-3	-4	-3	-4	-4	-4	-4	-4	-2	x
	lb	-2	-2	-3	-3	-4	-3	-3	-3	-4	-4	-4	-4	-4	-4	-3	-2
	bal	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
	tf	-5	-4	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5
	lf	x	-5	x	x	x	-6	-7	-7	-7	-7	-7	-7	-7	-7	-4	x
	tot	-2	-2	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-1	-2
15	pf	x	--	x	x	x	x	-4	-5	x	-4	-5	-5	-5	-2	x	x
	mf	x	--	x	x	x	x	-3	-4	x	-3	-4	-4	-4	-2	x	x
	lb	-2	-2	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-2
	bal	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tf	-5	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5
	lf	x	--	x	x	x	x	-7	-7	x	-7	-7	-7	-7	-5	x	x
	tot	-2	-2	-4	-4	-4	-4	-3	-3	-4	-3	-4	-4	-4	-2	-4	-2

Appendix 7. Case 1: Full time hermit, without radio (continued).

Km		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
20	pf	x	--	x	x	x	x	-5	-6	x	-5	-6	-6	-6	-3	x	x
	mf	x	--	x	x	x	x	-3	-4	x	-3	-4	-4	-4	-3	x	x
	lb	-2	-3	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3
	tf	-5	-4	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5
	lf	x	--	x	x	x	x	--	--	x	--	--	--	--	--	x	x
	tot	-2	-3	-4	-4	-4	-4	-3	-4	-4	-3	-4	-4	-4	-3	-4	-3
30	pf	x	--	x	x	x	x	x	x	x	--	--	--	--	--	x	x
	mf	x	--	x	x	x	x	x	x	x	--	-3	-5	--	-3	x	x
	lb	-3	-3	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-3
	tf	-5	-5	-4	-4	-4	-4	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5
	tot	-3	-3	-4	-4	-4	-4	-4	-4	-5	-5	-3	-4	-5	-3	-5	-3
40	pf	x	--	x	x	x	x	x	x	x	x	--	--	x	--	x	x
	mf	x	--	x	x	x	x	x	x	x	x	-4	-5	x	-3	x	x
	tf	-5	-5	-4	-4	-4	-4	-5	-5	-5	-5	-6	-6	-6	-6	-6	-5
	tot	-5	-5	-4	-4	-4	-4	-5	-5	-5	-5	-4	-5	-6	-3	-6	-5
50	pf	x	--	x	x	x	x	x	x	x	x	--	--	x	--	x	x
	mf	x	--	x	x	x	x	x	x	x	x	-4	-5	x	-3	x	x
	tf	-5	-5	-4	-4	-4	-4	-5	-5	-5	-5	-6	-6	-6	-6	-6	-5
	tot	-5	-5	-4	-4	-4	-4	-5	-5	-5	-5	-4	-5	-6	-3	-6	-5
100	tf	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-5
200	tf	-6	-6	-5	-5	-5	-5	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6

Appendix 7. Case 2: Typical Worker (same abbreviations as Case 1)

Km		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
5	pf	-3	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-4
	mf	-5	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-5
	lb	-4	-4	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-4
	bal	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
	tf	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-7
	lf	-6	-7	-9	-9	-8	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-7
	vg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tot	-3	-4	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5	-4
10	pf	x	-5	x	x	x	-6	-6	-6	-6	-6	-6	-6	-6	-6	-4	x
	mf	x	-5	x	x	x	-6	-6	-6	-6	-6	-7	-7	-7	-6	-5	x
	lb	-4	-5	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-5
	bal	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9
	tf	-7	-7	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8
	lf	x	-8	x	x	x	-9	-9	-9	-9	-9	-9	-9	-9	-9	-7	x
	tot	-4	-4	-6	-6	-6	-5	-6	-6	-6	-6	-6	-6	-6	-6	-4	-5
15	pf	x	--	x	x	x	x	-7	-7	x	-7	-7	-7	-7	-5	x	x
	mf	x	--	x	x	x	x	-6	-7	x	-6	-7	-7	-7	-5	x	x
	lb	-5	-5	-6	-7	-7	-7	-6	-7	-7	-7	-7	-7	-7	-7	-7	-5
	bal	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	tf	-7	-7	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8
	lf	x	--	x	x	x	x	-9	-10	x	-10	-10	-10	-10	-8	x	x
	tot	-5	-5	-6	-6	-6	-6	-6	-6	-7	-6	-6	-6	-6	-5	-7	-5
20	pf	x	--	x	x	x	x	-8	-8	x	-8	-8	-8	-8	-6	x	x
	mf	x	--	x	x	x	x	-6	-7	x	-6	-7	-7	-7	-5	x	x
	lb	-5	-5	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-5
	tf	-7	-7	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8
	tot	-5	-5	-7	-7	-7	-7	-6	-6	-7	-6	-7	-7	-7	-5	-7	-5
30	mf	x	--	x	x	x	x	x	x	x	x	-6	-7	--	-5	--	--
	lb	-6	-6	-7	-8	-8	-8	-7	-8	-8	-8	-8	-8	-8	-8	-8	-6
	tf	-8	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8	-8
	tot	-6	-6	-7	-7	-7	-7	-7	-7	-7	-7	-6	-7	-8	-5	-7	-6
40	mf	x	--	x	x	x	x	x	x	x	x	-6	-7	x	-6	x	x
	tf	-8	-7	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8	-8
	tot	-8	-7	-7	-7	-7	-7	-7	-7	-8	-8	-6	-7	-8	-6	-8	-8
50	mf	x	--	x	x	x	x	x	x	x	x	-7	-8	x	-6	x	x
	tf	-8	-7	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8	-8	-8
	tot	-8	-7	-7	-7	-7	-7	-7	-8	-8	-8	-7	-8	-8	-6	-8	-8
100	tf	-8	-8	-7	-7	-7	-7	-7	-8	-8	-8	-8	-8	-8	-8	-8	-8
200	tf	-9	-8	-8	-8	-8	-8	-8	-8	-9	-9	-9	-9	-9	-9	-9	-9