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Semiquantitative assessment of changing volcanic risk at Mount St. Helens, Washington

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Abstract

A method for quantifying long- and intermediate-term volcanic risk (year to year and month to month, respectively) is extended to cover short-term (week to week or shorter) variation in the activity of Mount St. Helens. The short-term state of the volcano is interpreted from observation of eruptions and eruption precursors; estimates of risk are based on those interpretations (factual statements and forecasts or predictions) rather than on any specific measure of activity.

Long- and intermediate-term estimates of risk to persons near Mount St. Helens, as of January 1984, suggest slightly lower risk than estimated in February 1982. New short-term estimates of risk during various states of the volcano vary by approximately 4 orders of magnitude from a quiet state to an explosive eruption. Estimated risks also vary greatly with distance and direction from the volcano, and with human factors such as the duration of exposure to risk and the reliability of predictions and warnings. Uncertainties in all of the estimates are high--at least an order of magnitude.

The estimates of risk in this report are likely to change as the current series of eruptions continues and as more is learned about volcanic processes at Mount St. Helens and elsewhere. However, the methods of risk estimation described here are flexible enough to be applied to changing conditions. Examination of the method as well as the resulting risk estimates will illustrate the various factors that control volcanic risks around Mount St. Helens, the sources of uncertainties, and what might be done to reduce both risks and uncertainties--information that may be more useful than the risk estimates themselves.

Introduction

Volcanic <u>hazards</u> are volcanic phenomena (e.g., pyroclastic flows, ashfall) that can pose a threat to persons or property. Volcanic <u>risk</u> is the exposure of individuals to death or injury, and of structures to damage from volcanic hazards. Residents and officials responsible for public safety near active volcanoes commonly ask volcanologists to appraise risk at various places near the volcano and during various states of the activity of the volcano. Volcanologists may reply in qualitative terms such as "high" or "low," but such terms have different meanings for different people. In addition, volcanologists may compare volcanic risk at one location and time to risk at another location and time, with words such as "much higher than at ... (or during ...)," or "about the same as at ... (or during ...)"--more helpful, but still difficult for the non-volcanologist to understand or use in discussions with others. Some way is needed to translate the volcanologist's appraisal of volcanic risk into terms that can be compared to more familiar risks.

A method for quantifying long- to intermediate-term volcanic risk was described by Newhall (1982) (U.S. Geological Survey Open-File Report 82-396). The present report updates Open-File Report 82-396 (henceforth referred to as OF 82-396), and describes an extension of its method to permit assessment of risk during various short-term states of Mount St. Helens. Short-term states are defined on the basis of public statements made by the U.S. Geological Survey regarding Mount St. Helens; the statements are themselves based on observations of eruptions and eruption precursors. The five short-term states are:

quiet, when seismicity, ground deformation, and gas emissions are at low levels such as observed during previous quiet periods, and have been at these low levels for at least a few days;

slight unrest, a state of slightly elevated seismicity, ground deformation, or gas emission, at least several days in advance of an eruption (=the time between the issuance of an extended outlook advisory and the upgrading or cancellation of that advisory);

severe unrest, a state of high or rapidly accelerating precursory seismicity and ground deformation (=those periods of public warnings that an eruption will begin within 3 days or less);

dominantly non-explosive dome growth, when the dome of Mount St. Helens is growing day by day, endogenously (internally) or exogenously (externally, with new lobes), and no geophysical or geochemical evidence suggests that more explosive activity is imminent; and

explosive eruption, if explosive activity is in progress, accompanied by an eruption column several km or more above the crater rim, or by a pyroclastic flow, surge, or blast extending laterally for several kilometers or more, or if such activity has occurred within the previous day.

The approach described in this report and in OF 82-396 is neither mathematically sophisticated nor rigorously quantitative. Rather, it is an attempt to make semi-quantitative approximations of risk that will be more useful to public officials than purely qualitative statements such as those described above. Uncertainties in estimates of volcanic risk are inevitably high, and public officials concerned with risk mitigation at Mount St. Helens have prudently used several lines of information, including but not limited to risk estimates from OF 82-396, for decisions about public safety near Mount St. Helens. Equally or more important than the risk estimates themselves, OF 82-396 has helped public officials to understand factors that control long- and intermediate-term risks, and to compare those risks in various locations. The present report is intended to help public officials understand the effects of various short-term states of Mount St. Helens on risks around the volcano.

In this report, long-term refers to periods of years or longer, intermediate-term refers to periods of months, and short-term refers to periods of weeks or less. Occasional references to long-term, intermediate-term, and short-term risk are to risks averaged over those lengths of time ("timeframes") rather than to risks summed over those periods.

Immediate death and structural damage are the only risks considered in this report; long-term risk in the sense of slow-acting effects on persons or structures (e.g., effects of prolonged exposure of the respiratory system to volcanic dust, or the slow corrosive effect of acidic rainfall near a volcano, or flooding as an indirect result of slow sedimentation downstream from a volcano) are beyond the scope of this report.

No attempt is made to consider the population at risk or the number and value of structures in each area near Mount St. Helens. These areas are sparsely populated, and many of the individuals who are exposed to risk are present only a small fraction of the time. Few structures now exist near Mount St. Helens. Thus the approach in this report is not to estimate the total risk to present residents or structures, but rather to estimate risk to an individual or a structure that might be near Mount St. Helens in the future.

A brief review of the methodology described in OF 82-396, and modifications regarding types of eruptions and the exposure level of individuals

The probability of a volcanic hazard 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 events, $E_{2,3,...n}$. Each conditional probability $P_{n\ n-1}$ 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 more of explosive or non-explosive supply of volcanic material onto the earth's surface, without any repose that lasts longer than 1 week);

$E_{4a,b,c,d}$ = four mutually exclusive types of eruptions, namely (a) a major explosive eruption (defined here as one producing 0.1 km^3 or more of pyroclastic ejecta) (e.g., the eruption of Mount St. Helens on May 18, 1980), (b) a minor explosive eruption (dominantly explosive, but producing less than 0.1 km^3 of pyroclastic ejecta) (e.g., the eruption of Mount St. Helens on June 12, 1980), (c) dominantly non-explosive dome growth with greatly subordinate explosive activity (e.g., the eruption of Mount St. Helens from February 1983 and continuing as of January 1984), and (d) an entirely non-explosive eruption (e.g., September 1981), respectively;

E_{5a-g} = seven eruptive phenomena that can occur singly or together, namely (a) pyroclastic flows, (b) mudflows, (c) laterally-directed blasts, (d) ballistic fragments, (e) tephra fall, (f) lava flows, and (g) dangerous concentrations of volcanic gases;

E_{6a-i} = events 5_{a-g} that reach at least as far as nine specified distances from the vent (5, 10, 15, 20, 30, 40, 50, 100, and 200 km);

E_{7a-p} = events 6_{a-i} that affect any one of sixteen 22.5° 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 would be lethal or destructive at that site if a person or structure were present.

The probability of a volcanic event (E_n) is P_n, where

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

That is, the probability of a volcanic event E_n is the probability of the most general event E_1, times the probabilities of increasingly specific events E_2 given E_1, E_3 given E_2, ... E_n given E_{n-1}.
The probability of a relatively general event, e.g., the beginning of an eruption (E_3), is calculated as

$$P_3 = P_1 \times P_{2|1} \times P_{3|2}.$$

The probability of a more specific event, e.g., of a pyroclastic flow that will be lethal at a specific location 10 km due north of the vent, is calculated as

$$P_{9a} = P_1 \times P_{2|1} \times P_{3|2}$$
$$\times [(P_{4a|3} \times P_{5a|4a})+(P_{4b|3} \times P_{5a|4b})+(P_{4c|3} \times P_{5a|4c})]$$
$$\times P_{6b|5a} \times P_{7a|6b} \times P_{8a|7a} \times P_{9a|8a}.$$

The present report changes the conventions for E_4 from those used in OF 82-396, for it became apparent that the definition of three broad types of eruptions--(4a) major explosive, (4b) minor explosive, and (4c) non-explosive--did not satisfactorily address the hazards associated with dominantly but not entirely non-explosive dome growth. In OF 82-396, an explosion during dome growth caused that eruption to be included in the category of minor explosive eruptions, and the category of non-explosive eruptions did not allow for any explosive activity at all. However, at a volcano with dominantly andesitic and dacitic magma, such as Mount St. Helens, even dominantly non-explosive eruptions are likely to have a minor explosive component. A more useful categorization of eruptions is therefore adopted: (4a) major explosive eruptions, as before, (4b) moderate to small-size explosive eruptions in which explosive activity is the dominant activity, (4c) dominantly non-explosive eruptions, e.g., dome growth, that can also have minor explosive activity, and (4d) entirely non-explosive eruptions.

The newly-defined (4c) category is of particular interest because eruptions of Mount St. Helens since December 1980 have been dominantly non-explosive, and nearly continuous dome growth has been in progress since early February 1983. Rockfalls and ballistic fragments from the growing dome have reached only a few hundred meters from the dome. However, future dome growth at Mount St. Helens could pose hazards outside the crater, principally dome-collapse pyroclastic flows (sometimes called a "nuees ardentes d'avalanche" or "Merapi-type pyroclastic flows"). Large, hot rockfalls that travel down steep slopes can become pyroclastic flows that travel several kilometers. The vertical drop and gradient over which such masses travel exerts a major control on the distance to which they travel. Such flows are relatively low energy events if compared to other types of pyroclastic flows, but they are nonetheless destructive and dangerous enough to consider as a hazard during dominantly non-explosive eruptions.

To calculate volcanic risk to an individual's life, the probability of the hazard (P_9) is multiplied by the probability of routine exposure to that hazard (P_{10}) and the probability that an individual will remain in the area even when an eruption is imminent (P_{11}). In OF 82-396, P_{10} and P_{11} were defined for two occupancy cases--the "full-time resident" and the "typical worker". The first case assumed that an individual remains near the volcano 100% of each year (P_{10}=1.0), without provision for warning or evacuation (P_{11}=1.0); the second case assumed that an individual remains near the volcano 20% of each year (P_{10}=0.2), with full provision for warning and evacuation (P_{11}= a low number). In view of the large number of visitors to the new Mount St. Helens National Volcanic Monument, this report considers a third case--the occasional visitor--who is assumed to be near the volcano 1% of each year (P_{10}=0.01), and who would be warned and evacuated by emergency officials if necessary (P_{11}= a low number, assumed to be the same for the typical worker).

