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Proceedings of the Workshop on Present and Future Directions in Volcano-Hazard Assessments

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Volcano Hazards Program

Edited by Marianne C. Guffanti, Charles R. Bacon, Thomas C. Hanks, and William E. Scott

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FOREWORD

This report constitutes the Proceedings of the Workshop on Present and Future Directions in Volcano-Hazard Assessments convened by the Volcano Hazards Program of the U.S. Geological Survey (USGS) on September 23-24, 1998, in Menlo Park, California. The purpose of the workshop was to discuss various approaches to volcano-hazard assessment that are being used or developed, with emphasis on probabilistic methods and applications.

Assessment of the nature and likelihood of potential hazards at volcanoes is a major component of the Volcano Hazards Program, and the investigations highlighted in these Proceedings build on a substantial body of work by the USGS, beginning with the seminal report of Crandell and Mullineaux (1967) on Mount Rainier. The record of previous eruptions and mass-flow events at volcanoes, as interpreted from examination and dating of volcanic deposits, is the primary guide to the most likely types of future hazards and frequencies of their recurrence. Hazard assessments provide an essential basis for design of monitoring networks, eruption forecasts, land-use planning, emergency preparedness, and other mitigation actions. A bibliography of volcano-hazard assessments and hazard-zonation maps published by the USGS is included in this report. By their nature, volcano-hazard assessments are works in progress, subject to revision when pertinent new data or interpretations become available; accordingly, updated assessments have been published for some volcanoes.

The workshop assembled scientists having expertise in many aspects of volcanology and also in seismic hazards and statistics. Invited talks with unstructured discussion time stimulated fruitful exchange of ideas and methodologies among this diverse group. Some general factors to guide volcano-hazard assessment were clarified:

- The time scale over which the potential for volcano hazards is assessed ranges from long term (tens of thousands of years) at quiescent, infrequently active volcanoes to short term (hours to days) at restless ones building toward or in eruption. Moreover, volcano hazards are multiple in nature — including lava flows, tephra falls, ash clouds aloft, debris avalanches, lahars (mudflows), pyroclastic flows, shock waves, gaseous emissions, seismicity, tsunami — and the magnitude/frequency relationship will vary considerably by type of hazard at a given volcano. Thus, the nature of volcano hazards requires that a variety of probabilistic methods be employed, as no single approach serves all assessment purposes.

- Tephra fall is the phenomenon most amenable to traditional probabilistic hazard assessment. In this method, the probability of exceeding a certain hazard threshold (e.g., depth of ash accumulation) within a specified area and time period is calculated.

- The foundation for meaningful long- and short-term assessments is comprehensive understanding of the frequencies and types of past hazardous events at volcanoes. The necessary data are obtained only by thorough field study and dating of volcanic deposits which the Volcano Hazards Program will continue to conduct as a high-priority activity.

- Robust, physically accurate models of various mass-flow phenomena offer an additional method for hazard assessment. Research on volcanic processes will continue to be needed to refine such models.

- Ideally, publication of a long-term volcano-hazard assessment for a particular volcano should follow thorough multi-disciplinary investigations well documented in the scientific literature. Sometimes, however, an assessment will be published before such investigations are completed because of circumstances such as the onset of unrest or a land-use-planning requirement, with the recognition that a revised assessment may be necessary.

- Reasons to revise an existing assessment at a particular volcano include acquisition of significant new data or scientific understanding, development of new assessment methodologies, need for a new report format (e.g., digital map products), or lack of a recent (published within the past 10-15 years) assessment report.

- Short-term hazard assessment involves analysis of possible outcomes at a volcano during a period of ongoing unrest, with official hazard statements issued as often as hourly. The physico-chemical processes driving unrest are incompletely understood, making it difficult for scientists to distinguish between temporary fitfulness and actual eruption precursors at a restless volcano and to predict the magnitude of an eruption. Decision trees and elicitations of expert opinions are useful in rapidly changing situations, but must be recognized as still involving substantial subjectivity.

- The term risk refers to the harmful impacts of hazardous natural volcanic phenomena on people, communities, and economies. Risk can be lessened, or mitigated, but volcano hazards — the natural phenomena — cannot be. A formal, quantitative risk assessment takes into account both the hazard probability and the value of people and property vulnerable to the hazard. The Volcano Hazards Program typically contributes the assessment of hazard probabilities rather than prepares the quantitative risk assessment. However, working with other agencies and communities to help them understand their risk and evaluate mitigation options is within the program's purview.

- Effective communication about the potential for volcano hazards requires different products for diverse user groups. The Volcano Hazard Program will prepare quantitative probabilistic assessments where appropriate while also continuing to produce hazard information in other forms.

WORKSHOP ON PRESENT AND FUTURE DIRECTIONS IN VOLCANO HAZARD ASSESSMENTS

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WORKSHOP ON PRESENT AND FUTURE DIRECTIONS IN VOLCANO HAZARD ASSESSMENTS
Menlo Park, California
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Agenda

Wednesday, September 23

Morning Session, Tom Hanks, Chair

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0840 Why "probabilistic" hazard analysis?--*Tom Hanks*

0910 The National Seismic Hazard Maps--*Art Frankel*

0940 An example of a probabilistic volcano hazard assessment - Cerro Negro, Nicaragua--*Chuck Connor*

1050 Some observations on probabilities of volcanic eruptions and applications involving recent USGS hazards assessments--*Manny Nathenson*

Afternoon Session, Charlie Bacon, Chair

1300 Volcanic ash hazards to aviation in the North Pacific--*Tom Miller*

1330 Long-term, probabilistic assessment of tephra accumulation in the Pacific Northwest--*Rick Hoblitt*

1400 Contrasts between Mount Hood and Crater Lake and the significance of long-term evolution of volcanoes for hazard assessment--*Willie Scott, Charlie Bacon*

1510 Probabilistic approaches to origin, triggering mechanism, and mobility of debris avalanches and lahars--implications for long-term mitigation strategies--*Kevin Scott*

1540 Statistical approach to hazard assessment and zonation for debris avalanches and lahars--*Dick Iverson*

1610 Risk-based volcanology: A Bayesian approach to lahar frequency analysis using reconstructed history and data uncertainties--*Roger Denlinger*

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0830 Assessing probability of lava flow inundation in Hawaii --*Jim Kauahikaua*

0900 Challenges in Attempting Conditional Probability Estimates in Long Valley Caldera--*Dave Hill*

1010 Real-time volcano hazard assessment incorporating recursive modeling and multiple parameter monitoring--*Bob Smith*

1040 Probability trees for volcanic crises--*Rick Hoblitt, Chris Newhall*

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Yucca Mountain as an example of a PVHA

1300 *Bob Youngs*

1340 *Chuck Connor*

1410 Uncertainty, diversity, and experts--*Allin Cornell* and *George Thompson*

1520 Volcano hazard assessments: Questions, Answers, and Issues Panel-- *Bob Youngs, Chuck Connor, Allin Cornell, Tom Hanks (moderator), Chris Newhall, Chris Waythomas*

PROBABILISTIC NATURAL HAZARD ANALYSIS: PxHA

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The essential ingredients of natural hazard analysis, whether it be for volcanoes, earthquakes, hurricanes, river floods, wildfires, or avalanches is to know where these things occur (spatial domain), how often these things occur (temporal domain), and how big these things are (size distribution). Taken to very specific limits on where, when, and how big, one is dealing with natural hazard prediction, and most participants in this workshop will know that some success has been achieved in the way of volcano eruption prediction. More generally, however, one is dealing with some to considerable uncertainty as to where, when, and how big, especially when the spatial domain is large, the rate of occurrence is low, and the premonitory signal is weak, the case for earthquakes in the eastern United States, for example. The final ingredient in hazard analysis is hazard specific; it describes the relationships between events (rainfall as a function of place and duration, say) and effects (overbank heights as a function of distance downstream).

Until fairly recently, at least in the case of earthquakes, hazard analysis was predicated on a deterministic or, even worse, on a worst-case scenario basis. There is no element of time in these formats, and given enough time, there will always be a situation worse than the "worst case", the "huge" earthquake, for example. Probabilistic hazard/risk analysis is predicated on the basis that bad happens and so does worse, given enough time or--to be more precise--low enough probability levels.

PxHA is a formalism with which the spatial domain, temporal domain, and size distribution, together with the appropriate event-effect(s) relationship(s), are systematically accounted for. Just as importantly, it provides for a systematic treatment of uncertainties in the matters to be dealt with. Novices to PxHA need to know that, at least in this business, things like volcanoes, earthquakes, and river floods are not hazards. Neither are things like ashfall depth, ground-motion amplitude, or overbank height. Hazards are the probabilities of exceeding some specified ashfall depth, ground-motion amplitude, or overbank height; they are just small numbers, with units of 1/yr. In the case of seismic design, commercial structures in California's finest earthquake country are designed at a hazard level of approximately 10**-3/yr, that is, for a ground motion with a probability of exceedance of 10**-3/yr. Critical structures like nuclear reactors are nominally designed for a hazard level of 10**-4/yr.

