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A COMPOUND POWER-LAW MODEL FOR VOLCANIC ERUPTIONS: IMPLICATIONS FOR RISK ASSESSMENT OF VOLCANISM AT THE PROPOSED NUCLEAR WASTE REPOSITORY AT YUCCA MOUNTAIN, NEVADA

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INTRODUCTION

The final report for the research in the area of "A Compound Power-Law Model for Volcanic Eruptions: Implications for Risk Assessment of Volcanism at the Proposed Nuclear Waste Repository at Yucca Mountain, Nevada" includes the following contributions:

A. Articles

(1) Ho, C.-H., 1995. Sensitivity in Volcanic Hazard Assessment for the Yucca Mountain High-Level Nuclear Waste Repository Site: The Model and the Data, Mathematical Geology, v. 27 (to appear).

(2) Ho, C.-H., 1994. Volcanism at the Yucca Mountain Nuclear Waste Repository Site, U.S.A.: A Decision Analysis Perspective (submitted for publication).

(3) Ho, C.-H., 1994. Quantitative Comparison of Two Volcanic Repose Time Series (submitted for publication).

B. Papers Presented

(1) "Sensitivity in Risk Assessment for the Yucca Mountain High-Level Nuclear Waste Repository Site," presented in the meeting of the National Academy of Sciences' Committee on the Technical Bases for Yucca Mountain Standards, held on November 9-10, 1993, in Las Vegas, NV.

(2) "Sensitivity in Risk Assessment for the Yucca Mountain High-Level Nuclear Waste Repository Site," invited speaker at the Fourth International Meeting and a Decade Volcano Workshop held in Colima, Mexico, January 24-28, 1994.

(3) Alternative Geologic Models: Their Significance with Respect to Calculation of Volcanic Hazard at Yucca Mountain," presented (with E.I.: Smith) in the meeting of the United States Nuclear Waste Technical Review Boards' panel on structural geology and geoengineering, held on March 8-9, 1994 at San Francisco.

(4) "Volcanism at the Yucca Mountain Nuclear Waste Repository Site, U.S.A.: A Decision Analysis Perspective," poster presentation at the 5th Valencia International Meeting on Bayesian Statistics held in Alicante, Spain, 6/5/94 - 6/9/94.

(5) "The Role of the Bayesian Prior in Volcanic Risk Calculations at the Yucca Mountain Nuclear Waste Repository Site, U.S.A.: presented at the 2nd Annual Meeting of the International Society for Bayesian Analysis held in Alicante, Spain, 6/10/94-6/11/94.

FUTURE WORK:

Sensitivity Analysis on Smith's AMRV Model

Future work will concentrate on the following:

(1) The statistical aspects of a second sensitivity analysis which is designed to overhaul the geological and statistical techniques of Smith's AMRV model.

(2) Also, new model development for the volcanism at NTS will continue.

APPENDIX 1

Article (2): Volcanism at the Yucca Mountain Nuclear Waste Repository Site, U.S.A.: A Decision Analysis Perspective

Volcanism at the Yucca Mountain Nuclear Waste Repository Site, U.S.A.: A Decision Analysis Perspective

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ABSTRACT

Much of the ongoing debate on the use of nuclear power plants in U.S.A. centers on the safe disposal of the radioactive waste. Congress, aware of the importance of the waste issue, passed the Nuclear Waste Policy Act of 1982, requiring the federal government to develop a geologic repository for the permanent disposal of high level radioactive wastes from civilian nuclear power plants. The Department of Energy (DOE) established the Office of Civilian Radioactive Waste Management (OCRWM) in 1983 to identify potential sites. When OCRWM had selected three potential sites to study, Congress enacted the Nuclear Waste Policy Amendments Act of 1987, which directed the DOE to characterize only one of those sites, Yucca Mountain, in southern Nevada. To characterize the site, the DOE must study in detail the natural environment and various natural processes to which a proposed deep geologic repository might be subject. For a site to be acceptable, theses studies must demonstrate that the site could comply with regulations and guidelines established by the federal agencies that will be responsible for licensing, regulating, and managing the waste facility.