Uncertainties and subjectivity in estimates of volcanic risk

The principal uncertainties in estimates of volcanic risk are due to inadequate data and to the assumptions made when data are unavailable. Most of these uncertainties are described on p. 5-6 of OF 82-396. The calculations are sensitive to even small differences in input values, and readers should be aware that at most steps, seemingly reasonable but slightly different input values can give quite different results. For example, estimates of P_{11}--the probability that persons will still be near the volcano even if an eruption is imminent--are quite subjective and dependent on individuals themselves and on rules regarding access near Mount St. Helens. Slightly higher or lower values for P_{11} than those assumed here will lead to significantly different estimates of risk.

Strictly objective selection of input values does not always yield reasonable estimates of risk, and what seem to be the most reasonable estimates are a result of several iterations of selecting input values, checking results, and revising input values until the estimates are internally consistent and intuitively reasonable. Internal consistency and reasonableness is evaluated by comparing the estimated risks from one location to another, from one occupancy case to another, and from one time (or level of volcanic activity) to another. For example, risks at the southern edge of Spirit Lake are intuitively higher than those at a comparable distance south of the volcano, during the same level of volcanic activity. Similarly, risks at a given location are higher during an eruption than during quiet periods. The calculations naturally show this to be so, but if they showed otherwise, the input values should be re-examined. Alternate but still reasonable values may be tried until intuitively reasonable relations between these two places and all other places and cases are shown. In some comparisons, the relation may not be intuitively obvious, e.g., whether risks during periods of dome growth are higher or lower than those during periods of slight unrest. In such cases, my approach is to use what seem to be the most reasonable, objective input values available, and to accept the output values unless they are clearly unreasonable.

This iterative process, or "fine-tuning," requires subjective volcanologic judgement of the user, and the resulting risk estimates are thus partly subjective. What seems reasonable to one volcanologist, however, may not seem reasonable to another. The method of estimating volcanic risks does not guarantee "correct answers"; instead it requires that persons who estimate the risks be able to explain the basis of their estimates. This iterative approach also increases the likelihood that relative risks, i.e., the differences among risks at various times or places, will be reasonable even if the absolute magnitudes of the estimates are incorrect.

As put by a colleague, estimates from this method are "guesses that are not intuitively objectionable, bracketed by higher or lower estimates that evoke visceral rejection."

Given that estimates of the probabilities of volcanic events have high uncertainties, are the uncertainties so high that the estimates are misleading or useless? How great are the uncertainties, and what level of uncertainty is tolerable for the purposes for which estimates in this report might be used? The uncertainty of a probability estimate is a definable function of uncertainties in each item of data upon which the probability is based. How can one quantify the uncertainty of a judgement about the most appropriate of several possible data sets to be considered, e.g., at steps 4 and 5? Or how can one quantify the uncertainty of a value that is assumed, e.g., values for P_{11}?

As an alternative to rigorous assessment of uncertainty, I have tested how much the calculated risks vary if alternate data sets and assumptions are used. By using the values that will lead to highest and lowest risks, I can easily vary risk estimates by plus or minus one or two orders of magnitude, and with extreme assumptions vary them by three or even four orders of magnitude. Relative risks at different times or locations, regardless of the data and assumptions used, do not vary by as much.

The tolerable level of uncertainty involves a balance between the value of making an estimate and the consequences of being wrong. Decisions about tolerable uncertainty are like those about acceptable risk--best made by individuals who can consider a full spectrum of social, economic, and scientific factors. It is the job of the volcanologist to estimate the risks and the uncertainties in those estimates, and to let public officials and private individuals decide whether and how to use these estimates.

The timeframe of risk assessments and the concept of probability gain

In general, a forecast or risk assessment looks no farther forward than backward. If the data are exclusively from the geologic or historical record, the resulting risk assessment is for the long-term future. If the data refer to activity of the volcano in the previous few months, the risk assessment probably looks ahead for a few weeks to months. If the data are from the previous few hours, the risk assessment will be for the next few hours, and so on. A long-term hazard or risk assessment provides a wide spectrum of possibilities--a context within which to interpret short-term activity. A short-term hazard or risk assessment generally forecasts a subset of the activity described in the long-term forecast, although in special circumstances an unprecedented type of activity may need to be forecast for the short-term (e.g., the landslide and blast of May 18, 1980).

One approach to estimating intermediate- and short-term risks is to modify long-term estimates according to the activity of the volcano in the preceding months, weeks, or less. Aki (1981) defined "probability gain" as the ratio of the conditional probability of an event, given that certain precursors to that event have been observed, to the unconditional or long-term probability of that event. A probability gain of 10 signifies that the event is 10 times more likely once the precursors have occurred than over the long-term. A probability gain of 0.1 signifies that the event is 10 times less likely than over the long-term, as might occur if there were a decline in precursory activity below normal background levels, or if one such event had just occurred and another could not yet reasonably recur. The concept of probability gain has been applied to earthquakes (Cao and Aki, 1983) and in a modified form to volcanic eruptions (Klein, 1984).

In OF 82-396, objective estimates of long-term probabilities of volcanic events were modified by an emphasis on the recent behavior of the volcano. For example, a moderately high long-term probability of an explosive eruption at Mount St. Helens was thought to be lower for the immediate term (during the remainder of 1982) because eruptions in 1981 and early 1982 were dominantly non-explosive and because monitoring data showed significant declines in seismicity, edifice-wide ground deformation, and gas emission compared to that in the explosive period of 1980. In this example, the probability gain relative to the long-term probabilities of the 1980s was less than 1.

The present report estimates the probability gain for short-term changes in the level or rate of change of precursory activity at Mount St. Helens. Ideally, such an estimate would be based directly on correlations between measured precursors and eruptions, as recently done for Kilauea by Klein (1984). However, the data for Mount St. Helens are still too few, monitoring stations too short-lived, and the behavior of the volcano too variable to assess the probability gain due to specific, rigidly defined changes in precursor activity. It would be unsound at the present time to conclude that a specified increase, for example, of seismicity or ground deformation, implies a quantifiable increase in the probability of an eruption. A more flexible scheme, but one that is harder to apply consistently, is to judge from each change in precursory activity how soon an eruption is likely to start, and then to estimate the resulting probability gain.

At Mount St. Helens, short-term predictions have been made using "prediction windows"--periods within which the eruption is expected to begin (Swanson and others, 1983). Prediction windows become progressively shorter as the eruption nears. Typically in 1981-1982, windows of successive predictions were 1 to 3 weeks, 1 to 5 days, and 12 to 24 hours "wide"; prediction windows were largely irrelevant in 1983 because dome growth was more continuous. In this report, short-term probability gain is estimated for only three pre-eruption conditions--quiet, slight unrest, and severe unrest. Broadly, these correspond, respectively, to periods when no eruption is predicted, periods in which an eruption is expected to begin within three weeks, and periods in which an eruption is expected to begin within three days or less. Consideration of probability gain as a function of predictions (rather than the more conventional opposite relation) incorporates possible error on the part of scientists who are predicting eruptions. That inclusion is an advantage in that we can provide public officials with a simple, empirically sound statement, but a disadvantage in that it obscures whether a "false alarm" is a human error or a "false start," in which precursors begin but never complete a trend toward an eruption.

An entirely different approach to estimating intermediate- and short-term gain in the probability of an eruption is through statistical analysis of repose periods (e.g., Wickmann, 1966; Wadge and Guest, 1981; Wood and Whitford-Stark, 1982; Klein, 1982). At some volcanoes, the probability of an eruption is time-dependent, often increasing with time since the previous eruption. If a regular pattern can be defined, probability gain can be estimated as a function of time since the previous eruption. A related approach, considering the volume of the previous eruption, is described by Bacon (1982). Such estimates are useful under some circumstances, for long-term planning or for intermediate-term forecasts when no monitoring is conducted, but they are less useful at Mount St. Helens where the historical record is short and monitoring provides adequate notice of impending eruptions (Swanson, 1983; Whitford-Stark and Wood, 1983).

Recent activity of Mount St. Helens

Explosive eruptions of Mount St. Helens in 1980 have been followed by dominantly non-explosive dome-building eruptions in 1981, 1982, and 1983 (Christiansen and Peterson, 1981; Swanson and others, 1983; Staff of the Cascades Volcano Observatory and others, 1984). Dome-building eruptions were episodic in 1981 and 1982--eruptions lasted for a few days and were separated by a few weeks to a few months of repose. In contrast, an eruption that began in February 1983 is continuing to the present, with fluctuations in the rate and style of dome growth. Slow growth occurs largely as endogenous (internal) growth whereas rapid growth is both endogenous and exogenous (internal and external). Table 1 shows recent eruptions of Mount St. Helens and a list of predictions that have been made of those eruptions. Details about the eruptions may be found in Lipman and Mullineaux (1981) and Swanson and others (1983).

Long- and intermediate-term estimates of volcanic risk

Risks that Mount St. Helens will pose to human life and structures in the next few years have been estimated using the method described in OF 82-396 and the data and assumptions in Table 2. The chance of moderate-scale explosive activity in the next few years (long-term) is greater than that in the next few months (intermediate-term), as reflected in values for $P_{4b|3}$. Long-term estimates of risk to life and structures use common values for P_{1-8} (the likelihood of various volcanic events affecting specified locations), but different values for P_9 (severity of effects on humans and structures). The values of P_9 for structures are approximations based on damage to structures during eruptions of Mount St. Helens and other volcanoes with similar eruptions. Relatively slow-moving volcanic hazards (e.g., lava flows and some mudflows) pose greater risks to immobile structures than to human life. Volcanic gases pose lesser immediate risk to structures than to human life, even though gases may pose long-range risks to both health and structures. Occupancy Case 1--full-time occupancy, without the possibility of removal from the area--must be assumed for most structures.

Intermediate-term estimates of risk to life are several times lower than the previous estimate of February 1982 (OF 82-396). Dominantly non-explosive dome building has continued, and the risks themselves have probably not changed much since February 1982, but estimates in the present report are lower because (a) the distance factors for lateral blasts ($P_{6|5}$) have been reduced and (b) the new category of dominantly non-explosive dome growth assigns a more accurate level of hazard to some eruptions that were previously over-rated.