PxHA has reached its fullest expression in the case of seismic hazards, also the first expression of PxHA beginning 30 years ago. Important differences between PSHA and other forms of PxHA are the large spatial domains in which earthquakes occur and the large zone of influence in which damaging to potentially destructive ground motions occur. In contrast, volcanic eruptions generally occur in pre-existing vents, and lahars and lava flows generally flow in previously occupied channels/runout areas. The volcanic ashfall problem is probably the closest to the PSHA problem.

National Seismic Hazard Maps

A. Frankel, C. Mueller, T. Barnhard, S. Harmsen, R. Wesson, E. Leyendecker, F. Klein, D. Perkins, N. Dickman, S. Hanson, and M. Hopper

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The USGS recently completed new probabilistic seismic hazard maps for the United States, including Alaska and Hawaii. The maps depict peak ground acceleration and spectral response values with 10%, 5%, and 2% probabilities of exceedance in 50 years, corresponding to return times of about 500, 1000, and 2500 years, respectively. The maps are based on calculations of hazard curves on a grid of about 100,000 sites. Each hazard curve shows the annual rates of exceeding a set of ground motion levels. The hazard curves are derived by summing the rates of exceedance from all potential earthquake sources within a certain distance of a site. This requires a specification of the expected magnitudes and recurrence rates for earthquakes in each source location and a description of the ground motions at the site that would be produced by these potential earthquakes.

In the national maps, earthquake sources are characterized by three basic models. First, we use spatially-smoothed historic seismicity to determine the recurrence rates of future earthquakes. In this model, we apply the general observation that moderate and large earthquakes tend to occur near areas of previous small or moderate events. Second, we consider large background source zones based on broad geologic criteria to quantify hazard in areas with little or no historic seismicity, but with the potential for generating large events. Third, we include the hazard from specific fault sources. We use about 450 faults in the western U.S. and derive recurrence times from either geologic slip rates or the dating of pre-historic earthquakes from trenching studies.

We apply logic trees to incorporate different seismicity models, fault recurrence models, Cascadia great earthquake scenarios, and ground-motion attenuation relations. The contribution of different sources to the hazard at a site is displayed in various "de-aggregation" plots. A Monte Carlo technique is used to estimate uncertainties for 30 cities in the central and eastern U.S. In general, larger uncertainties are found for areas of low historic seismicity but with the potential for damaging earthquakes.

An Application of PVHA: Cerro Negro volcano, Nicaragua

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Probabilistic volcanic hazard assessment (PVHA) involves identification of specific hazards (e.g., tephra dispersion, pyroclastic flows) and estimation of the probability of their occurrence. Sometimes it is appropriate to include exposure in a PVHA, to account for the length of time a particular facility is exposed to a volcanic hazard or the possibility of multiple events affecting an area within a given period of time. PVHA can be extended to a probabilistic risk assessment if the consequences of volcanic activity (e.g., fatalities, economic loss) are also estimated. Using these definitions, the probability of >10 cm of ash falling on, or a pyroclastic flow reaching, a given area are the purview of PVHA; risk results from the construction of facilities or the occupation of that area. In some case, the consequences of volcanic activity are complex. For instance, when nuclear facilities are exposed to hazards the consequences of volcanic activity may include the release of radiation, possibly also resulting in fatalities or loss of use of a contaminated zone for a long period of time.

Volcanic eruptions are often comparatively low probability and high consequence events. This makes it particularly important to evaluate volcanic hazards in a consistent and quantitative manner. It follows that PVHAs should include: 1) clear definition of the hazard(s) considered, 2) a geologically accurate and freely disseminated data base, 3) discussion about model assumptions, 4) uncertainty analysis and sensitivity study.

Cerro Negro volcano, Nicaragua, is a small basaltic cinder cone active since 1850 and provides a straightforward application of PVHA. This volcano has erupted 23 times since 1850, for a total of 436 days of eruption and an effusion rate of 3.7×10^5 m^3 /day DRE, very typical for cinder cone eruptions. For details of the 1992 and 1995 eruptions of Cerro Negro, see Hill et al. (1998). The main hazard associated with eruptions of Cerro Negro is ash fall. This is particularly a problem for the city of Leon (200,000 people) because trade winds nearly always blow ash from the 2-6 km-high-eruption columns over the city. This ash fall, although never very thick, has resulted in numerous fatalities (9 reported in 1992) and has resulted in large evacuations because of disrupted water supplies. We decided to perform a PVHA for Cerro Negro primarily to test models of basaltic ash dispersion, but also to probabilistically estimate ash fall hazard for Leon.

Recurrence rate of eruptions of Cerro Negro are estimated using volume-predictable models. Cerro Negro has exhibited a reasonably steady-state volume effusion rate since 1900, and based on this an eruption is expected before 2006 with 95% confidence. Assuming eruptions occur independently through time and are not volume predictable, there is a 74% chance of eruption before 2006. An empirical ash dispersion model is used to estimate ash thicknesses in Leon from Cerro Negro eruptions. Stochastic sampling of eruption and atmospheric parameters derived from previous eruptions is used to calculate a complementary cumulative distribution function for fall deposit thickness in Leon, effectively summarizing ash fall hazard. For example, given an eruption of Cerro Negro, there is a 50% chance of ash thickness exceeding 0.2 cm and a 5% chance of ash thickness exceeding 11 cm.

Hill, B.E., C.B. Connor, M.S. Jarzemba, P.C. La Femina, M. Navarro, and W. Strauch. 1998. 1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions. Geol. Soc. Am., Bull. In press, October 1998 issue.

Some Observations on Probabilities of Volcanic Eruptions and Applications Involving Recent USGS Hazards Assessments

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An underlying assumption of USGS hazards assessments is that the probability of volcanic eruptions may be treated as a Poisson process. The properties of a Poisson process include the characteristic that the conditional probability of waiting till an eruption occurs does not depend on the time that we have already waited only on the time that is in the future. A problem with field data for eruption intervals between volcanic eruptions is that there are usually only a few (a dozen to thirty) data points, and it is difficult to assess if such small data sets actually follow a Poisson process. Statistical tests are sometimes useful but may give equivocal results. Having derived some distribution for eruption intervals, it is a relatively simple matter to perform numerical experiments to assess variations that are likely to occur because of the small sample size. Such experiments are particularly useful in gaining a qualitative understanding of possible variability and show that quite large variations occur in mean recurrence rate and standard deviations with small samples.

Recent hazards assessments for the Cascades are generally based on calculation of a recurrence rate and either an annual or 30-year probability for an eruption. For a Poisson process, this relation is obtained from the exponential distribution for the probability that an eruption will occur in a time T less than or equal to the interval time t:

$$P\{T \le t\} = 1 - e^{-\mu t}$$
$$\approx \mu t, \quad \text{for } \mu t \text{ small,}$$

where μ is the mean occurrence rate of events per year. Since occurrence rates are small in the Cascades, the approximate relation shown is normally used. For the case of lava flows from isolated vents covering an area a in a volcanic field of total area A, a factor $p = a/A$ can be factored in as $\mu t p$ to account for the probability of areal coverage. This analysis assumes that the occurrence of vents are homogeneous in space within the defined area of the volcanic field.

Mullineaux's (1974) data for eruption times for tephra layers at Mount Rainier have the property that there are three long intervals (>2000 years) and seven short intervals (<600 years). This division into long and short intervals occurs in other eruption interval data sets (e.g. Mount St. Helens). The exponential model does not represent these data very well. The Weibull distribution introduced by Bebbington and Lai (1996) is also unable to effectively deal with these disparate intervals. An alternate distribution is the double exponential

$$P\{T \le t\} = 1 - p_1 e^{-\mu_1 t} + p_2 e^{-\mu_2 t}$$

where p_1 is the fraction of short intervals, μ_1 is the average occurrence rate for the short intervals, and p_2 and μ_2 are the same parameters for the long intervals. The basic notion embodied in this relation is that there are two states, one involving short intervals and a second involving long intervals. The probability of an eruption occurring in each of these states is governed by an exponential distribution. The double-exponential distribution appears to match the available data reasonably well and resolves a conceptual problem for volcanoes with disparate eruption time intervals. Probabilities for a 30-year time period calculated using the double exponential for tephra eruptions for Mount Rainier are about twice those for the single exponential.

Volcanic Ash Hazards to Aviation Across the North Pacific

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A newly emerging volcanic hazard posed by encounters between jet aircraft and airborne volcanic ash has only recently been recognized by the airline industry, volcanologists, and public officials throughout the world. More than 100 such encounters since 1980 have resulted in widespread engine failure and damage to avionics and aircraft structure causing hundreds of millions of dollars in damages in Indonesia, Alaska, and the Philippines. Loss of life has only narrowly and fortuitously been averted. This hazard exists not only proximal to an erupting volcano but at distances of >1,500 km. Furthermore, the hazard is compounded by the post-cold-war increase in commercial aviation worldwide and the development of large (wide-body) jet aircraft whose engines operate at ever higher temperatures making them even more susceptible to damage by volcanic ash. Volcanic ash clouds are not presently detectable by aircraft radar nor are they likely to be in the foreseeable future.