Advocates and critics disagree on the significance and interpretation of critical geological features which bear on the safety and suitability of Yucca Mountain as a site for the construction of a high-level radioactive waste repository. Recent volcanism in the vicinity of Yucca Mountain is readily recognized as an important factor in determining future public and environmental safety because of the possibility of direct disruption of a repository site by volcanism. In particular, basaltic volcanism is regarded as direct and unequivocal evidence of deep-seated geologic instability. In this paper, statistical analysis of volcanic hazard assessment at the Yucca Mountain site is discussed, taking into account some significant geological factors raised by experts. Three types of models are considered in the data analysis. The first model assumes that both past and future volcanic activities follow a homogeneous Poisson process (HPP). The second model uses a Weibull process (WP) to estimate the instantaneous recurrence rate based on the historical data near the Yucca Mountain site. The model then uses an HPP to predict future events. The third model assumes that the prior historical trend based on a WP will continue for future activities. Volcanic hazards (at least one disruptive event over the next 10,000 years) using both classical and Bayesian approaches are evaluated from data for the following two observation periods: Pliocene and younger, and Quaternary. Combinations of various counts of events at volcanic centers of controversy and inclusion (or exclusion) of the youngest date at Lathrop Wells Center (= 0.01 Ma) generate 90 different data sets. Hazard analysis is performed for each data set and the minimum and the maximum risks for each model are summarized. Finally, the Bayes action and the minimax nonrandomized action based on a decision-theoretic paradigm are considered and compared.

INTRODUCTION

In the United States today, commercial nuclear power facilities produce almost 21 percent of the nation's electric power. One by-product of nuclear energy production, radioactive spent nuclear fuel, is accumulating at the nation's nuclear power plants. Because of its radioactivity, it will require isolation from the public and the accessible environment for thousands of years. In 1982, Congress assigned the U.S. Department of Energy (DOE) the responsibility of designing and implementing a system to manage the disposal of this spent fuel. Current plans call for the construction of a underground geologic repository that will isolate the waste for at least 10,000 years. In 1987, Congress chose a site at Yucca Mountain, Nevada, to be evaluated for its suitability as a possible location for a repository.

Yucca Mountain, the proposed site for disposal of the nation's spent fuel and high-level radioactive waste, is located in an arid area of the western United States. The present mean annual precipitation at the site is approximately 150 mm per year. If the site is found suitable, plans call for the repository to be located in welded tuff (a formation of hardened and compacted volcanic ash) approximately 300 meters below the earth's surface and some 200 meters above the regional water table. This places the proposed repository in the unsaturated or vadose zone. The United States is unique in the world in its active investigation of a deep unsaturated zone for a geologic repository. Most other countries concerned about the disposal of high-level radioactive waste lack that option and are concentrating their efforts on rocks such as granite, clay, and salt in saturated zones well below the water table.

The advantages of siting a geologic repository in the unsaturated zone in an arid climate are fairly obvious. The unsaturated zone in Yucca Mountain, however, is not problem free and does present the DOE with some difficult challenges. An important element in assessing the suitability (or lack of suitability) of the Yucca Mountain site is an assessment of the potential for future volcanic activity. A potentially adverse condition with respect to volcanism is judged to be of concern at the Yucca Mountain site (DOE, 1986) because the late Tertiary geologic history of southwestern Nevada has been dominated by volcanism and the consequent deposition of volcanic flows and tuffaceous rocks. Yucca Mountain, like most surrounding ranges, is composed dominantly of a series of Miocene ashflow tuff units and silicic volcanic rocks.