Five short-term states of the volcano, and assumptions for estimating corresponding risks

This section describes risk estimates for the five simplified short-term states of Mount St. Helens that were defined in the introduction: (1) quiet, (2) slight unrest, (3) dome growth, (4) severe unrest, and (5) an explosive eruption in progress. In general, $P_{3|2}$ (probability of an eruption given a sequence of eruptions like that of 1980-present), $P_{4|3}$ (general types of eruptions), and $P_{5|4}$ (specific eruptive phenomena) vary with the state of the volcano, and P_{10} (routine occupancy) and P_{11} (occupancy in the event of increased activity) vary with man's response to the state of the volcano. P_1 (eruptive period) and $P_{2|1}$ (eruptive sequence) are unaffected by short-term change once an eruptive sequence has begun. $P_{6|5}$ (hazards to specified distances), $P_{7|6}$ (hazards in specified sectors), $P_{8|7}$ (proportion of each pie-shaped block that will be affected by each hazard), and $P_{9|8}$ (severity of each hazard) vary slightly from one type of eruption to another but are held constant here because available data are insufficient to estimate separate values.

Quiet state:

Mount St. Helens may be considered to be in a state of short-term quiet when seismicity, ground deformation, and gas emissions are (a) at low levels, such as observed during previous quiet periods, and (b) have been at these low levels for at least a few days.

The following values for P_1 through P_{11} have been used to estimate risks during quiet periods.

P_1 and $P_{2|1}$ = 1.

P_1 and $P_{2|1}$ have been equal to 1, by definition, ever since the 1980-83 eruptive period began in March 1980.

$P_{3|2}$ = 0.0003/day.

From March 1980 to the time of this writing (January 1984) no eruption that posed hazards outside the crater has occurred during a "quiet" period. On this basis, $P_{3|2}$ should be 0 per 1000 days, or 0/day. However, no volcanic event has a probability of zero so this report assumes 1 eruption in 10 years of quiet, hence $P_{3|2}$ = 0.0003/day. Vigorous gas emissions that sometimes carry ash and larger fragments are common within the crater even during quiet periods, but because these events do not pose hazards outside the crater they are not included in this or subsequent calculations.

$P_{4a|3}$ = 0.01; $P_{4b|3}$ = 0.1; $P_{4c|3}$ = 0.9; $P_{4d|3}$ = 0.01.

Statistics on the types of eruptions that occur suddenly, during quiet periods, are virtually non-existent. The numbers shown here are the same as those assumed for the intermediate-term future.

$P_{5|4a,b,d}$ are as in OF 82-396, except for minor changes shown in Table 2; $P_{5|4c}$ is described below, under "Dominantly non-explosive dome growth." The computation for quiet and other states of the volcano sums the risk of being killed by each of these specific volcanic phenomena, E_{5a-g}, because an individual could be killed by any one of these events. Unfortunately, this procedure tends to overestimate risks because E_{5a-g} are not independent events. If a person was killed, for example, by a pyroclastic flow, then there is little risk that he will be killed "again" by a mudflow, lateral blast, or other eruptive phenomenon. The overestimation is a minor one, errs on the side of safety and, to be resolved, would require more data than are available at the present time.

$P_{6|5}$, ...$P_{9|8}$ are as in OF 82-396.

P_{10}, for Occupancy Case 3, occasional visitor = 0.01, or 1% of each year.

P_{11}, for Occupancy Case 1, = 1.0, by definition; for Occupancy Cases 2 and 3, =0.5. No warnings of imminent activity are issued during quiet states of the volcano, so the probability is low that a worker or tourist will recognize impending risk and leave the area before an eruption during a quiet state. Scientists would not be expecting an eruption and public officials might not be as prepared to warn people quickly as they would be during active times. The value of 0.5 for Cases 2 and 3, rather than 1.0, assumes that even for an unexpected event, some warning might be provided before an eruption reaches a hazardous magnitude or character.

State of slight unrest:

Eruptions of Mount St. Helens in 1981, 1982, and 1983 have been dominantly non-explosive and have been preceded by 5 days or more of increased precursor activity. As soon as a trend of renewed activity has become clear, a low-key "extended outlook advisory" is issued, forecasting an eruption within several days or several weeks. For the purposes of this report, a state of slight unrest is defined as a state of slightly elevated seismicity, ground deformation, or gas emission, at least several days in advance of an eruption. The duration of "slight unrest" at Mount St. Helens is taken to be the length of time between the issuance of an extended outlook advisory and the upgrading or cancellation of that advisory. The first extended outlook advisory was issued on March 30, 1981. In order to include the period from March 1980 until March 30, 1981, this report also considers the number of days that would have been under an extended outlook advisory, had such advisories been used during that period.

P_1 and $P_{2|1}$ = 1, unchanged from OF 82-396.

$P_{3|2}$ = 0.05/day.

In the period from March 20, 1980 to the time of this writing (January 1984), Mount St. Helens has been in a state of slight unrest for approximately 130 days. One eruption began during these 130 days of slight unrest--on February 2, 1983. An average over the entire 130 days suggests a value of about 0.01/day. However, as the dome continues to grow, relatively low levels of unrest (e.g., that prior to February 2, 1983) may cause portions of the dome to fail and thereby trigger subsequent eruptions before precursory activity has run its normal, full course. For this reason, a value of 0.05/day is assumed for states of slight unrest.

$P_{4a|3}$ = 0.01; $P_{4b|3}$ = 0.1; $P_{4c|3}$ = 0.9; $P_{4d|3}$ = 0.01.
Because only one eruption has begun during this state of the volcano, correct values for $P_{4a-d|3}$ are unknown. The estimates given here are the same as adopted for intermediate-term estimates.

$P_{5|4a,b,d}$ = as in OF 82-396, except for minor changes shown in Table 2; $P_{5a|4c}$ = .05, $P_{5b|4c}$ = .1, $P_{5c,d,e|4c}$ = .05, $P_{5f|4c}$ = .001, $P_{5g|4c}$ = .001. Several episodes of dominantly non-explosive dome growth have had explosive onsets, e.g., March 19, 1982 and February 2, 1983. The values shown in Table 2 for $P_{5|4c}$ during slight and severe unrest assume one explosive onset in every ten eruptions, resulting in a pyroclastic flow <u>or</u> a small lateral blast.

$P_{6|5}$, ...$P_{9|8}$ = as in OF 82-396.

P_{10}, Occupancy Case 3 (Occasional visitor) = 0.01, by definition.

P_{11}, Occupancy Case 1 = 1.0, by definition; for Occupancy Cases 2 and 3, P_{11} = 0.1. Periods of slight unrest develop slowly, allowing parties to be notified and to evacuate if they wish. On the other hand, parties have not generally evacuated during periods of slight unrest at Mount St. Helens, but instead have waited until unrest became more severe before leaving the area. Thus the value assumed for P_{11} is between that for quiet periods (0.5) and that for periods of greater unrest (0.01-0.05).

<u>State of severe unrest:</u>

Nearly all of the 1980-1983 eruptions of Mount St. Helens have been preceded by a few hours or a few days of rapidly accelerating seismicity and ground deformation. All pre-eruption episodes of high-level or rapidly accelerating precursory seismicity and ground deformation are considered as "severe unrest," even though some may lead to relatively non-hazardous eruptions. This report considers Mount St. Helens to have been in a state of "severe unrest" during those periods of public warnings that an eruption will begin within 3 days or less, and during those periods in 1980, before statements were as explicit as this, but for which there was an equivalent level of concern.

P_1, $P_{2|1}$ = 1 or very nearly 1.

$P_{3|2}$ = 0.9/day.
Severe unrest occurred between late March 1980 and May 18, 1980, and on May 25, 1980, with two magmatic and many phreatic eruptions. Depending on the way one chooses to count the phreatic eruptions from March through May, $P_{3|2}$ for this early stage of the current eruptive sequence could be between about 0.1/day and 1/day. Since June 1, 1980, 14 eruptions have begun in 16 days of "severe unrest." The value from this latter period, 14/16=0.9/day, is used in this report.

$P_{4a|3}$ = 0.01; $P_{4b|3}$ = 0.1; $P_{4c|3}$ = 0.9; $P_{4d|3}$ = 0.01.
These are the same as values adopted for the intermediate term, as of January 1984. All of the past ten eruptions have been dominantly non-explosive, but two of these (March 19, 1982 and

February 2, 1983) have had explosive onsets that were large enough to pose some hazards outside the crater. The explosive onset of the March 19, 1982 eruption began directly from a state of severe unrest, so that a value of 0.1 is used for $P_{4b|3}$, even though that eruption continued as dominantly non-explosive dome growth. $P_{4a|3}$ is assumed to be one-tenth of $P_{4b|3}$, based on the ratio of major to minor explosive eruptions in the history of Mount St. Helens. $P_{4d|3}$ is assumed to be 0.01, the same as for slight unrest and other short-term states as of January 1984, and thus $P_{4c|3}$ is (by difference) 0.88, or approximately 0.9. These values are suitable for long-term planning, but $P_{4a,b,c,d|3}$ should be re-assessed for each individual eruption on the basis of the precursors to that specific eruption.

The values of $P_{4a|3}$ and $P_{4b|3}$ during severe unrest depend significantly on the intermediate-term state of the volcano. Severe unrest during a period of explosive eruptions like that of the summer of 1980 implied higher values for $P_{4a|3}$ and $P_{4b|3}$ than did severe unrest during 1981-82. $P_{4a|3}$ and $P_{4b|3}$ may also depend on the rate at which precursors escalate into a state of severe unrest. Precursors to explosive eruptions of Mount St. Helens in the summer of 1980 were relatively short (a few days or less). In contrast, precursors to dominantly non-explosive eruptions have been relatively long (several days to several weeks) and have included long periods of "slight unrest." The volatile (mainly water) content of dacitic magma at Mount St. Helens seems to exert a strong influence on the explosiveness of eruptions (Melson, 1983); high volatile contents in 1980 characterized explosive eruptions, and lower volatile contents in 1981-83 characterized dominantly non-explosive eruptions. If precursors to non-explosive eruptions have developed slowly because the volatile content of the magma has been low, then slow development of precursors to a future eruption may indicate that the eruption is inherently unlikely to be explosive. If, at the time of this writing (January 1984), seismicity and ground deformation should increase over the course of several days or weeks to a state of severe unrest, $P_{4a|3}$ and $P_{4b|3}$ could be assumed to have the same, low values as those during the current, relatively non-explosive intermediate-term activity. If, however, severe unrest should once again develop over only a day or less, $P_{4a|3}$ and $P_{4b|3}$ would be higher than shown here.