Aircraft flying the long international air routes across the remote North Pacific between North America-Europe and Asia pass by 100 historically active volcanoes in Alaska, Kamchatka, and the Kurile Islands. Although the rate of volcanic eruptions in this region continues to be constant at ***5-6 per year***, air traffic has now increased to ***>200 flights per day*** carrying an estimated ***20,000 passengers*** and including ***>90% of the all-cargo*** flights between North America and Asia. ***Empirical*** estimates based on a comparison of eruptive events for the past 20 years and a 200-year historical record suggest that volcanic ash will be in the heavily traveled North Pacific (***NOPAC***) air corridors at critical altitudes of ***>30,000 ft (9 km)*** at least ***4 days per year***, placing life and property at significant risk. On an additional ***10-12 days per year***, volcanic ash clouds are estimated to be close enough to flight routes to be a matter of concern to aviation. The Federal Aviation Administration estimate an ***8% per year growth*** in air traffic across the North Pacific for the ***next 5 years*** and Boeing projects little change in the type of cargo aircraft or their operations over the next 20 years. **Thus, while the hazard (eruptions) remains constant, vulnerability (increased air traffic, etc.) will continue to increase significantly raising the overall risk to life and property.**

Recognition of this serious problem by volcanologists, foreign and domestic airlines, and governmental aviation and meteorological agencies in the United States, Russia, Japan, and Canada has led to increased funding over the past 5 years for monitoring and mitigation of the hazard. Real-time seismic monitoring now exists for over 20 active volcanoes in the region allowing identification of eruptive events and, in some cases, prediction. Satellite monitoring of the entire North Pacific using AVHRR, GOES, and GMS is now done routinely twice a day by the Alaska Volcano Observatory (AVO), and more frequently during times of volcanic unrest. Other standard monitoring techniques such as ground deformation, gas analyses, geologic field studies, and aerial observations have also been increased. Close working relations have been developed between the AVO, Kamchatka Volcanic Eruption Response Team (KVERT), National Weather Service, FAA, and airline dispatchers through joint work on frequent eruptions, drills, formal written response plans, and conferences. The result is a rapid flow of information to user groups (ultimately the airlines) through the Anchorage Volcanic Ash Advisory Center (VAAC) and AVO.

The ultimate goal of these efforts is to provide warnings of eruptive events to user groups within minutes of their occurrence, detect thermal anomalies, track volcanic ash clouds across air routes in this remote region, and furnish information on size, character, and likely duration of an eruption. While these multidisciplinary efforts have been successful to date in the mitigation of hazards posed to aircraft operations by numerous recent volcanic eruptions in the North Pacific, much remains to be done.

Long-term, probabilistic assessment of tephra accumulation in the Pacific Northwest

Rick Hoblitt

As part of a report prepared for the U.S. Nuclear Regulatory Commission[1], a scheme for estimating the long-term tephra accumulation probabilities in the Pacific Northwest was constructed; this builds on earlier work by Newhall[2]. Consider some point at an azimuth A and distance D from some volcano. In essence, the probability that tephra accumulation at this point will exceed some specified thickness is taken as the product of three probabilities: (1) P_E, the probability that the given volcano will erupt, (2) P_A, the probability that azimuth A is downwind from the volcano, and (3), P_D, the probability that the specified tephra thickness will be exceeded at distance D. We assume eruptions conform to a Poisson distribution (eruptions occur randomly in time), with $P_E = (1/R)(e^{-1/R})$, where R is the mean recurrence interval in years and P_E is the annual probability of eruption. For the rather long recurrence intervals of the Cascade volcanoes, $P_E \sim 1/R$. P_A, the "downwind" probability, is estimated from National Weather Service wind-frequency data collected over a 20-yr period at Quillayute, Washington, at altitudes between about 3 to 16 km. These data are used for the entire Pacific Northwest because high-level winds are essentially the same throughout the region. P_D, the tephra thickness exceedance probability, was taken from tables of exceedance probabilities compiled by Newhall[2] from world-wide distance-thickness data on well characterized eruptions.

The total probability--that due to all contributing volcanoes—is effectively the sum of the volcano-specific probabilities. Probabilities are calculated for grid points across the area of interest with a user-friendly PC computer program written for that purpose. The total probability grid is then contoured using Surfer, a commercial program.

Hoblitt, R.P., Miller, C.D., and Scott, W.E., 1987, Volcanic hazards with regard to siting nuclear-power plants in the Pacific Northwest: U.S. Geological Survey Open-File Report 87-297, 196 p.

Newhall, C.G., 1982, A method for estimating intermediate- and long-term risks from volcanic activity, with an example from Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 84-272, 29 p.

Contrasts between Mount Hood and Crater Lake and the significance of long-term evolution of volcanoes for hazard assessment: Mount Hood

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PVHA Workshop, September 23-24, 1998

Mount Hood is long-lived (>1 my) andesitic (58-64 wt. % SiO_2) volcanic center that lies within a broad field of mafic (50-58 wt. % SiO_2) monogenetic volcanoes. The bulk of Hood's 100 ± 40 km^3 edifice is composed of lava flows; lava domes and clastic deposits related to dome collapse are subordinate. Greater erodibility of clastic deposits, the tendency of lava domes to hydrothermally alter and disappear in debris avalanches, and poor outcrop potential of clastic deposits enhances greatly the lava-flow fraction. The past 50,000 years has produced roughly equal portions of each; the past two episodes were solely lava dome eruptions. Explosive plinian or subplinian events are apparently absent. Although subject to substantial uncertainties, extruded magma volume during individual episodes (lasting months to centuries?) ranges chiefly from 10^7 to 10^8 m^3. A few lava-flow episodes may have exceeded 1 x 10^9 m^3. Debris avalanches remove similar volumes in single events, some of which accompany eruptive episodes.

The limited variation in past eruptive behavior reduces uncertainty about the character of future eruptions. Remaining notable uncertainties include position of future vents, lava flow vs. lava dome, and volume-duration issues for eruptions, and location and volume of debris avalanches and lahars generated by sector or flank collapses. In our hazard assessment, we state that lava dome growth and collapse is the most likely type of future eruptive event on the basis of latest Quaternary activity. Extrusion will likely occur at or near the conduit used during the last two episodes, but that a new vent location is certainly possible. We envision the most likely volume of a lava-dome episode to be similar to that of Hood's Holocene episodes (10^7 to 10^8 m^3) and that duration would probably be similar to some comparable historical examples--months to several years (Redoubt, Unzen, Montserrat)--but might continue intermittently for decades or centuries. Downstream inundation by lahars during the Holocene episodes serves as a good guide for delineating areas at risk of inundation during future events.

Greater uncertainty surrounds the location and volume of future debris avalanches, which are probably the most significant issues in terms of hazard assessment. Debris avalanches and related lahars of a few hundred million cubic meters would sweep through both Sandy and Hood River valleys to the Columbia River in a few hours. Such an event at or near the beginning of an eruptive episode about 1.5 ka removed the southwest side of the summit and isolated the forks of Hood River from the vent area. Owing to the volcano's shape and pattern of hydothermal alteration, future avalanches of this size, or several times larger, are probably most likely from the steep east, north and west flanks, and may well change the summit geometry so that lava domes have access to the Hood River basin. Probabilistic assessments of such events are a difficult, but important challenge.

The latest Quaternary eruptive history of Mount Hood also illustrates well the problem of making probabilistic statements about recurrence itself, let alone about all of the issues above. We have a limited sample set of two late Holocene episodes (about 1.5 and 0.2 ka) that followed an apparent dormant interval of at least 10 kyr. Last and late glacial eruptive episodes are difficult to date precisely, but their distribution, stratigraphic relation to glacial deposits, and limited paleomagnetic evidence suggest clusters of several dome-building episodes separated by millennia-long dormant intervals. Therefore, in our recent hazard assessment we propose that the annual probability of an eruptive episode (using the late Holocene vent) is 1 in 500 to 1 in 1000, reflecting our judgement that we are more likely in a time period of clustered activity like those of the late glacial rather than at the start of a long dormant interval. We estimate the annual probability of eruption at a vent elsewhere on the summit or upper flanks is about one order of magnitude less likely than at the late Holocene vent. Ideas for better methods are welcome.

Known vents of monogenetic volcanoes of Quaternary age lie no closer than 4 to 5 km of the summit of Mount Hood. The average late Quaternary frequency of monogenetic volcanism in the region within a 25 km radius of Mount Hood is roughly 1 per 30,000 yr, a rate that is largely insignificant for most planning purposes.