STRUCTURAL CONTROLS OF BASALTIC VOLCANIC ACTIVITY

Yucca Mountain is located in the southcentral part of the Southwestern Nevada Volcanic Field (SNVF), a major volcanic province of the southern Great Basin first defined by Christiansen et al. (1977) and extended by Byers et al. (1989). Interested readers are referred to the papers of Byers et al. (1989) for the location of geographic features of the SNVF, and Crowe (1990) for the basaltic volcanic episodes of the Yucca Mountain region. Crowe and Perry (1989) describe the distribution of volcanic centers, emphasizing a southwest stepping of volcanism between 6.5 and 3.7 Ma. They describe a recurrence pattern of basaltic events where new eruptive sites are marked by probable coeval clusters of centers. These clusters appear to be of similar age within the limits of K-Ar age determinations. They note that all basalt centers of the youngest episode of volcanism, except the basalt of Buckboard Mesa, occur in a narrow northwest trending zone. They named this zone the Crater Flat volcanic zone (CFVZ, see Fig. 1). Crowe and Perry (1989), and Crowe (1990) suggest a southwest migration of basaltic volcanism in the Yucca Mountain area based on this structural parallelism, a pattern that may reflect an earlier southwest migration of silicic volcanism in the Great Basin. Smith et al. (1990) examine the spatial and temporal patterns of post-6 Ma volcanism in the southern Great Basin. They describe the area of most recent volcanism (AMRV, see Fig. 1) near Yucca Mountain as an area enclosing all known post-6 Ma volcanic centers in the region and examine the implications of the information for an assessment of volcanic risk. Smith et al. (1990, 1993) provide a different point of view of the migration trends of volcanism in the Yucca Mountain region. They suggest that the structural control of basaltic volcanism should be considered at two scales. The control of large-scale regional structures (strike-slip faults, detachments) and volcano alignments related to these structures should be evaluated. Independently, control of structures on and adjacent to Yucca Mountain and volcano alignments related to these structures should also be evaluated. Models for structural control because of the different scales of geologic structures may be different. For example, northwest striking structures may result in a regional alignment of Pliocene and Quaternary cones in a northwest direction. But, at the scale of Yucca Mountain, northeast striking structures control the alignment of volcanoes (Smith et al., 1990). Although both models may be supported by the data, a judgment must be made as to which model is most appropriate for volcanic hazard studies at Yucca Mountain.

The following is a summary of field and chronology data using the most current information from site characterization studies (Crowe et al. 1993).

Pliocene volcanic events in the Yucca Mountain region include:

1. 4.6 Ma Centers: **Basalt of the Thirsty Mesa**. This is a lava mesa formed from three coalesced vents. It is treated as one or three events with an age of 4.6 Ma.

2. 4.4 Ma Center: **Basalt of the Amargosa Valley**. This volcanic event is represented by the aeromagnetic anomaly located a few kilometers south of the town of Amargosa Valley.

3. 3.7 Ma Centers: **Basalt of southeast Crater Flat.** This Pliocene unit consists of five centers representing one to five events. The age of the centers is assumed to be well dated at 3.7 Ma.

4. 2.9 Ma Centers: **Basalt of Buckboard Mesa**. This consists of one center or event forming a lava mesa and small cone in the moat zone of the Timber Mountain caldera.

Quaternary events in the Yucca Mountain region include:

1. 1.1 Ma Centers: **Quaternary basalt of Crater Flat**. These are treated by Crowe et al. (1993) as four individual centers. Smith et al. (1993) suggest that at least six centers must now be considered in the calculation from the Quaternary basalt of Crater Flat: NE Little Cone, SW Little Cone, Black Cone, Northern Cone, Red Cone 1, Red Cone 2.

2. 0.38 Ma Centers: **Basalt of Sleeping Butte**. These are treated as two individual centers clustered on a northeast-trend 45 km northwest of the Yucca Mountain site.

3. 0.1 Ma Centers: **Lathrop Wells Center**. This is treated as a single event center formed in two pulses of activity, one at about 100 to 140 ka, the other at > 40 ka. The existence of a potential young volcanic event (10 ka) at the center remains controversial (Crowe et al. 1993).

MODELING OF VOLCANIC ACTIVITY

For volcanism, Ho (1991a,b) considers a nonhomogeneous Poisson process (NHPP) with intensity function $\lambda(t) = (\beta/\theta)(t/\theta)^{\beta-1}$ for $\beta, \theta > 0$. The parameters β and θ are sometimes referred to as shape and scale parameters, respectively. Because $\lambda(t)$ is the failure rate for the Weibull distribution, the corresponding process has been called the Weibull process (WP). Goodness-of-fit, maximum likelihood (ML) estimates of β and θ, confidence intervals, and inference procedures for this process are presented in Bain and Engelhardt (1980), Bassin (1969), Crow (1974, 1982), Finkelstein (1976), and Lee and Lee (1978). In a simulation study, Bain et al. (1985) conclude that the test which is derived as an optimal test for the WP also is rather powerful as a test of trend for general NHPP's. In other words, the test is "robust" against other model assumptions. This is the rationale of our choice of a WP to amend a simple Poisson model which neglects the time trend of the volcanic activities. Suppose we assume that the successive volcanic eruptions at the Yucca Mountain region follow a WP. For a time-truncated WP, let t be predetermined and suppose $n > 1$ eruptions are observed during $[0, t]$ at time $0 < t_1 < t_2 < \cdots < t_n$. Some useful theoretical results to be used later are summarized as follows:

1. The maximum likelihood estimates (MLE) of β and θ are given (Crow, 1974) by:

$$\hat{\beta} = n / \sum_{i=1}^{n} \ln (t/t_i)$$
$$\hat{\theta} = t/n^{1/\hat{\beta}}$$

2. If a WP is assumed during the observation time period $[0, t]$, the intensity (instantaneous recurrence rate) is $\lambda(t) = (\beta/\theta)(t/\theta)^{\beta-1}$ at time t. In the application of the WP to volcanic eruptive forecasting, the estimate of $\lambda(t)$ is of considerable practical interest since $\lambda(t)$ represents the instantaneous eruptive status of the volcanism at the end of the observation time t. Crow (1982) derives the MLE for $\lambda(t)$ as

$$\hat{\lambda}(t) = (\hat{\beta}/\hat{\theta})(t/\hat{\theta})^{\hat{\beta}-1} = n\hat{\beta}/t.$$

3. Using the same WP, the number of occurrences, N, in time $[t, t+t_0]$, is a Poisson random variable,

$$P(N = k) = \exp[-m(t_0)][m(t_0)]^k/k!; \quad k = 0, 1, \cdots$$

where

$$\begin{aligned} m(t_0) &= \int_t^{t+t_0} \lambda(s)ds \\ &= \left[(t+t_0)^\beta - t^\beta\right] \Big/ \theta^\beta \end{aligned}$$

(m obviously depends on t but our notation suppresses t because t is the known observation period.)

MODELING OF VOLCANIC DISRUPTION

Classical Approach

If we consider the fact that not every eruption would result in disruption of the repository, and let **p** be the probability that any single eruption is disruptive, then the number of occurrences of such a disruptive event $X(t_0)$ in $[0, t_0]$ also follows a homogeneous Poisson random variable with constant rate (Meyer, 1965, p. 156). Notice that this fact applies to the WP as well (see result 3 of the previous section). An important element in assessing the suitability of the site is an assessment of the potential for future volcanic disruption of the repository. Therefore, the probability of at least one disruptive event during the next t_0 years is of considerable practical interest and is quoted as "hazard." In a classical statistical analysis, we would use the Poisson probability distribution formula,

$$\begin{aligned} \text{hazard} &= \Pr(\text{at least one disruptive event before time } t_0) \\ &= 1 - \exp\{-\lambda \mathbf{p} t_0\} \end{aligned}$$

for an HPP. And,

$$\text{hazard} = 1 - \exp\{-m(t_0)\,\mathbf{p}\}$$

for a WP. Point or interval estimates for the hazard can be obtained based on those of $\mathbf{p}$, λ, and $m(t_0)$.

Bayesian Approach

For the Bayesian approach, we consider λ and $m(t_0)$ to be fixed for both the HPP and the WP, and we permit prior distribution for $\mathbf{p}$. The prior distribution, $\pi(p)$, of $\mathbf{p}$ expresses our beliefs regarding the numerical values of $\mathbf{p}$. This would incorporate uncertainty about the probability of repository disruption $\mathbf{p}$ that are eventually averaged out as shown in the following equations. In this case, using the model of constant λ

$$\text{hazard} = 1 - \int_p \exp\{-\lambda p t_0\}\pi(p)dp$$

for the HPP. And,

$$\text{hazard} = 1 - \int_p \exp\{-m(t_0)p\}\pi(p)dp$$

for the WP. The technical machinery (Bayesian approach) involved in the above equations would support much more informative answers if the prior distribution $\pi(p)$ is adequately chosen.

Point estimation and prior determination of p

Crowe et al. (1982) assume that every eruption has the same probability of repository disruption $\mathbf{p}$, and provide a point estimate for $\mathbf{p}(= a/A)$. The calculations are based on a fixed value of a (= area of the repository estimated at 6-8 km^2), and several choices of A. (An area, range from 1,953 km^2 to 69,466 km^2, corresponds closely to a defined volcanic province and satisfies the requirement of a uniform value of λ.) Additional results of point estimates of $\mathbf{p}$ proposed by several experts are listed in Table 7.1 of Crowe et al. (1993). The values range from 1.1×10^{-3} to 8×10^{-2}. We shall use these two bounds of $\mathbf{p}$ for the classical approach in the sensitivity data analysis.