$P_{5|4a,b,d}$ = as in OF 82-396, except for minor changes noted in Table 2; $P_{5|4c}$ as described under "Slight unrest."

$P_{6|5}, \ldots P_{9|8}$ = as in OF 82-396.

P_{10}, Occupancy Case 3, =0.01, by definition.

P_{11}, Case 1 = 1.0, by definition; Occupancy Cases 2 and 3 = 0.01. A low value of 0.01 for cases 2 and 3 is based on the assumption that severe unrest will cause a suitable warning to be given to public officials, and that workers and tourists will therefore move away from the volcano.

State of dominantly non-explosive dome growth:

Mount St. Helens is in this state when (a) its dome is growing day by day, endogenously (internally) or exogenously (externally, with new lobes), and (b) no geophysical or geochemical evidence suggests that more explosive activity is imminent.

P_1, $P_{2|1}$, $P_{3|2}$ = 1/day, by definition.

$P_{4a|3}$ = 0.0001; $P_{4b|3}$ = 0.001; $P_{4c|3}$ = 0.99; $P_{4d|3}$ =0.01

The likely continuation of activity during dome growth is more dome growth. From December 1980 until the present (January 1984), dominantly non-explosive dome growth at Mount St. Helens has been followed by quiescence, rather than by a shift to explosive or entirely non-explosive activity. The values given here for $P_{4a|3}$ and $P_{4b|3}$, .0001 and .001, are based on an assumption that during any 3 years of dome growth, one minor explosive eruption will also occur without a prior change into a state of notable unrest.

$P_{5|4a,b,d}$ = as in OF 82-396, except for minor changes shown in Table 2; $P_{5|4c}$ = as follows:

$P_{5a|4c}$ = 0.001 (dome collapse pyroclastic flow);

$P_{5b|4c}$ = 0.002 (with a permanent snowfield developing in the crater, either a dome-collapse pyroclastic flow or a small lateral blast could generate a mudflow);

$P_{5c|4c}$ = 0.001;

$P_{5d|4c}$ = 0.001;

$P_{5e|4c}$=0.001 (for tephra in quantities comparable to that in "minor explosive eruptions", E_{4b});

$P_{5f|4c}$ = 0.001 (for a lava flow that extends well beyond the dome);

$P_{5g|4c}$= 0.001 (for a dangerous concentration of gases).

Note: The probabilities of events in pre-eruption states have been expressed as daily probabilities. Values for $P_{5|4}$ must also be daily probabilities, i.e., the probabilities that a specific volcanic event will occur within the next 24 hours, given that the volcano is in a specified type of eruption. This convention was not explicitly stated in OF 82-396 because eruptions considered in that report lasted for only a few hours or a few days; however, the convention needs to be stated explicitly in the case of prolonged dome growth because the probability that a specified volcanic event (e.g., a pyroclastic flow) will occur within the next 24 hours is much lower than the probability that the same event will occur at some time during the period of dome growth. Mount St. Helens has been in a state of dominantly non-explosive dome growth for approximately 400 days since mid-1980, within which time there have been no pyroclastic flows, lateral blasts, or lava flows that extend beyond the dome, and insignificant localized accumulation of tephra, ballistic fragments, and gases. The explosive onsets to episodes of dome growth are considered separately, under slight and severe unrest. The values of $P_{5|4}$ shown above assume that one modest-sized explosive event and one lava flow will begin during any three years of dominantly non-explosive dome growth.

$P_{6|5}$, $P_{7|6}$, ...$P_{9|8}$ = as in OF 82-396.
Pyroclastic flows, lateral blasts, ballistic fragments, and tephra fall during this state of the volcano are not likely to be as severe as during dominantly explosive eruptions. However, in the absence of good statistics for this state, values for $P_{6,7,8, \text{ and } 9|4c}$ are assumed to be the same as those during minor explosive eruptions ($P_{6,7,8 \text{ and } 9|4b}$). The effect of this assumption is to overestimate hazards during dome growth.

P_{10}, Case 3 (Occasional visitor) = 0.01.

P_{11}, Occupancy Case 1 = 1.0, by definition; Occupancy Cases 2 and 3 = 0.05. Dome collapse pyroclastic flows are difficult to predict at the current or any foreseeable level of monitoring, so P_{11} during dominantly non-explosive dome growth is controlled principally by whether individuals avoid the hazardous areas (in and immediately north of the crater) during dome growth.

<u>For an explosive eruption in progress:</u>

For this report, Mount St. Helens is considered to be in an explosive eruption if explosive activity is accompanied by an eruption column several km or more above the crater rim, or by a pyroclastic flow, surge, or blast extending laterally for several kilometers or more, or if such activity has occurred within the previous day. Mount St. Helens has been in this state for only 13 days since May 18, 1980. This category does not include small explosions associated with dominantly non-explosive dome growth.

P_1, $P_{2|1}$, and $P_{3|2}$ = 1

$P_{4a|3}$ = 0.1; $P_{4b|3}$ = 0.9; $P_{4c|3}$ = 0; $P_{4d|3}$ = 0.
The definition of this state automatically reduces $P_{4c|3}$ and $P_{4d|3}$ to near zero. Any risk from dome growth or an entirely non-explosive eruption is negligible during this state of explosive eruption. The values for $P_{4a|3}$ and $P_{4b|3}$ are based on the relative proportions of various sizes of explosive eruptions in Mount St. Helens' prehistoric and historical past, including from 1980 to the present (see data in OF 82-396).

$P_{5|4a,b}$ = as in OF 82-396, except for minor changes shown in Table 2; $P_{5|4c,d}$ estimates are shown to be the same as those for other short term states, but do not enter into the risk estimates as long as $P_{4c|3}$ and $P_{4d|3}$ are assumed to be zero.

$P_{6|5}$, ...$P_{9|8}$ = as in OF 82-396.

P_{10}, Occupancy Case 3, = 0.01, by definition.

P_{11}, Occupancy Case 1 = 1.0, by definition; Occupancy Cases 2 and 3 = 0.01. Explosive eruptions are unlikely to occur without warning--at least a few minutes and usually a few hours or longer are required for the rise of magma and the exsolution of volatiles to escalate to produce an explosive eruption. Slight and severe unrest will alert scientists, public officials, and thence workers and tourists that a potentially explosive eruption is likely.

Results and Discussion

Volcanic risks have been calculated for pie-shaped blocks defined by distance and compass bearing from the crater of Mount St. Helens (see Newhall, 1982). Resulting risk estimates were plotted on a map of the Mount St. Helens area and contoured to show zones of roughly equal risk (Figure 1). Major topographic diversions of flowage hazards are considered in the calculation; detail in the boundaries between zones reflects local topography. For example, the volcanic risk to life in the block between 5 and 10 km due north of the crater is much higher in the valley of the North Toutle River than it is high on the adjacent ridge (Johnston Ridge). The difference is not reflected in the average risks for this block, but the boundary between risk zones has been drawn to reflect greater flowage hazards in the valley than on the ridge top.

Figure 1 summarizes volcanic risk to an individual or a structure at various locations around Mount St. Helens. Each zone in Figure 1 is labeled with a risk matrix, in which columns refer to various timeframes and short-term states of the volcano and rows refer to occupancy by residents, workers, and visitors. The approximate level of risk during each timeframe or state of the volcano and for each occupancy case is shown by a letter in the appropriate column and row of Figure 1, and in Figure 2. The letters A-J correspond to ten orders of magnitude of annual risk of death or destruction by volcanic causes. Owing to uncertainties, correct values may be at least 10 times higher or lower than the estimates given here. For example, the letter C indicates an annual risk between 0.001 and 0.01, i.e., between 0.1% and 1% per year; with the uncertainty included, risk in areas labeled "C" is between 0.01% and 10% per year. Table 3 shows average risks at various distances during the same timeframes and short-term states of the volcano.

Several generalizations can be made about the estimates of volcanic risk in the present report and in OF 82-396.

(1) Risks vary by as much as 4 orders of magnitude from one short-term state to another. Risks during quiet periods between eruptions are approximately 10 to 100 times lower than the long- and intermediate-term risks, as much as 100 to 1000 times lower than risks during dome growth, and as much as 10,000 times lower than risks just before or during an explosive eruption. These differences are substantial. Risks during the early stages of buildup toward another eruption (slight unrest) are not much higher than the long-term risks and risks during dome growth. When precursors indicate that the volcano is preparing for another eruption, the probability of an eruption increases faster than the risk, because predictions and evacuations mitigate that risk.

(2) Intermediate-term estimates of risk are slightly lower in January 1984 than estimates of February 1982, discussed in OF 82-396. Part of the decline is due to continued non-explosive activity of the volcano,

part to continued improvement in predictive capability, and part to some revised assumptions regarding long- and intermediate-term behavior of the volcano (discussed above).

(3) Long-term risks for the next several years (1984-?) are several orders of magnitude higher than would have been estimated in February 1980 (OF 82-396). Based on past eruptive periods of Mount St. Helens, there is little likelihood that the volcano will end its current eruptive period within the next few years, so even the long-term risk for the next several years remains higher than the risk averaged over the entire lifetime of Mount St. Helens.

(4) Risks decrease sharply from the crater to a distance of about 5 to 10 km and then decrease more slowly with increasing distance from the volcano. Roughly, risk decreases by an order of magnitude with each 10 km increment away from the volcano, up to a distance of about 30 km; at greater distances, the rate of decrease is slower.

(5) The shapes of the zones of equal short-term risk during various activities of the volcano are similar to the shapes in the long-term average; the differences are mainly in the level of hazard in a particular zone. For this reason, risks for all states of the volcano can be shown on a single map (Fig. 1).