Contrasts between Mount Hood and Crater Lake and the significance of long-term evolution of volcanoes for hazard assessment: Crater Lake

Charles R. Bacon, USGS, Menlo Park, California

Crater Lake caldera formed by collapse of the roof of a shallow magma chamber during eruption of ~50 km^3 of magma about 7,700 years ago. Detailed study of the eruptive history of Mount Mazama, the Cascade volcanic center in which Crater Lake caldera formed, provides insight into assessing hazards at long-lived volcanic centers that produce a wide range of magma compositions: (1) Differentiated, potentially explosive magmas formed at the site of earlier silicic volcanism. (2) Mount Mazama consisted of a complex of overlapping andesitic to dacitic shield and stratovolcanoes, each of which was active for a comparatively short period. (3) Peripheral basaltic to andesitic shield volcanoes and isolated vents were active intermittently throughout the lifetime of the Mazama focus, as at many other Cascade centers (e.g., Mount Adams). (4) Mount Mazama erupted frequently between 400 ka and 35 ka, punctuated by a few particularly voluminous episodes. (5) Voluminous, explosive dacitic eruptions occurred ~70 ka, followed by a return to dominantly andesitic volcanism. (6) There is no record preserved of andesitic or dacitic eruptions at Mazama between 35 ka and caldera collapse but basaltic to andesitic magmas were erupted in considerable volume from peripheral vents. (7) At the same time, the climactic magma chamber developed and it's low-density rhyodacitic magma prevented escape of denser basaltic to andesitic input melts. (8) Accumulation of rhyodacitic magma is tracked by eruptions of preclimactic rhyodacite from ~25 ka until just before the climactic eruption. (9) Catastrophic venting of the chamber and caldera collapse dramatically changed the setting for postcaldera volcanism. (10) Filling of Crater Lake and disappearance of the high part of the Mazama edifice leads us to forecast types of eruptions that would be uncommon elsewhere in the Cascades and a low probability of the lahars considered to be major hazards at large stratovolcanoes.

The history of the Mazama center is illustrated by a plot of radiometric ages of eruptive units (K-Ar, $^{40}Ar/^{39}Ar$, and ^{14}C) against stratigraphic order determined by geologic mapping. Symbol color indicates composition and symbol size gives relative volume. Comparatively voluminous silicic volcanism occurred when peripheral (regional) volcanoes also were vigorously active, as though the regional flux of magma originating in the mantle was strongest then. At such times, the thermal input to the Mazama system would have been sufficient for differentiated melts to accumulate rather than crystallize between magmatic recharge events.

Forecasting behavior at long-lived centers with diverse products, such as Mazama, is inherently less certain than at volcanoes that periodically erupt magma of nearly constant composition. Mount Hood is a Cascade volcano more akin to the latter type where analysis of the character, magnitude, and probability of future eruptions is more amenable to mathematical approaches. Simpler still is assessment of the probability of eruption of new vents representing regional volcanism if we assume that occurrence of new vents is a random process (which we have seen is not entirely consistent with knowledge of eruptive history). We have assigned eruption probabilities for regional volcanoes in the Crater Lake area, without factoring in possible effects of regional structures or temporal variation in eruption rate (see 1997 hazard assessment). Poisson behavior is assumed and probability of eruption is based on counts of eruptive episodes during the last 100 k.y. This results in an annual probability of eruption anywhere in the greater Crater Lake area of 10^{-4} or a 30-year probability of $3x10^{-3}$. We consider an eruption at Mount Mazama to be at least as likely but cannot give a numerical estimate because of the drastic resetting of the system brought about by the climactic eruption and caldera collapse. An eruption within the caldera, where all postcaldera volcanism has occurred, potentially would produce pyroclastic surges that could surmount the caldera walls and affect the upper slopes and valleys of Mount Mazama. Particularly energetic ballistic blocks could impact the caldera rim. Lahars in major drainages are a possibility if sufficient lake water is ejected or if hot material melts a large volume of winter snow and mobilizes unconsolidated debris remaining from the climactic eruption. A major explosive eruption, breaching of the caldera wall and draining of the lake, or sudden release of CO_2 from the lake are extremely unlikely events.

Behavioral Probabilities of Debris Avalanches and Lahars

A. Volcano collapse (>~ 0.1 km^3) commonly produces debris flow (**cohesive; clay-rich**) by direct transformation, rather than a debris avalanche of limited runout potential.

How is this known?: Case history studies at Rainier, Baker, and Adams (plus examples in Mexico, Colombia, and Chile).

Why not previously recognized?: 1. Behavior of 1980 Mount St. Helens; 2. Scale-dependent; 3. Most field studies with proximal focus.

B. Surges from lake breakouts and natural dam failures at volcanoes can transform to debris flow (**noncohesive; granular**) by sediment entrainment (bulking).

How is this known?: By documentation of huge prehistoric (2,500 BP) debris flows from breakouts (or displacement) of avalanche-dammed Spirit L.

Why not previously recognized?: 1. No previous documentation; 2. Mistakenly contraindicated by one element of hydraulic theory.

>>>>>

Are these serious issues? Possible scenarios in 1980 at Mount St. Helens

Scenario A--The 2.5 km^3 sector collapse transformed directly to debris flow, **like most of its known analogs in the Cascades Range.**

Result--Inundation by cohesive lahar extending to Portland OR and Pacific Ocean.

Scenario B--The sector collapse occurred 30 degrees toward the NE rather than due N, displacing rather than damming and raising Spirit Lake.

Result--Inundation by noncohesive lahar extending to Portland OR and Pacific Ocean.

>>>>>

CONCLUSIONS RELEVANT TO VOLCANIC HAZARD ASSESSMENT

1. Limiting the runout distance of volcanic landslides on the basis that flow will occur as a debris avalanche is generally not possible. Flow mobilities must be assumed to be such that large populations far from a volcano may be at significant risk (i.e., Rainier), if flow history indicates a significant magnitude and frequency of collapse.

2. Distinguishing past lahars of landslide origin (cohesive) from those of syneruptive, meltwater or rainfall origin (noncohesive) is a *sine qua non* in defining future flow hazards. Documention of past events (with paleohydrology) is the key to preventing future volcanic flow disasters (B. Voight, 1988, 1990, 1996).

3. Volcanoes for which I am contributing to hazard assessments in the Western Hemisphere (Baker, Rainier, Nevado de Toluca, Colima, El Chichón, Tacaná, Nevado del Huila, Planchón-Peteroa, and others) have remarkably different flow histories as well as different risk issues requiring different mitigation strategies (thus different approaches, not different philosophies).

4. Few volcanoes present the level of risk to major populations that is resulting in the "Rainier mitigation strategy"--land-use planning, AFM networks, ESWEV, possible eventual SRS's.

Kevin Scott

Objective Delineation of Lahar-Inundation Hazard Zones

(GSA Bulletin, August 1998)

R.M. Iverson, S.P. Schilling, J.W. Vallance

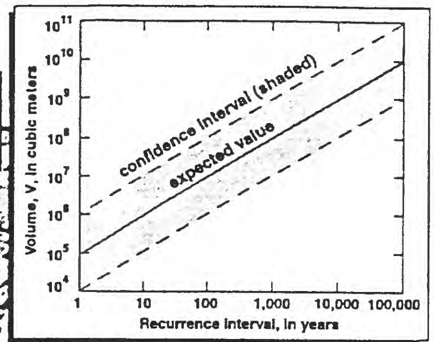


Figure 11. Hypothetical relationship between lahar volume and lahar recurrence at Mount Rainier.