We now turn to the description of the prior density for the Bayesian approach (Ho, 1992, 1995). Since the permissible range of $\mathbf{p}$ is $0 \leq p \leq 1$, without use of expert opinions regarding the geological factors at NTS, a natural choice for $\pi(p)$ is a noninformative prior. For instance, $U(0,1)$ (uniform 0, 1) assumes an average of 50% "direct hit," which is unrealistically conservative (overestimation). Ho (1992, 1995) settles on one particular prior based on the geological structure of the volcanic centers at NTS.

According to Smith et al. (1990), the area of most recent volcanism (AMRV) includes all known post-6-Ma volcanic complexes in the Yucca Mountain area and encompasses the four volcanic centers in Crater Flat, the Lathrop Wells cone, several centers in southeast Crater Flat, two centers at Sleeping Butte, and a center at Buckboard Mesa within the moat of the Timber Mountain Caldera. They conclude that future volcanic events in the Yucca Mountain area will be associated with Quaternary centers in Crater Flat, at Sleeping Butte, or at the Lathrop Wells cone (see Fig. 2). Based on their assumption, a future eruption may occur either to the north-northeast or south-southwest of an existing cone or group of cones. They show high risk zones within the AMRV in Fig. 3 by placing two rectangles on each group of Quaternary cones. The proposed high-level nuclear waste repository at Yucca Mountain falls within the larger high-risk Lathrop Wells rectangle and just to the east of the high-risk zones constructed for the Crater Flat chain as described in Fig. 3. The dimensions of the larger Lathrop Wells rectangle are 50 km long and 3 km wide as determined by analog studies of Pliocene volcanic centers in the Fortification Hill field (Lake Mead area, Arizona and Nevada) and the Reveille Range (south-central Nevada). The lower half of this rectangle is outside the AMRV.

Now, using the idea of Crowe et al. (1982), assume there is no heterogeneity with respect to disruptiveness in the upper-half of the rectangle that encloses the repository (the eruptions to the south-southwest of the Lathrop Wells cone are outside the AMRV, and have near zero probability of disrupting the site). So, given $A = 75$ km^2 (=half of the area of the rectangle), $a = 8$ km^2 (area of the repository), we obtain $p = a/A = 8/75$. Therefore, a more informative prior, $U(0, 8/75)$, which assumes $8/75$ as the upper limit for $\mathbf{p}$ seems to be more suitable. We shall conduct all Bayesian analysis based on this prior which is developed from the geological structure of the volcanic centers at NTS.

SENSITIVITY ANALYSIS AND RESULTS

One issue in the sensitivity analysis is to specify the observation period, $[0, t]$, in modeling the volcanic history at NTS. Most of the volcanic hazard assessment studies in the Yucca Mountain area are centered around the post-6-Ma (Pliocene and younger) and Quaternary (< 1.6 Ma) volcanism (Crowe et al., 1988, 1989, Smith et al., 1990; Wells et al., 1990). We shall use the above dates to estimate the recurrence rate of volcanism during the following two observation periods: Pliocene and younger (< 6.0 Ma), and Quaternary (< 1.6 Ma). Therefore, let the beginning of the Pliocene period ($\doteq$ 6.0 Ma) be time zero, so $t = 6.0$ Ma. For the study on Quaternary volcanism, $t = 1.6$ Ma. Prediction of future volcanic activities (volcanic eruption and site disruption) will focus on the entire life of the repository (10^4 years is recommended as the required isolation period during which radioactive waste may decay to an acceptable level). Thus, we shall evaluate the hazard with $t_0 = 10,000$.

Three types of models (Ho, 1995) are considered in the following sensitivity analysis. The first model (HPP) assumes that both past and future volcanic activities follow an HPP. The second model (WP-HPP) uses a WP to estimate the instantaneous recurrence rate based on the historical data at NTS. The model then switches from a WP of past events to a predictive HPP (a constant rate for future events). The third model (WP) assumes that the prior historical trend based on a WP would continue for future activities. Hazards (at least one disruptive event before time t_0) using both classical and Bayesian approaches are evaluated based on the data for the following two observation periods: Pliocene and younger, and Quaternary.