(6) Risks for those who receive and heed warnings about volcanic activity, and who limit the amount of time they spend near the volcano, are 1 to 3 orders of magnitude (10 to 1000 times) lower than risks to a full-time resident who does not heed warnings.

The most important point of this report is that risk varies greatly from place to place and from time to time around Mount St. Helens.

Levels of risk (Figures 1 and 2) are shown in Table 4 alongside familiar risks of the same order of magnitude. At most locations near the volcano, risks during quiet periods are of magnitudes that most people routinely accept. In contrast, risks near the volcano during heightened activity are of magnitudes that most people are unwilling to accept. At many locations and times, a reduction of exposure time and use of a communications and warning system can reduce unacceptable risks to acceptable levels. Comparisons between estimated volcanic risks and more familiar risks may help individuals and public officials to decide which levels of volcanic risk are acceptable and, from this, which areas around the volcano are acceptably safe, or can be made acceptably safe through mitigation measures.

Applications to other volcanoes

The methodology of OF 82-396 is generally applicable to other volcanoes, using data from the volcano in question. The methodology outlined in the present report for estimating risk during short-term states of Mount St. Helens is not as easily applicable to other volcanoes. Short-term estimates of the probabilities of an eruption, P_3, and of various types of volcanic activity ($P_{4|3}$ and $P_{5|4}$), are based indirectly on predictions of eruptions at Mount St. Helens, where intensive monitoring and partly repetitive precursor patterns have led to a relatively good predictive capability. This approach could be used at other volcanoes at which many eruptions have been predicted. A more direct and general approach is to correlate observed precursors and eruptions and to define a probability function based on those precursors

(Klein, 1983). This more direct approach, when possible, will improve predictions of the time and type of eruptions. The present method uses predictions of when Mount St. Helens will erupt to approximate how much risks increase before an eruption. A goal for the future at Mount St. Helens and other volcanoes is to incorporate changes in the probability of various types of eruptions into predictions and risk assessments.

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Figure caption

Figure 1.

Volcanic risk map of Mount St. Helens. Risks are evaluated for each of the five zones that are separated by heavy solid lines on the map. Risk matrices in each zone show long-term, intermediate-term, and short-term estimates of volcanic risk, for full-time residents, workers, and occasional visitors. Short-term estimates are for five different short-term states of activity--quiet, slight unrest, severe unrest, dome growth, and explosive eruption (see text for details). The level of risk for each timeframe, state of activity, and occupancy case is shown by a letter, from A to J, corresponding to 10 orders of magnitude of annual risk. The key in the upper left-hand part of the figure is a guide to the risk matrix; the key in the upper right-hand part of the figure shows the order-of-magnitude range of risk corresponding to each letter, and the expanded range when uncertainties are considered. Except for long-term risk to structures, all other matrix positions refer to the risk of immediate death by volcanic causes.

For example, a letter "C" in row 1, column 1 indicates a long-term risk of between 1 in 1000 and 1 in 100 per year to structures (or between 1 in 10,000 and 1 in 10, considering uncertainty). A letter "D" in row 3, column 5 indicates a risk of between 1 in 10,000 and 1 in 1000 per year (or between 1 in 100,000 and 1 in 100, including uncertainty) to occasional visitors during slight unrest at Mount St. Helens.

Figure 1 was drawn by calculating the risk for each specific volcanic hazard (e.g., pyroclastic flow, mudflow) at each of nine distances in each of sixteen 22.5° sectors. Total risk from flowage hazards and non-flowage hazards was noted on a topographic base map that was divided into 9 x 16 = 144 pie-shaped blocks. Contours of equal intermediate-term risk were drawn, with detail added by eye to reflect the topography. Contours of risk for other cases have shapes similar to those from the intermediate-term case, and different levels of risk in various cases are shown by the risk matrix.

LEVELS OF VOLCANIC RISK NEAR MOUNT ST. HELENS

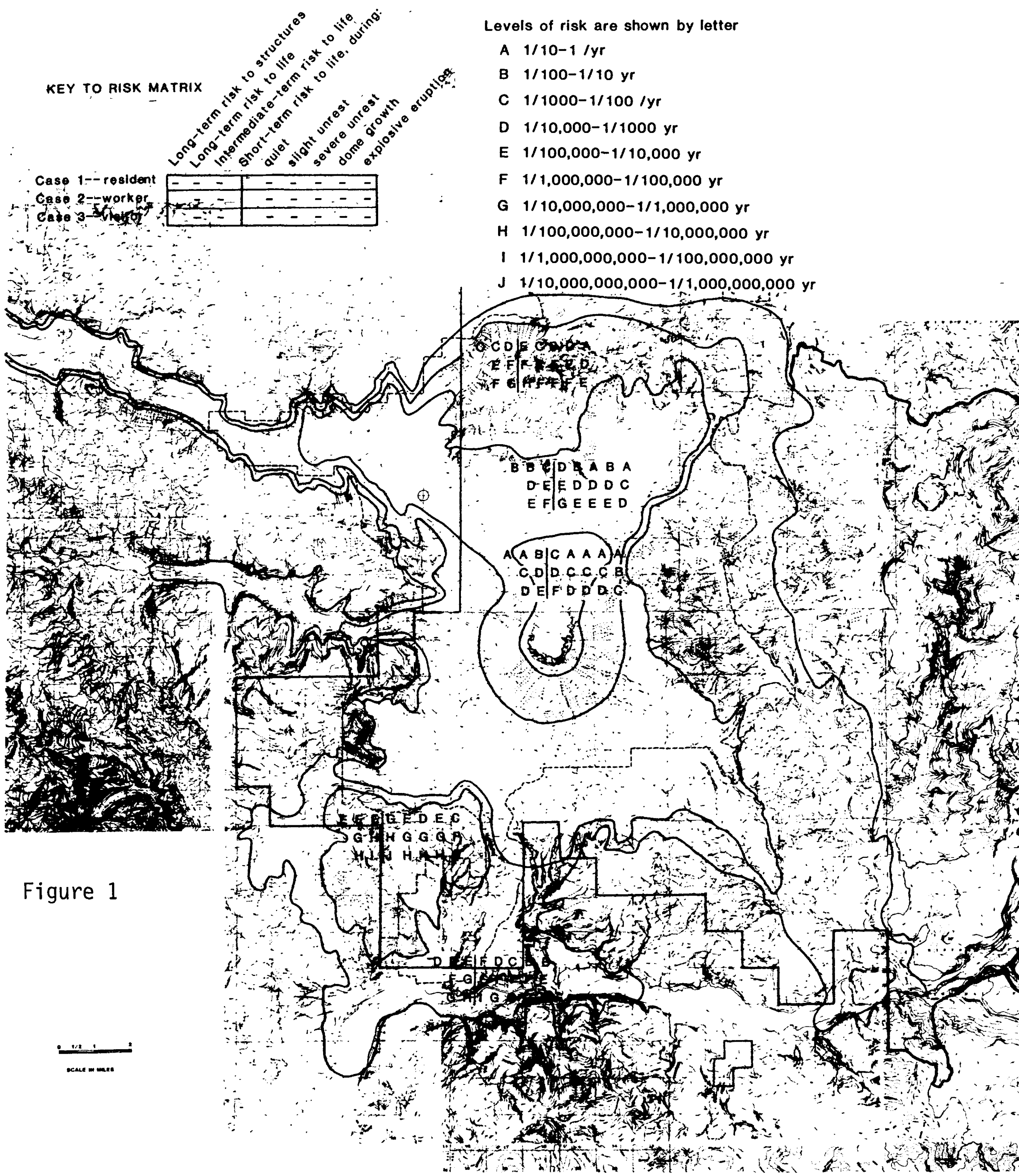

Figure 1

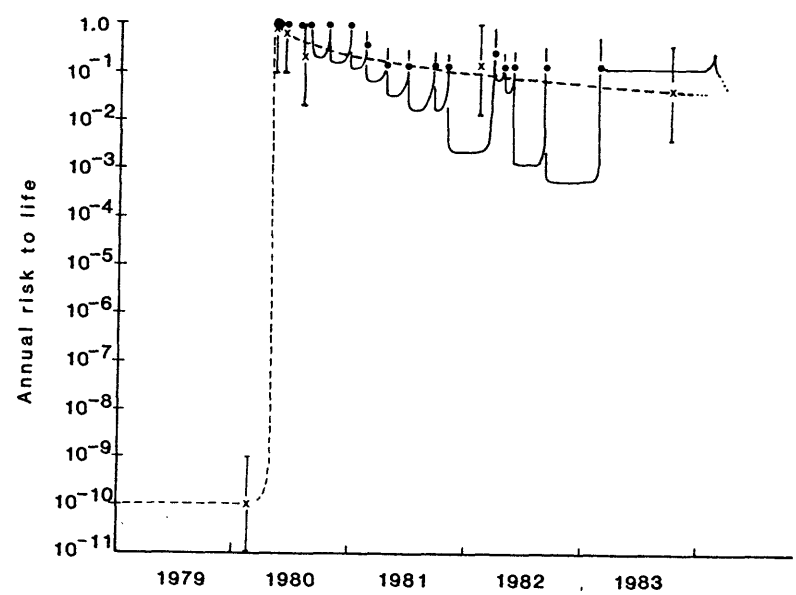

Figure 2. Volcano-related risk to the life of a full-time resident, 5 km north of the crater of Mount St. Helens, from 1979 to 1983. The estimates assume that this full-time resident has no provision for warning or evacuation (described as Case 1 in the text); risk for individuals who spend less time at that location or who have provision for warning and evacuation is much lower, as is risk at locations farther from the volcano. Dashed line= intermediate-term estimate of risk; solid line= short-term estimate of risk. X's along the dashed line, with vertical error bars, mark dates for which estimates of intermediate-term risk have been made, and the estimated error of ± one order of magnitude.

Table captions

Table 1. Chronology of eruptions, factual statements, forecasts, and predictions at Mount St. Helens (modified from Swanson and others, 1983).

Table 2. Assumed values of P_1 through P_{11}, for various timeframes and short-term states of activity at Mount St. Helens. These values are the input data for a computer program that calculates risk from specific hazards at various distances and directions from the volcano.