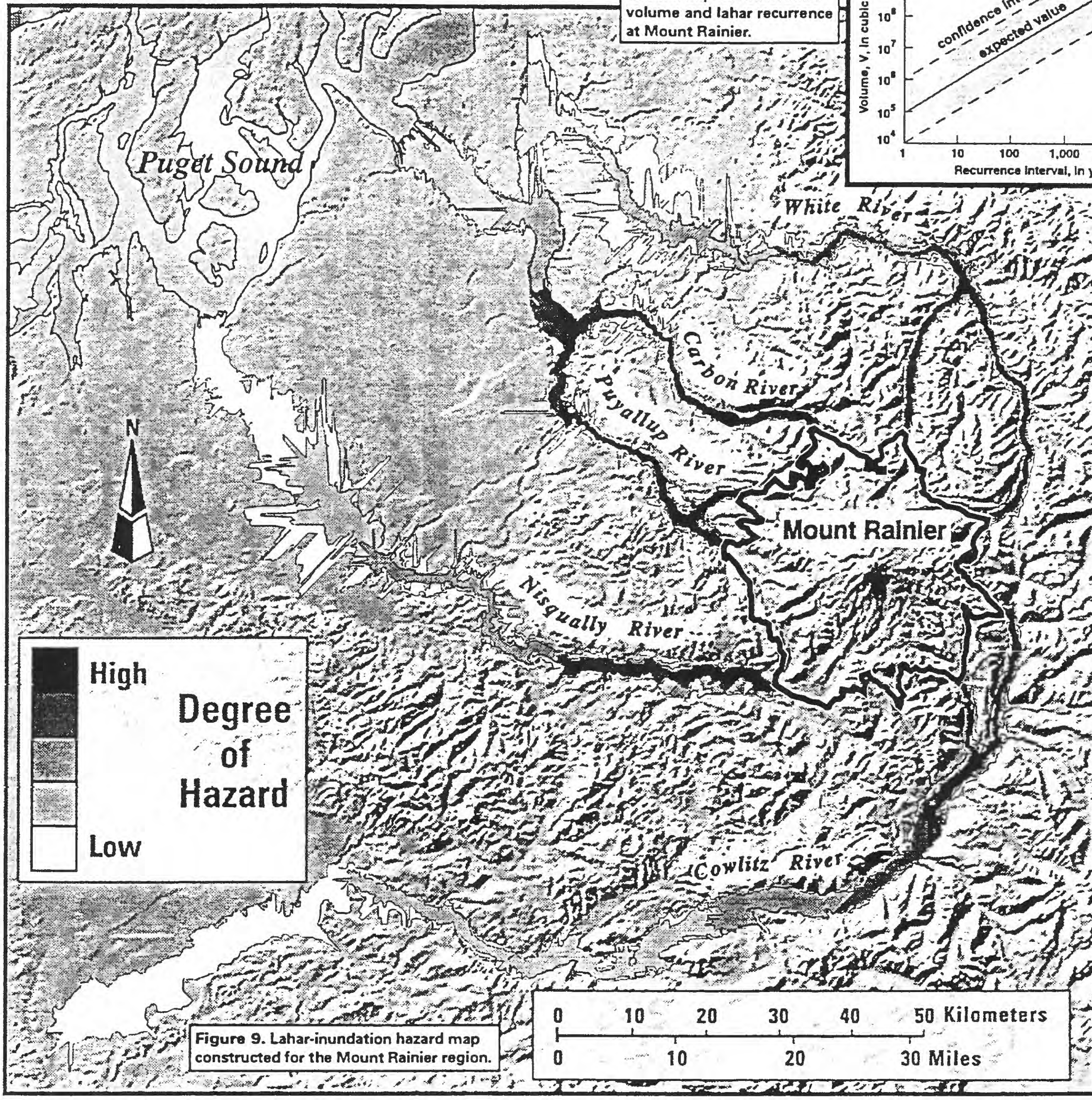


Figure 9. Lahar-inundation hazard map constructed for the Mount Rainier region.

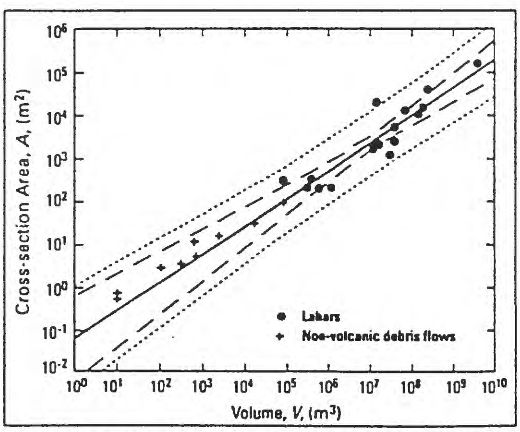


Figure 5. Scatter plot of inundated valley cross-section area *A* as a function of lahar volume *V*. The best-fit-log-log regression line and 95% confidence intervals for regression (dashed lines) and prediction (dotted lines) are also shown.

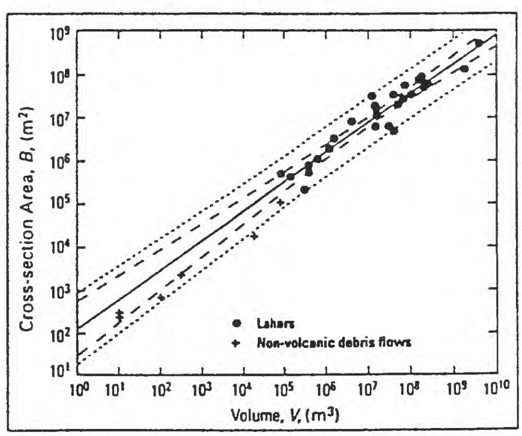


Figure 6. Scatter plot of inundated planimetric area *B* as a function of lahar volume *V*. The best-fit-log-log regression line and 95% confidence intervals for regression (dashed lines) and prediction (dotted lines) are also shown.

Risk Based Volcanology: A Bayesian Approach to Lahar Frequency Analysis Incorporating Data and Model Uncertainties

R. Denlinger and D. O'Connell

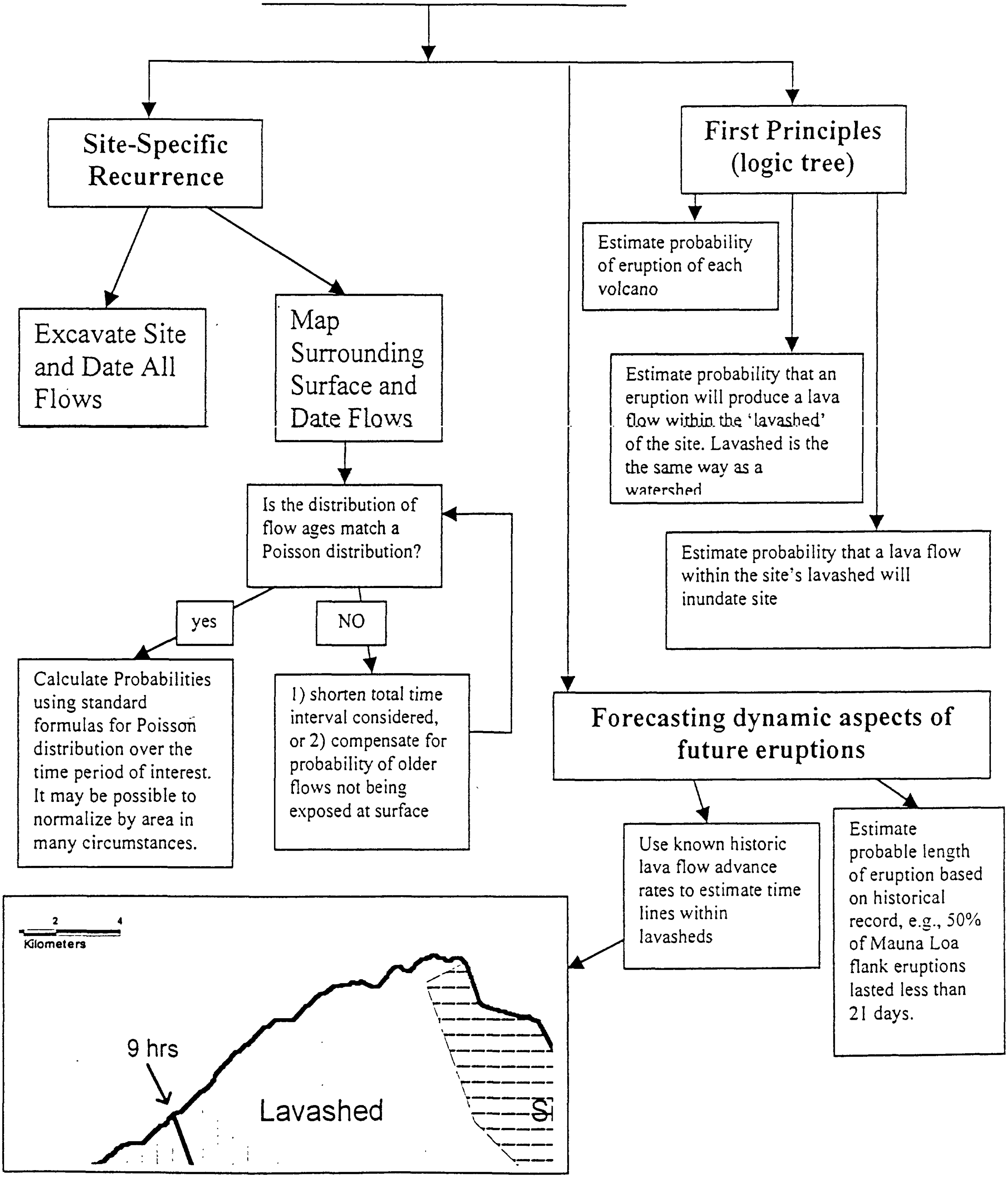
The primary goals of this statistical analysis are to determine the annual risk (probability) of a lahar exceeding a given threshold in the drainage of a volcano. Another goal is to quantify the incorporation of field data into the statistical analysis of lahar frequency. A Bayesian methodology (Tarantola, 1987) and likelihood functions modified from Stedinger and Cohn(1986) are used to incorporate data and parameter uncertainties. Parameter and flood frequency likelihoods and probability intervals are calculated directly by numerical integration. Systematic parameter space searches provide the most powerful method to determine flood frequency probabilities. This is feasible with high speed workstations: a systematic search of a parameter space of four or less can be completed without resorting to Monte Carlo methods of statistical sampling and integration. This approach is used with field data to develop lahar frequency probabilities, to estimate the annual probability of lahar volume exceeding a certain magnitude, and to quantify the statistical value of incorporating field measurements into the analysis.

The Bayesian approach here explicitly acknowledges that the parameters and the data are never perfectly known. Both parameter and data uncertainties are incorporated into risk and probability interval estimates of lahar frequency. It directly measures how well data constrain model parameters. The Bayesian paradigm is a special case of the more general information theory of Tarantola (1987). These approaches quantitatively rank how well particular models fit data sets. For example, the value of each data point is somewhat uncertain, and the ranking or goodness of fit of each possible frequency function is proportional to how often the frequency function predicts values close to the observed data (high likelihood) or predicts values far from the observed data (low likelihood). The Bayesian approach uses a global parameter integration grid in a systematic quantitative framework to identify what ranges of frequency functions are consistent with the data at various probabilities. By selecting broad probability intervals, conservative evaluations of risk are obtained.

Assessing Probability of Lava Flow Inundation in Hawai`i

By Jim Kauahikaua and Frank Trusdell
USGS Hawaiian Volcano Observatory

Lava Flow Inundation is defined as a lava flow covering part or all of a selected area. First define the site and the time period of interest.



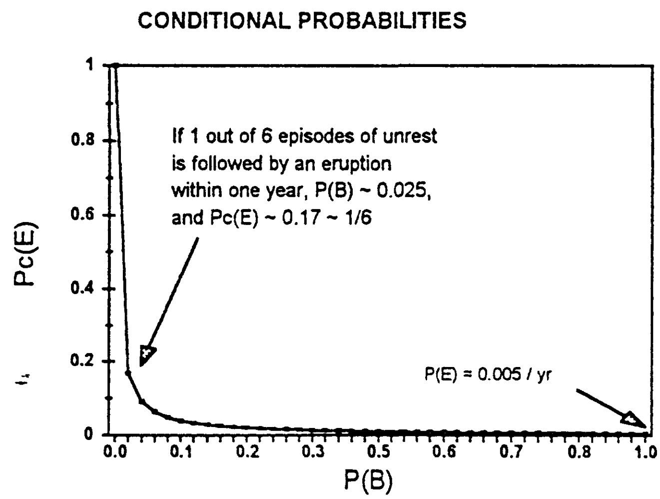
CHALLENGES IN ESTIMATING CONDITIONAL PROBABILITIES FOR ERUPTIONS IN LONG VALLEY CALDERA

David P. Hill

The intrusion of magma into the shallow crust is a noisy process, which makes short-term eruption forecasting a scientifically viable endeavor. Indeed, we have seen a number of successful eruption forecasts for central vent volcanoes over the past couple of decades based on the patterns of volcanic unrest prior to the eruptions. Large, restless calderas such as Long Valley, however, pose a special challenge in this regard because of 1) the limited number of well-documented eruptions from these complex magmatic systems and 2) the propensity of these volcanic systems to exhibit multiple episodes of magmatic unrest between infrequent eruptions. One way of approaching this problem is to explore the conditional probability, Pc, for an eruption, E, given an episode of unrest that may be either "background" activity, B, or the short-term precursor to an eruption, S. Taking advantage of the relation developed by Agnew and Jones (JGR, 1991) for the conditional probability of a large earthquake (mainshock) given a smaller earthquake that may or may not be a foreshock, we have

$$Pc(E) = P(E|B \cup S) = P(E) / [P(E) + P(B)] \qquad (1)$$

where $P(E)$ is the unconditional annual probability for an eruption based on recurrence intervals in the geologic record, and $P(B)$ is the annual probability that the unrest episode is not a short-term precursor to an eruption. In obtaining *(1)*, we have also taken advantage of the fact that, for volcanoes, the probability of a short-term precursor given an eruption, $P(S|E) \sim 1$. (In the case of earthquakes, the analogous probability of a foreshock, F, given a mainshock, M, is somewhere in the range $P(F|M) = 0.2$ *to* 0.5, and this term must be retained in *(1)*.) A plot of Pc vs $P(B)$ using *(1)* emphasizes that, to be reasonably confident that an unrest episode portends an eruption, $P(B)$ must be quite small.



Recognizing that $P(B) \sim NP(E)$ when $NP(E) << 1$, where N is an average number of background unrest episodes between eruptions, we can write *(1)* as $Pc \sim 1/(1 + N)$. Thus, an obvious strategy for enhancing the conditional probability, Pc, is to reduce N by distinguishing between types of unrest and eliminating "benign" episodes from consideration. In Long Valley, we have taken a step in this direction by distinguishing between progressively more threatening types of unrest ranging from "green" (no immediate threat) through "yellow", to "orange" (eruption "likely" in hours to days). We still have a long way to go, however, to quantify this scheme in a way that can effectively be incorporated into the formalism of equation *(1)*. An important step involves specifying what "short-term" means in terms of a probability distribution for the time interval between precursory unrest and the onset of an eruption. A year (used in the above plot) is rather long to be socially useful, and a few hours is too short.

Real-time Volcano Hazard Assessment: Multiple Parameter Monitoring And Recursive Modeling: With A Yellowstone Example

Smith, R. B., and C. M. Meertens, Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah.

A suggested approach to near real-time volcano risk assessment integrates access to near real-time data as seismic, GPS, remote sensing, gas emissions, etc. that can be modeled by automated predictive approaches for specific volcanic sources. Seismic networks with short period and broadband seismometry facilitate determinations of hypocenters and provide data for near real-time tomography, automated space-time analyses, and accurate focal mechanisms. Diurnal ground deformation by continuous geodetic measurements, such as GPS with real-time, predictive orbit processing, provide ground deformation fields. Along with seismic data this information can provide discrimination between seismic vs. asiemic sources employing automated 3-D elastic and visco-elastic models. Data from these observing systems can be input into a unified probabilistic volcano risk models to specify the probability of exceedance for eruptive conditions. Conditional probabilities based upon on realistic physical models for specific volcanoes can be updated as new data are acquired. Physical models must include source geometry, stress conditions, composition and gradient variations, fracture and volume porosity, heat transfer, fluid flow properties, etc. An example of the approach is being proposed incorporation of the first, combined, continuous recording broadband seismic (a cooperative USGS-university NSN station) and continuous GPS "Mountain Observatory" at Yellowstone from which data are telemetered via a satellite link. We will show how GPS derived volumetric change and seismic velocity models reveal common density-velocity fields indicative of source composition and geometries.

PROBABILITY TREES FOR VOLCANIC CRISES

CG Newhall and RP Hoblitt

ABSTRACT

Probability trees are useful frameworks for discussing possible outcomes of volcanic unrest. Each branch of the tree leads from a necessary prior event to a more specific outcome, e.g., from an eruption to a pyroclastic flow. Outcomes are selected to be comprehensive and mutually exclusive, so the sum of probabilities for each level (or order) of branches is 1.0. If the same final outcome can be reached by different paths, the probabilities of those paths are summed before results are presented to public authorities.

Where volcanic process is poorly understood, probability estimates might be purely empirical -- utilizing observations of past and current activity and an assumption that the future will mimic the past or follow a present trend. If process is better understood, probabilities might be estimated from a theoretical model, either subjectively or by numerical simulations. Estimates from empirical and theoretical approaches can be updated by use of Bayes' theorem.

Use of probability trees during volcanic crises can help volcanologists to rigorously examine their analysis of hazard, and help officials to compare volcanic risks to more familiar risks. Trees also emphasize the inherently probabilistic nature of volcano forecasts, with multiple possible outcomes. We and colleagues have used probability trees with mostly positive results at Mount St. Helens, Mount Pinatubo, Soufriere Hills (Montserrat) and Popocatépetl.

See Figure (1) on following page.