Table 3. Average volcanic risks, by occupancy case, distance from Mount St. Helens, timeframe, and short-term state of the volcano. Values are average annual risks, rounded to one significant figure. To derive these estimates, risk from each specific hazard (e.g., pyroclastic flow, mudflow) has been summed to a total volcanic risk at each of 9 distances and 16 directions from the volcano (e.g., at 5 km N of the crater, or at 20 km WNW of the crater). Then, an unweighted average has been taken of from all 16 directions at each distance, to obtain the averages shown here. Such averages are useful for generalizations about the variation of risk from one occupancy case to another, and from one timeframe or short-term state of activity to another. They are also useful for generalizations about the decrease in risk with increasing distance from the volcano, with the caution that the exact rate of decrease with distance varies greatly from one area to another (Figure 1), depending largely on topography.

Table 4. A comparison of levels of volcanic risk (at Mount St. Helens) and death rates from familiar causes. The letters down the left margin of the table refer to orders of magnitude of annual risk, as shown by numbers above and below each letter and on Figure 1. There is no universally accepted value for "acceptable risk." Some people might wish to limit their volcanic risk to a proportion of their total risk (in which case soldiers, elderly people, and drug addicts would be willing to take the highest risks). Other people might wish to limit their total risk (in which case those already in high-risk groups would accept the least additional volcanic risk). Still others will assess the return or value of taking a particular risk, regardless of their background risk. These are but three of many philosophies of determining acceptable risk, and some individuals may not consciously follow any rational philosophy at all.

Table 1. Chronology of eruptions, factual statements, forecasts and predictions at Mount St. Helens

Eruption start		Eruption type[1]	Factual statements		Forecasts			Predictions			
Date	Time		Date	Subject	Date	Interval	Basis[2]	Date	Time	Predictive window	Basis[2]
3/27/80	1236	Expl and D-b	3/20/80	Earthquake	1975,1978	Next few decades	H				
		Expl						3/25/80		Few days or weeks	S
5/18/80	0832	Expl	4/14/80	Bulge				4/1/80		No date given	E,S,CD
			5/18/80	Onset of eruption				4/14/80		No date given	CD,S
5/25/80	0236	Expl	3/25/80	Onset of eruption						Not predicted	
6/12/80	2111	Expl and D-b			5/26/80	Weeks to months	E,H				
			6/12/80	Onset of eruption	6/1/80	Weeks to months	E,H	6/12/80[4]	1800	Soon	
7/22/80	1714	Expl	7/22/80	Onset of eruption	7/1/80	Weeks to months	E,H	7/22/80[4]	1040	Next several hrs	S
8/7/80	1623	Expl and D-b	8/7/80	Onset of eruption				8/7/80[4]	1227	Next several hrs	S,(G)
10/16/80	2158	Expl and D-b	10/16/80	Onset of eruption	9/1/80	Weeks to months	E,H	10/16/80[4]	2026	Next several hrs	S
12/27/80	?	D-b			11/15/80	Weeks to months		12/25/80[4]	1850	Next 24-48 hrs	S
			12/27/80	Dome growth confirmed				12/27/80	1520	Implied very soon	S
2/5/81	a.m.	D-b[3]	2/5/81	Dome growth confirmed	2/2/81	Weeks to months	E,H	2/4/81	2400	Implied soon	S,(CF)
			2/7/81	Dome growth slowed				2/5/81	0400	Next 12 hrs	S
			2/10/81	End of eruption							
4/10/81	0821	D-b[3]	4/10/81	Onset of eruption	3/27/81	Weeks to months	CD,S,G,E	3/30/81		Within 2 wks	CF,(S)
			4/14/81	Dome growth slowed				4/9/81	2300	Next 24 hrs	S
			4/15/81	End of eruption				4/10/81	0630	This morning	S
6/18/81	2400	D-b[3]	6/18/81	Dome growth suspected				6/12/81		Within 2 wks	CF,(G)
			6/19/81	Dome growth confirmed				6/18/81	1100	Within 1-2 days	S,CF,(G)
			6/21/81	End of eruption				6/18/81	1715	Within 12 hrs	S, CT
9/6/81	Late p.m.	D-b	9/6/81	Dome growth confirmed	8/5/81	Weeks to months	CD,S,G,E	8/26/81		Within 1-3 wks	CF,(G)
			9/7/81	Dome growth slowed				9/6/81	0800	Within 12-48 hrs	S,CF
			9/7/81	End of eruption				9/6/81	1330	Within 12 hours	S,CT
10/30/81	p.m.	D-b[3]						10/24/81		Within 2 wks	CF
			10/31/81	Dome growth confirmed				10/30/81	1100	Within 24 hrs	S,CT
3/19/82	1927	Expl (minor) & D-b	3/5/82	Increased seismicity				3/12/82		Within 3 wks	DD,(CF)
			3/19/82	Onset of eruption				3/15/82		Within 1-5 days	DD,CF
			3/24/82	Continued endogenous growth				3/19/82	0900	Within 24 hrs	S,(DD,CF,I)
			4/4/82	Renewed eruptive activity							
			4/12/82	End of eruption							
5/14/82	1100?	D-b[3]						5/11/82		Within next week, possibly few days	DD,(S)
			5/14/82	Dome growth confirmed				5/13/82	2300	Within 36 hrs, possibly 12 hrs	S
			5/20/82	End of eruption							
8/18/82	1030?	D-b	8/18/82	Endogenous growth underway				7/30/82		Within 3 wks	S,DD,CF
			8/18/82	Exogenous growth underway				8/16/82		Within 4 days, possibly 2 days	DD,CF,S
			8/19/82	Fewer earthquakes							
			8/23/82	End of eruption				8/17/82	0655	Within 24 hrs	S,DD,CF
								8/18/82	0745	Soon	S,DD,CF
2/2/83	2339	Expl (minor) & D-b	2/3/83	Small explosions, mudflow				2/5/83	2100	Within 2 wks, likely 1 wk	S,DD,CF,G,I
			2/7/83	Dome growth confirmed							
			2/17,2/18,2/20	Continuing dome growth				3/8/83	1500	Within 3 wks	S
			2/21/83	Dome growth slowed							
			3/1/83	"February eruption over"							
			3/6/83	Increased seismicity							
			3/29/83	Decreased seismicity, possible but unconfirmed changes on dome							
			4/19/83	Continuing dome growth, confirmed							
			5/5,6/1, 8/1,9/13/83	Continuing dome growth "				10/1/83		Within 10 days	DD,(I)
			10/11, 12/30/83	New loci of extrusion							

[1]Expl, Explosive activity; D-b, Dome-building eruption;
[2]S, seismicity; G, gas; CT, crater tilt; CF, crater-floor deformation; DD, dome deformation; CD, cone deformation; I, incandescence; H, stratigraphic and historic records; E, the previous few eruptions; (parentheses) indicate this factor was of lesser importance
[3]Small tephra-laden plumes accompanied start of extrusion
[4]Verbal communications to Forest Service and State Department of Emergency Services; written predictions not initiated until 27 December 1980

Table 2

Assumed values of P_1 through P_{11}, for various timeframes and short-term levels of activity at Mount St. Helens:

Probability		February 1982: Intermediate-term risk to human life	1983-84: Long-term risk to: life	structures	Intermediate-term risk to human life	Short-term risk to human life: Quiet	Sl. unrest	Sev. unrest	Dome growth	Expl. eruption
P_1	(eruptive period)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$P_{2\|1}$	(eruptive sequence)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$P_{3\|2}$	(eruption)	.02	.02	.02	.01	.0003	.05	0.9	1.0	1.0
$P_{4a\|3}$	(major explosion)	.05	.02	.02	.01	.01	.01	.01	.0001	.1
$4b\|3$	(minor explosion)	.2	.3	.3	.1	.1	.1	.1	.001	.9
$4c\|3$	(dome growth)	*	.6	.6	.9	.9	.9	.9	.99	0
$4d\|3$	(non-explosive)	.75	.08	.08	.01	.01	.01	.01	.01	0
$P_{5a\|4a}$	(pyro. flow in major explosion)	.75	.75	.75	.75	.75	.75	.75	.75	.75
$5a\|4b$	(pyro. flow in minor explosion)	.38	.3	.3	.3	.3	.3	.3	.3	.3
$5a\|4c$	(pyro. flow in dome growth)	*	.05	.05	.05	.001	.05	.05	.001	.05
$5a\|4d$	(pyro. flow in non-expl. erupt.)	*	0	0	0	0	0	0	0	0
$P_{5b\|4a}$	(mudflow in major explosion)	1.0	.75	.75	.75	.75	.75	.75	.75	.75
$5b\|4b$	(mudflow in minor expl.)	.2	.3	.3	.3	.3	.3	.3	.3	.3
$5b\|4c$	(mudflow in dome growth)	*	.1	.1	.1	.002	.1	.1	.002	.1
$5b\|4d$	(mudflow in non-expl. eruption)	.05	0	0	0	0	0	0	0	0
$P_{5c\|4a}$	(lat. blast in major explosion)	.25	.1	.1	.1	.1	.1	.1	.1	.1
$5c\|4b$	(lat. blast in minor explosion)	.025	.1	.1	.1	.1	.1	.1	.1	.1
$5c\|4c$	(lat. blast in dome growth)	*	.05	.05	.05	.001	.05	.05	.001	.05
$5c\|4d$	(lat. blast in non-expl. erupt)	0	0	0	0	0	0	0	0	0
$P_{5d\|4a}$	(ball. frag. in major explos.)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$5d\|4b$	(ball. frag. in minor explos.)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$5d\|4c$	(ball. frag. in dome growth)	*	.05	.05	.05	.001	.05	.05	.001	.05
$5d\|4d$	(ball. frag. in non-expl. erupt)	0	0	0	0	0	0	0	0	0
$P_{5e\|4a}$	(tephra fall, maj explosion)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$5e\|4b$	(tephra fall, min explosion)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$5e\|4c$	(tephra fall, dome growth)	*	.05	.05	.05	.001	.05	.05	.001	.05
$5e\|4d$	(tephra fall, non-expl. erupt)	0	0	0	0	0	0	0	0	0
$P_{5f\|4a}$	(lava flow in major explosion)	0	0	0	0	0	0	0	0	0
$5f\|4b$	(lava flow in minor explosion)	.125	.1	.1	.1	.1	.1	.1	.1	.1
$5f\|4c$	(lava flow in dome growth)	*	.001	.001	.001	.001	.001	.001	.001	.001
$5f\|4d$	(lava flow in non-expl. erupt.)	*	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$P_{5g\|4a}$	(gas concent. in major explos)	0	0	0	0	0	0	0	0	0
$5g\|4b$	(gas concent. in minor explos)	0	0	0	0	0	0	0	0	0
$5g\|4c$	(gas concent. in dome growth)	*	.001	.001	.001	.001	.001	.001	.001	.001
$5g\|4d$	(gas concent. in non-expl. erupt)	0	.001	.001	.001	.001	.001	.001	.001	.001

* not estimated in February 1982

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Table 2, cont.