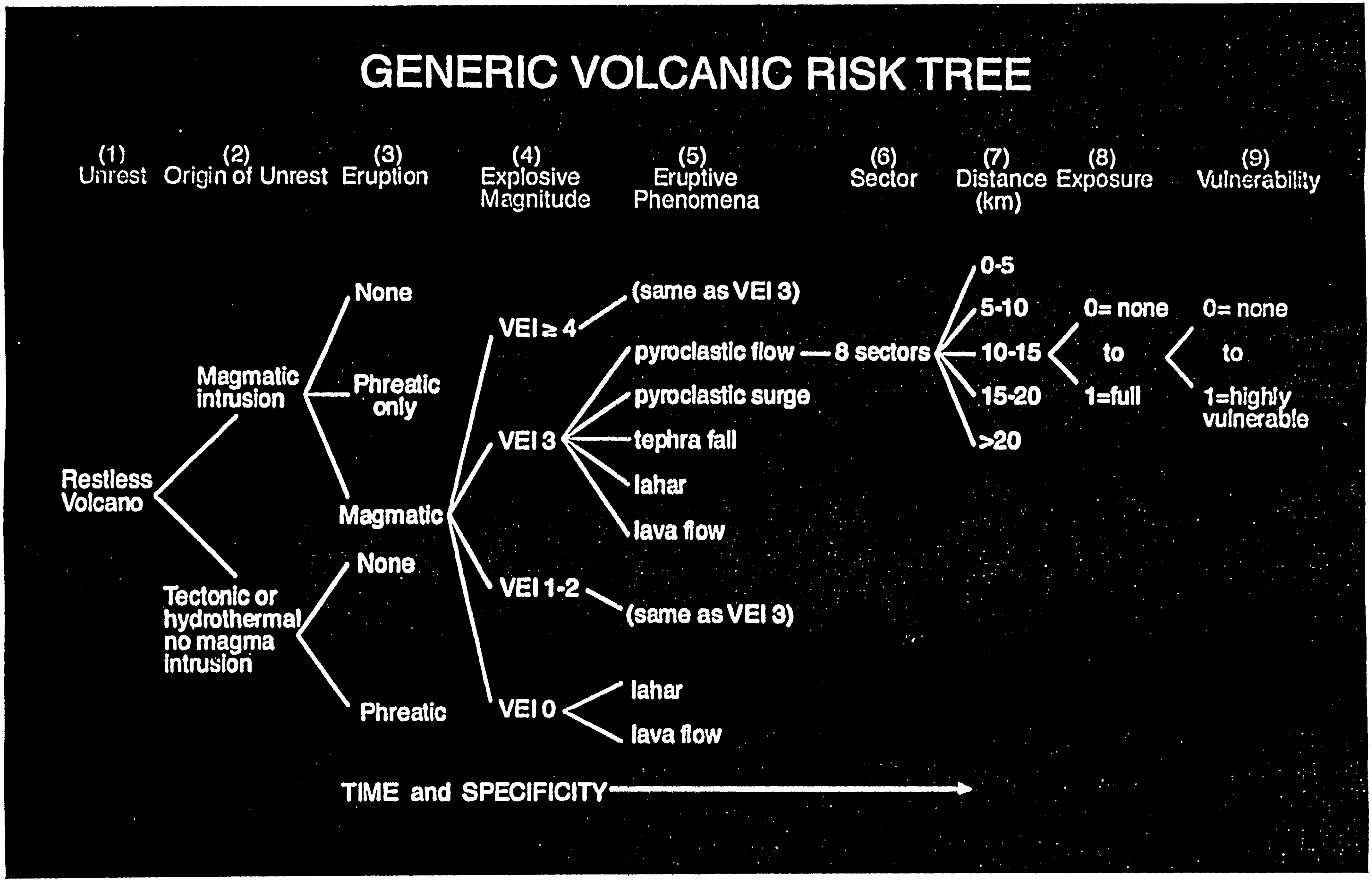

GENERIC VOLCANIC RISK TREE
(1) Unrest
(2) Origin of Unrest
(3) Eruption
(4) Explosive Magnitude
(5) Eruptive Phenomena
(6) Sector
(7) Distance (km)
(8) Exposure
(9) Vulnerability
Restless Volcano
Magmatic intrusion
Tectonic or hydrothermal no magma intrusion
None
Phreatic only
Magmatic
None
Phreatic
VEI ≥ 4
VEI 3
VEI 1-2
VEI 0
(same as VEI 3)
pyroclastic flow
pyroclastic surge
tephra fall
lahar
lava flow
(same as VEI 3)
lahar
lava flow
8 sectors
0-5
5-10
10-15
15-20
>20
0= none
to
1=full
0= none
to
1=highly vulnerable
TIME and SPECIFICITY

Figure 1

Probabilistic Volcanic Hazard Analysis for the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada

Robert Youngs: Geomatrix Consultants, 100 Pine St., 10th Floor, San Francisco, CA, 94111, e-mail: byoungs@geomatrix.com

The proposed high-level radioactive waste repository at Yucca Mountain, Nevada is located in an area of volcanic activity. From 17 to 11Ma a number of calderas were formed, producing the tuff deposits in which the repository is to be built. From 10 Ma to the present volcanic activity has consisted of a relatively infrequent small-volume basaltic eruptions. A number of volcanic centers have formed within Crater Flat, located approximately 5 km to the west. The youngest of these is located at Lathrup Wells and occurred within the past 100,000 years. Thus, volcanic hazards is an important issue in evaluating site suitability and performance.

Over a decade of research on volcanic hazard at Yucca Mountain has produced a large amount of data and a variety of interpretations of this data. These alternative interpretations have led to uncertainty about the level of hazard at the site. To address this issue, DOE commissioned a probabilistic volcanic hazard analysis designed specifically to quantify the *current* state of scientific uncertainty about the volcanic hazard at the site through the use of multiple expert judgments. The process used was based on the procedures developed by the Senior Seismic Hazard Analysis Committee[1].

A expert panel of 10 individuals was formed by selecting from the scientific community individuals that met certain criteria including: good professional reputation; understanding of the problem at this or similar sites; willingness to participate fully in the process; and providing a balance of opinions, technical expertise, and institutional/organizational backgrounds. The panel attended a series of workshop in which they were exposed to and discussed: the available data, the alternative interpretations of these data, and the various modeling tools available to quantify the hazard. Each expert then developed a volcanic hazard model for Yucca Mountain, with emphasis placed on characterizing uncertainty in the appropriate probabilistic models and model parameters for the hazard calculation. The experts presented their models to the their fellow panel members for discussion. Sensitivity tests were provided to the experts to indicate the effects of various models and model components on the computed hazard. After feedback of panel comments and model sensitivities, the experts refined their models and prepared a report documenting the basis for their assessments. The entire process was designed to make the experts equally aware of the data and interpretations necessary for hazard evaluation in order that their assessments could be given equal weight in forming an aggregate assessment.

The computational framework for the volcanic hazard calculation was the logic tree methodology (see [1]) in which discrete alternatives are defined by the experts for the various spatial and temporal probability models and model parameters. The alternatives are given relative weights by the expert expressing the expert's degree of belief in the alternatives. The result is a distribution for the annual frequency of intersection of the repository by a volcanic event that expresses the expert's scientific uncertainty in the process. The 10 individual expert distributions were then combined with equal weights to produce an aggregate distribution for the annual probability of disruption of the repository by a volcanic event. This distribution has a mean value of 1.5×10^{-8} with an uncertainty expressed by a 90-percent confidence interval of 5.4×10^{-10} to 4.9×10^{-8}, or two orders of magnitude uncertainty. Most of this uncertainty is due to an individual expert's uncertainty in assessing the hazard, resulting primarily from uncertainty in estimating the frequency of volcanic events from a limited number of past events. As part of the project, a procedure was also developed and demonstrated for addressing the impact of new information on the assessment.

[1] SSHAC, 1996, Probabilistic seismic hazard analysis: a consensus methodology: Senior Seismic Hazard Analysis Committee, U.S. Department of Energy, U.S. Nuclear Regulatory Commission, Electric Power Research Institute.

A PVHA for Yucca Mountain, Nevada

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The proposed high-level radioactive waste repository at Yucca Mountain, Nevada, is located within a geologically active volcanic field. The main volcanic hazard to the proposed reposiotry is the potential for small volume basaltic eruptions within the repository that can transport radioactive material into the accessible environment. Probabilistic volcanic hazard models for future eruptions through the proposed repository depend heavily on our understanding of the spatial controls on volcano distribution at a variety of scales. On regional scales, Plio-Quaternary volcano clusters are all located east of the Bare Mountain fault. Extension has resulted in large-scale crustal density contrast (> 200 kg m^{-3}) across the fault. Vents are restricted to low-density areas and are especially abundant in the hangingwall of the Bare Mountain fault near the fault trace. Finite element modeling indicates that this crustal density contrast can result in transient pressure changes of up to 10 MPa at 40 km depth, sufficient to generate partial melts in areas where mantle rocks are already close to their solidus. On subregional scales, vent alignments, including one alignment newly recognized by ground magnetic mapping, parallel the trends of high-dilation tendency faults in the YMR. Forty percent of vents in the YMR are part of vent alignments that vary in length from 2-16 km. Locally, new geological and geophysical data show that individual vents and short vent alignments occur along and adjacent to faults, particularly at fault intersections, and left stepping en echelon fault segments adjacent to Yucca Mountain. Conditions which formed these structures persist in the YMR today, indicating that volcanism will likely continue in the region and that the proposed repository site is within an area where future volcanism may occur. Consequently, volcanic hazard models need to account for these structural features.