Probability	February 1982: Intermediate-term risk to human life	1983-84: Long-term risk to: life	structures	Intermediate-term risk to human life	Short-term risk to human life: Quiet	Sl. unrest	Sev. unrest	Dome growth	Expl. eruption
P6, Distance factors= Probabilities that eruptive phenomena 5a-5g will reach to specified distances, should they occur:									
P of pyroclastic flow to 5 km	.75	.75	.75	.75	.75	.75	.75	.75	.75
10 km	.1	.1	.1	.1	.1	.1	.1	.1	.1
15 km	.01	.01	.01	.01	.01	.01	.01	.01	.01
20 km	.001	.001	.001	.001	.001	.001	.001	.001	.001
30 km	0	0	0	0	0	0	0	0	0
P of mudflow to 5 km	.93	.93	.93	.93	.93	.93	.93	.93	.93
10 km	.44	.44	.44	.44	.44	.44	.44	.44	.44
15 km	.28	.28	.28	.28	.28	.28	.28	.28	.28
20 km	.21	.21	.21	.21	.21	.21	.21	.21	.21
30 km	.13	.13	.13	.13	.13	.13	.13	.13	.13
40 km	.10	.10	.10	.10	.10	.10	.10	.10	.10
50 km	.08	.08	.08	.08	.08	.08	.08	.08	.08
100 km	0	.05	.05	.05	.05	.05	.05	.05	.05
200 km	0	0	0	0	0	0	0	0	0
P of lateral blast to 5 km, in major explosion	.5	.5	.5	.5	.5	.5	.5	.5	.5
10 km, maj expl.	.3	.1	.1	.1	.1	.1	.1	.1	.1
15 km, maj expl.	.1	.05	.05	.05	.05	.05	.05	.05	.05
20 km, maj expl.	.05	.01	.01	.01	.01	.01	.01	.01	.01
30 km, maj expl.	.01	.001	.001	.001	.001	.001	.001	.001	.001
40 km+, maj expl.	0	0	0	0	0	0	0	0	0
P of lateral blast to 5 km, in minor expl. or dome growth	.5	.1	.1	.1	.1	.1	.1	.1	.1
10 km, " " " " " "	.1	.02	.02	.02	.02	.02	.02	.02	.02
15 km, " " " " " "	.01	.01	.01	.01	.01	.01	.01	.01	.01
P of ballistic fragments to 5 km	.01	.01	.01	.01	.01	.01	.01	.01	.01
10 km	.001	.001	.001	.001	.001	.001	.001	.001	.001
15+ km	0	0	0	0	0	0	0	0	0
P of 10 cm of tephra fall, at:									
5 km, major explosion	.99	.99	.99	.99	.99	.99	.99	.99	.99
10 km, major explosion	.98	.98	.98	.98	.98	.98	.98	.98	.98
15 km, major explosion	.96	.96	.96	.96	.96	.96	.96	.96	.96
20 km, major explosion	.93	.93	.93	.93	.93	.93	.93	.93	.93
30 km, major explosion	.9	.9	.9	.9	.9	.9	.9	.9	.9
40 km, major explosion	.8	.8	.8	.8	.8	.8	.8	.8	.8
50 km, major explosion	.7	.7	.7	.7	.7	.7	.7	.7	.7
100 km, major explosion	.5	.5	.5	.5	.5	.5	.5	.5	.5
200 km, major explosion	.1	.1	.1	.1	.1	.1	.1	.1	.1
10 cm of tephra fall, continued,									
5 km, minor explosion	.3	.3	.3	.3	.3	.3	.3	.3	.3
10 km, minor explosion	.2	.2	.2	.2	.2	.2	.2	.2	.2
15 km, minor explosion	.1	.1	.1	.1	.1	.1	.1	.1	.1
20 km, minor explosion	.05	.05	.05	.05	.05	.05	.05	.05	.05
30 km, minor explosion	.01	.01	.01	.01	.01	.01	.01	.01	.01
40 km+, minor explosion	0	0	0	0	0	0	0	0	0
P of lava flow to 5 km	.5	.2	.2	.2	.2	.2	.2	.2	.2
10 km	.1	.05	.05	.05	.05	.05	.05	.05	.05
15 km	.02	.01	.01	.01	.01	.01	.01	.01	.01
20+ km	0	0	0	0	0	0	0	0	0
P of gas concentration at 5 km	.01	.01	.01	.01	.01	.01	.01	.01	.01
10+ km	0	0	0	0	0	0	0	0	0

Table 2, cont.

Probability	February 1982: Intermediate-term risk to human life	1983-84: Long-term risk to: life	structures	Intermediate-term risk to human life	Short-term risk to human life: Quiet	Sl. unrest	Sev. unrest	Dome growth	Expl. eruption
P7, Sector factors= Probabilities that eruptive phenomena 5a-g will start traveling in specific sectors, should they occur:									
P of pyroclastic flow toward N	.6	.6	.6	.6	.6	.6	.6	.6	.6
NNE	.3	.3	.3	.3	.3	.3	.3	.3	.3
NE-E*	.0067	.01	.01	.01	.01	.01	.01	.01	.01
ESE	.0133	.02	.02	.02	.02	.02	.02	.02	.02
SE-NW*	.0067	.01	.01	.01	.01	.01	.01	.01	.01
NNW	.3	.3	.3	.3	.3	.3	.3	.3	.3
P of mudflow toward N	.4	.6	.6	.6	.6	.6	.6	.6	.6
NNE	.2	.3	.3	.3	.3	.3	.3	.3	.3
NE	.01	.01	.01	.01	.01	.01	.01	.01	.01
ENE	.03	.01	.01	.01	.01	.01	.01	.01	.01
E	.05	.01	.01	.01	.01	.01	.01	.01	.01
ESE	.01	.05	.05	.05	.05	.05	.05	.05	.05
SE	.08	.01	.01	.01	.01	.01	.01	.01	.01
SSE	.03	.01	.01	.01	.01	.01	.01	.01	.01
S	.05	.01	.01	.01	.01	.01	.01	.01	.01
SSW	.03	.01	.01	.01	.01	.01	.01	.01	.01
SW-W*	.01	.01	.01	.01	.01	.01	.01	.01	.01
WNW	.03	.01	.01	.01	.01	.01	.01	.01	.01
NW	.05	.01	.01	.01	.01	.01	.01	.01	.01
NNW	.01	.01	.01	.01	.01	.01	.01	.01	.01
P of lateral blast toward N	.9	.9	.9	.9	.9	.9	.9	.9	.9
NNE	.5	.5	.5	.5	.5	.5	.5	.5	.5
NE	.02	.02	.02	.02	.02	.02	.02	.02	.02
ENE	.015	.015	.015	.015	.015	.015	.015	.015	.015
E	.01	.01	.01	.01	.01	.01	.01	.01	.01
ESE	.015	.01	.01	.01	.01	.01	.01	.01	.01
SE	.02	.01	.01	.01	.01	.01	.01	.01	.01
SSE	.015	.01	.01	.01	.01	.01	.01	.01	.01
S-WNW*	.01	.01	.01	.01	.01	.01	.01	.01	.01
NW	.015	.02	.02	.02	.02	.02	.02	.02	.02
NNW	.4	.4	.4	.4	.4	.4	.4	.4	.4
P of ballistic fragments, all sectors	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
P of tephra fall toward the N	.04	.04	.04	.04	.04	.04	.04	.04	.04
NNE	.08	.08	.08	.08	.08	.08	.08	.08	.08
NE	.14	.14	.14	.14	.14	.14	.14	.14	.14
ENE	.16	.16	.16	.16	.16	.16	.16	.16	.16
E	.16	.16	.16	.16	.16	.16	.16	.16	.16
ESE	.13	.13	.13	.13	.13	.13	.13	.13	.13
SE	.10	.10	.10	.10	.10	.10	.10	.10	.10
SSE	.06	.06	.06	.06	.06	.06	.06	.06	.06
S	.04	.04	.04	.04	.04	.04	.04	.04	.04
SSW	.02	.02	.02	.02	.02	.02	.02	.02	.02
SW-NW*	.01	.01	.01	.01	.01	.01	.01	.01	.01
NNW	.02	.02	.02	.02	.02	.02	.02	.02	.02

* groups of sectors are inclusive, in a clockwise direction, e.g., NE-E = NE, ENE, and E.

Table 2, cont.