The probability of volcanic eruptions through the proposed repository is estimated to be 10^{-8}-10^{-7}/yr, approximately one order of magnitude greater than average rates of volcanic activity in the western Great Basin. These results are based on application of Gaussian and Epanechnikov kernel functions to the probability analysis, parameter estimation based on distribution of existing vents, vent alignment development in the YMR, and structural controls on patterns in basaltic volcanism. Integration of these factors yields hazard estimates that are greater than previous estimates (Connor and Hill, 1995) and are at the high end of previously proposed ranges (i.e., 1×10^{-10}– 4×10^{-8}/yr; DOE, 1998), primarily because of the location of the proposed repository within a broad crustal density low produced by a half-graben. Modification of Gaussian and Epanechnikov kernel functions to include this structure, which appears to have controlled past volcanic activity, provides a mechanism to link patterns in basaltic volcanism and crustal extension in a quantitative analysis for the first time. This technique may be widely applicable to assessment of volcanic hazards resulting from small-volume basaltic volcanic fields.

Lessons learned from the Yucca Mountain PVHA include: 1) the results of the PVHA changed with time because of improved understanding of the volcanology of the YMR, 2) An accurate volcanological database needs to be available, 3) definitions (i.e., what is an event?) and approaches need to be clear, 4) non-probabilistic statements do not help a PVHA, 5) scientific involvement of volcanologists is crucial at every stage, 5) probability distributions of probability models are probably wrong and are of very limited value.

Uncertainty, Diversity and Experts

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If the data and the theories are the zeroth order material, and if probabilistic volcano hazard analysis has been the first-order focus of this meeting, then I have been asked to talk about the second- and third-order problems: uncertainty and diversity of expert opinions. This does not imply that they are unimportant either to the science or especially to the application of volcano hazard analysis. Many of the presentations here have discussed the uncertainty in the parameters and models in seismic and volcano hazard analysis, and the sensitivity of numerical conclusions to these uncertainties. To report these elements of a scientific analysis is a professional and a practical responsibility. Also we have heard that not all experts think alike. This diversity of scientists' opinions about models and their parameter values is both a driver of research and a key, visible element of practical natural hazard problems, especially those that receive public attention.

Quantification of this uncertainty requires a probability of a second kind. A common model of uncertainty tries to distinguish rather carefully between the randomness (aleatory uncertainty) of the outcome of the next flip of a thumb tack and statistical (parameter, model, epistemic) uncertainty that might well be associated with the parameter value: the likelihood of heads on the next flip. It is common to place something like a probability distribution on this parameter to describe one's current state of knowledge about this parameterís true value. (In practical problems the true value has no metaphysical significance; it is simply the value one is willing to use for pragmatic decision making purposes.) The quantitative treatment of this uncertainty about a fixed (but uncertain) parameter is the realm of statistics (as distinct from probability), and there is (only a) little disagreement among professional statistitians about how this distribution will look if it is based on a comparatively large number of observations of flips of the tack. If that number is small, however, there will likely be a large component of subjective judgement in the distribution assignment, implying the opportunity for diversity of opinion. Even among experienced experts in thumb tacks.

To deal quantitatively with such expert diversity there are few standards. One proposal that has been quite carefully thought through for scientific phenomena is the SSHAC procedure (see, e.g., the forthcoming article in the Journal of Risk Analysis by Budnitz et al.). In its full-blown version, such as that used for the recent DOE volcano hazard assessment at Yucca Mountain (as described by Dr. Youngs at this meeting), the SSHAC procedure considers the differing roles of experts (e.g., proponent versus evaluator), the careful presentation of current data and interpretations, a scientific-process-like interaction of challenge and defense of interpretations (e.g., contending models), all facilitated by a knowledgeable TFI (technical facilitator-integrator) whose responsibility it is to insure an effective process and an integrated result. This result, which might be, for example, a probability distribution on the thumb tack's likelihood of coming up heads on the next flip, is designed to represent an informed scientific community's consensus (not on the value of the number itself, but) on the epistemic uncertainty distribution representing the current uncertainty and diversity of opinion about that likelihood. Other recent applications of the process include seismic and hydrological characterization of the Yucca Mountain site.

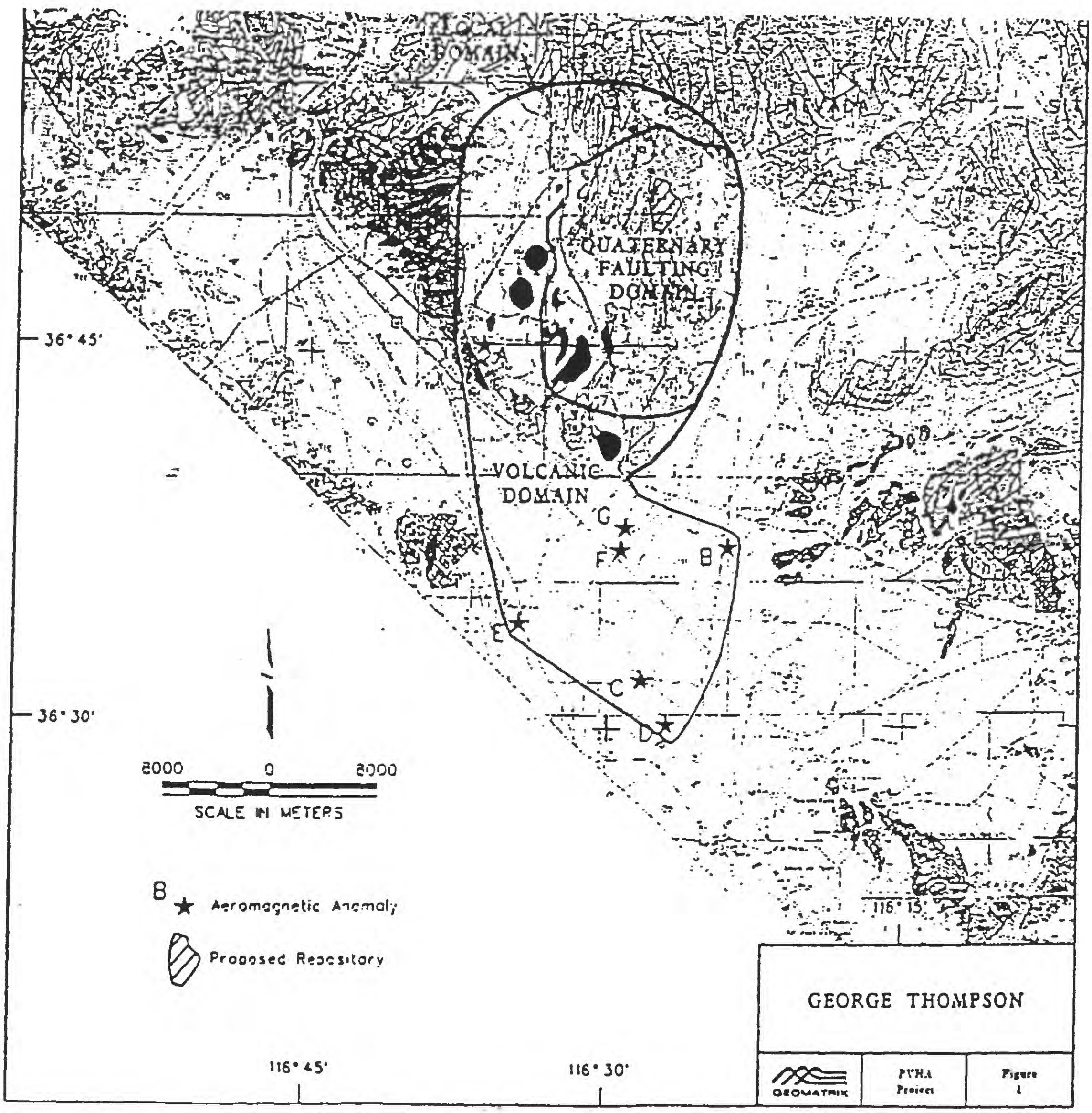
VOLCANIC HAZARDS ASSESSMENT

Workshop, September 23-24, 1998, Menlo Park
George Thompson

As a participant in the Proabilistic Volcanic Hazard Assessment for Yucca Mountain (1996), I've been asked to describe the pros and cons of the "expert panel" approach. How well did it work?

First, one needs to remember that nearly all the rocks at Yucca Mountain are volcanic, and young basaltic cinder cones dot the landscape nearby. Second, assurances of safety are critically important for a nuclear repository. That background, combined with large inherent uncertainties, demanded an *exhaustive* study of the volcanic hazards, despite the cost and large effort (which constitute the cons of the process).

Given those unusual requirements, the expert panel approach worked well. Initial sharp differences of opinion decreased as we learned from each other and confronted more of the evidence in field trips, technical literature, and workshop presentations. Remaining differences were still marked, but they had less effect on the probabilistic results than might have been expected.



USGS VOLCANO-HAZARD ASSESSMENTS
As of September 1999

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