Probability	February 1982 Intermediate-term risk to human life	1983-84 Long-term risk to: life	structures	Intermediate-term risk to human life	Short-term risk to human life Quiet	Sl. unrest	Sev. unrest	Dome growth	Expl. eruption
P_7, sector factors, continued									
P of lava flow toward N	.9	.9	.9	.9	.9	.9	.9	.9	.9
NNE	.05	.05	.05	.05	.05	.05	.05	.05	.05
NE-NW	.004	.001	.001	.001	.001	.001	.001	.001	.001
NNW	.05	.05	.05	.05	.05	.05	.05	.05	.05
P of gas concentration toward N	.6	.6	.6	.6	.6	.6	.6	.6	.6
NNE	.3	.3	.3	.3	.3	.3	.3	.3	.3
NE-SE	.01	.01	.01	.01	.01	.01	.01	.01	.01
SSE-WNW	0	0	0	0	0	0	0	0	0
NW	.01	0	0	0	0	0	0	0	0
NNW	.05	.05	.05	.05	.05	.05	.05	.05	.05
P_8, Coverage factors= proportion of each pie-shaped block affected by each eruptive phenomenon:									
$P_{8a\|5,6,7}$ (covered by pyro flow)	.33	.33	.33	.33	.33	.33	.33	.33	.33
$8b\|5,6,7$ (covered by mudflow)	.2	.2	.2	.2	.2	.2	.2	.2	.2
$8c\|5,6,7$ (covered by lateral blast)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$8d\|5,6,7$ (covered by ballistic fragments at: 0-5 km	.01	.01	.01	.01	.01	.01	.01	.01	.01
5-10 km	.001	.001	.001	.001	.001	.001	.001	.001	.001
10-15 km)	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001
$8e\|5e,6,7$ (covered by tephra fall)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$8f\|5f,6,7$ (covered by lava flow)	.2	.2	.2	.2	.2	.2	.2	.2	.2
$8g\|5g,6,7$ (covered by gas concent.)	.5	.5	.5	.5	.5	.5	.5	.5	.5
P_9, Severity factors= probability that effect of an eruptive phenomenon at a specific site would be fatal									
$P_{9a\|8a}$ (severity of pyro flow)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$9b\|8b$ (severity of mudflow)	.1	.1	.8	.1	.1	.1	.1	.1	.1
$9c\|8c$ (severity of lateral blast)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$9d\|8d$ (severity of ballist. frag.)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$9e\|8e$ (severity of tephra fall)	.001	.001	.001	.001	.001	.001	.001	.001	.001
$9f\|8f$ (severity of lava flow)	.001	.001	.9	.001	.001	.001	.001	.001	.001
$9g\|8g$ (severity of gas concentr.)	.5	.5	.001	.5	.5	.5	.5	.5	.5
P_{10} Routine occupancy,									
Full-time resident	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Worker	.2	.2	.2	.2	.2	.2	.2	.2	.2
Occasional visitor	not estimated	.01	.01	.01	.01	.01	.01	.01	.01
P_{11} Occupancy during times when an eruption is expected,									
Full-time resident	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Worker	.01	.02	n.a.	.02	.5	.1	.01	.05	.01
Occasional visitor	.01	.02	n.a.	.02	.5	.1	.01	.05	.01

Table 3 Average Risks, listed by occupancy case, distance from Mount St. Helens, and short-term state of the volcano

Distance (km)	Long-term risks to: life	structures	Intermediate-term risk to life	Short-term risks to life, during: Quiet	Slight unrest	Severe unrest	Dome growth	Explosive eruption
Occupancy Case 1								
5	6×10^{-3}	1×10^{-2}	2×10^{-3}	3×10^{-5}	1×10^{-2}	2×10^{-1}	5×10^{-3}	4×10^{-1}
10	1×10^{-3}	2×10^{-3}	4×10^{-4}	4×10^{-6}	2×10^{-3}	4×10^{-2}	1×10^{-3}	1×10^{-1}
15	4×10^{-4}	8×10^{-4}	2×10^{-4}	2×10^{-6}	6×10^{-4}	1×10^{-2}	4×10^{-4}	3×10^{-2}
20	5×10^{-5}	1×10^{-4}	2×10^{-5}	3×10^{-7}	6×10^{-5}	2×10^{-3}	8×10^{-5}	1×10^{-2}
30	2×10^{-5}	2×10^{-5}	8×10^{-6}	1×10^{-7}	2×10^{-5}	6×10^{-4}	3×10^{-5}	3×10^{-3}
40	1×10^{-5}	2×10^{-5}	5×10^{-6}	6×10^{-8}	2×10^{-5}	4×10^{-4}	2×10^{-5}	2×10^{-3}
50	8×10^{-6}	1×10^{-5}	4×10^{-6}	6×10^{-8}	1×10^{-5}	4×10^{-4}	2×10^{-5}	2×10^{-3}
100	4×10^{-6}	5×10^{-6}	2×10^{-6}	3×10^{-8}	6×10^{-6}	2×10^{-4}	1×10^{-5}	1×10^{-3}
200	6×10^{-7}	6×10^{-7}	3×10^{-7}	4×10^{-9}	8×10^{-7}	2×10^{-5}	2×10^{-6}	2×10^{-4}
Occupancy Case 2								
5	2×10^{-5}	n.a.	1×10^{-5}	2×10^{-6}	2×10^{-4}	4×10^{-4}	5×10^{-5}	1×10^{-3}
10	4×10^{-6}	n.a.	2×10^{-6}	4×10^{-7}	4×10^{-5}	8×10^{-5}	1×10^{-5}	2×10^{-4}
15	1×10^{-6}	n.a.	6×10^{-7}	2×10^{-7}	1×10^{-5}	2×10^{-5}	4×10^{-6}	8×10^{-5}
20	2×10^{-7}	n.a.	8×10^{-8}	3×10^{-8}	1×10^{-6}	5×10^{-6}	8×10^{-7}	2×10^{-5}
30	6×10^{-8}	n.a.	4×10^{-8}	8×10^{-9}	4×10^{-7}	1×10^{-6}	3×10^{-7}	6×10^{-6}
40	4×10^{-8}	n.a.	2×10^{-8}	6×10^{-9}	3×10^{-7}	8×10^{-7}	2×10^{-7}	4×10^{-6}
50	3×10^{-8}	n.a.	2×10^{-8}	6×10^{-9}	2×10^{-7}	8×10^{-7}	2×10^{-7}	4×10^{-6}
100	2×10^{-8}	n.a.	8×10^{-9}	3×10^{-9}	1×10^{-7}	3×10^{-7}	1×10^{-7}	2×10^{-6}
200	2×10^{-9}	n.a.	1×10^{-9}	4×10^{-10}	2×10^{-8}	5×10^{-8}	2×10^{-8}	3×10^{-7}
Occupancy Case 3								
5	1×10^{-6}	n.a.	6×10^{-7}	1×10^{-7}	1×10^{-5}	2×10^{-5}	2×10^{-6}	8×10^{-5}
10	2×10^{-7}	n.a.	8×10^{-8}	2×10^{-8}	2×10^{-6}	4×10^{-6}	5×10^{-7}	1×10^{-5}
15	8×10^{-8}	n.a.	3×10^{-8}	8×10^{-9}	6×10^{-7}	1×10^{-6}	2×10^{-7}	4×10^{-6}
20	1×10^{-8}	n.a.	4×10^{-9}	2×10^{-9}	6×10^{-8}	2×10^{-7}	4×10^{-8}	1×10^{-6}
30	3×10^{-9}	n.a.	2×10^{-9}	5×10^{-10}	2×10^{-8}	6×10^{-8}	2×10^{-8}	3×10^{-7}
40	2×10^{-9}	n.a.	1×10^{-9}	3×10^{-10}	2×10^{-8}	4×10^{-8}	1×10^{-8}	2×10^{-7}
50	2×10^{-9}	n.a.	8×10^{-10}	3×10^{-10}	1×10^{-8}	4×10^{-8}	1×10^{-8}	2×10^{-7}
100	8×10^{-10}	n.a.	4×10^{-10}	2×10^{-10}	6×10^{-9}	2×10^{-8}	6×10^{-9}	1×10^{-7}
200	1×10^{-10}	n.a.	6×10^{-11}	2×10^{-11}	8×10^{-10}	2×10^{-9}	8×10^{-10}	2×10^{-8}

The numbers in this table are annual risks of death, at the specified distances from the volcano, during specified timeframes and short-term states of activity. Numbers may be read as follows: $1 \times 10^{-1}=0.1$ or 1 in 10 per year; $1 \times 10^{-2}=0.01$ or 1 in 100 per year; $2 \times 10^{-3}=0.002$ or 2 in 1000 per year; $3 \times 10^{-4}=0.0003$ or 3 in 10,000 per year; and so on.

n.a. = not applicable

Table 4 Volcanic risks at Mount St. Helens compared with death rates from familiar causes (expressed as annual probabilities of death, for "average" participating individuals)

Levels of Volcanic Risk (corresponding to letters in Figure 1)	All Causes, based on mortality tables, for different age groups, U.S.	Occupational	Miscellaneous
1.0 (10^0) -----------			
A			
0.1 (10^{-1}) -----------	Age 90, ($2.3x10^{-1}$) Age 80, ($0.9-1.1x10^{-1}$)		
B		War U.S. forces in WWII, Korea, Vietnam($2-5x10^{-2}$)	
	Age 60, ($1.8-2.1x10^{-2}$)		
0.01 (10^{-2}) ----------			
	Avg, age-weighted ($6.4x10^{-3}$)	Helicopter pilots($6x10^{-3}$) Deep sea fishing($3x10^{-3}$)	Drug abuse($8x10^{-3}$) Smoking($5x10^{-3}$)(?)
C	Age 40, ($3x10^{-3}$) Age 20, $1.1-1.8x10^{-3}$)	Logging($2.5x10^{-3}$) Avg 33 hazardous occuptions($1.2x10^{-3}$) Mining & quarrying ($1x10^{-3}$)	Cardiovascular disease ($2.9x10^{-3}$) Cancer($1.3x10^{-3}$)
0.001 (10^{-3}) ---------			
D		Construction($7.2x10^{-4}$) Agriculture($6.3x10^{-4}$) Transportation & utilities($3.8x10^{-4}$) Law enforcement($2x10^{-4}$) Government,civilian($1.3x10^{-4}$) All U.S. workers($1.2x10^{-4}$) Manufacturing($1.0x10^{-4}$)	Accidents--all types ($4.5x10^{-4}$) Car accidents($2.5x10^{-4}$)
0.0001 (10^{-4}) --------			
		Trades($8x10^{-5}$)	Accidental falls($8x10^{-5}$)
E			Drowning,U.S.($4x10^{-5}$) Firearm accidents($1.4x10^{-5}$)
0.00001 (10^{-5}) -------			
F			Floods,world($2x10^{-6}$) Tornadoes,U.S.($1x10^{-6}$)
0.000001 (10^{-6}) -----			
G			Earthquakes, world($8x10^{-7}$) Hurricanes,U.S.($5x10^{-7}$) Volcanic eruptions, world($1x10^{-7}$)

Risks labeled H, I, and J on Figure 1 are lower than most familiar risks.

References for non-volcanic risk: Bailey (1980); Bullock, R. (1981, oral communication); Follmann (1978); Hewitt and Sheehan (1969); Insurance Information Institute (1965); Levett, S. (1981, oral communication); Pfeffer and Klock (1974); Pochin (1975); Rainey, W. (1981, oral communication); and Starr (1969).