Another key issue in the site characterization studies is the disagreement over age-dating of the rocks and counts of volcanic events (Ho, 1995). The following treatment of the data is to account for some significant differences raised by experts. The dates (in Ma) summarized from the previous section are: 4.6 (1 to 3 events), 4.4, 3.7 (1 to 5 events), 2.9, 1.1 (4 to 6 events), 0.38 (2 events), 0.1, 0.01 (this remains controversial but possible). Combinations of various counts at volcanic centers of controversy and inclusion (or exclusion) of the youngest date (= 0.01) generate 90 (= 3 × 5 × 3 × 2) different data sets (Pliocene and younger volcanism). Hazard analysis is performed for each data set and only the minimum and the maximum risks for each model are summarized in Table 1 (Quaternary volcanism) and Table 2 (Pliocene volcanism). In summary, sensitivity analysis based on the data of Quaternary volcanism predicts that the hazard is between 4.81×10^{-5} and 6.57×10^{-3}, while the corresponding hazard based on the data of Pliocene and younger is between 2.02×10^{-5} and 4.53×10^{-3}. Therefore, the estimated overall probability of at least one disruption of a repository at the Yucca Mountain site by basaltic volcanism over the next 10,000 years should be bounded between 2.02×10^{-5} and 6.57×10^{-3}.

TO CONSTRUCT OR NOT TO CONSTRUCT THE REPOSITORY: A DECISION-THEORETIC PARADIGM

In this section, we illustrate a structured approach called decision analysis to weigh the benefits against the volcanic hazards of a possible future repository. We shall need some terminology from decision theory. We define $L(\theta, a)$ as the loss incurred by choosing action a when the state of nature is θ. In this case, there are two relevant states of nature and two possible actions given time t_0:

$$\Theta = \begin{cases} \theta_1 : & \text{no disruption of repository in next } t_0 \text{ years} \\ \theta_2 : & \text{disruption of repository in next } t_0 \text{ years} \end{cases}$$

$$\mathcal{A} = \begin{cases} a_1 : & \text{build the repository at Yucca Mountain} \\ a_2 : & \text{do not build the repository at Yucca Mountain} \end{cases}$$

We shall consider our losses relative to the situation: the repository is built and there is no disruption. Our set of possible consequences (or rewards of interest) is as follows:

$$\mathcal{R} = \begin{cases} r_1: & \text{build the repository, and it is disrupted;} \\ r_2: & \text{do not build the repository, and there is no site disruption;} \\ r_3: & \text{do not build the repository, and there is a site disruption;} \\ r_4: & \text{build the repository, and it is not disrupted.} \end{cases}$$

(Here $r_k = (a_i, \theta_j)$ denotes action a_i being taken and θ_j being the state of nature that occurs.) High-quality expert judgment is necessary for the preference ordering of the rewards. For illustration purposes, using an example produced independently by a group of students who studied statistical decision theory under me, we use the following order of preference:

$$r_1 < r_2 < r_3 < r_4.$$

The rationale to the above preference ordering is:

> Clearly r_1 is worst. In cases r_2 and r_3, either another site had to be chosen that was more costly and/or less safe, or no site was built, prolonging the problem of waste disposal. r_3 is considered preferable to r_2 in this example, because in r_2, the loss of project money to Nevada and/or greater construction costs elsewhere were unnecessary. r_3 has the advantage over r_2 since r_3 shows that the short term monetary loss was more than offset by the avoidance of catastrophe. r_4 is preferable to r_3 because, while a possible calamity will have been averted in case r_3, it is still true that there will have been a severe volcanic eruption in this area, as well as the problems mentioned in r_2, so r_3 can hardly be considered ideal. Thus, r_4 is best.

If we let $0 < K_1 < K_2 < K_3$, we obtain the following loss matrix:

		Action Taken	
		a_1	a_2
State of	θ_1	0	K_2
Nature	θ_2	K_3	K_1

Using this matrix, we can calculate the Bayes action and the minimax nonrandomized action (Berger, 1988).

Bayes Action

Suppose $\pi(\theta)$ is the believed probability distribution of θ at the time of decision making. The Bayesian expected loss of an action a is

$$\rho\left(\pi, a\right) = E^{\pi} L\left(\theta, a\right) = \int_{\Theta} L\left(\theta, a\right) dF^{\pi}\left(\theta\right).$$

It is typically very easy to choose an optimal action when one can determine $\rho(\pi, a)$ for each a. An action $a \in \mathcal{A}$ which minimizes $\rho(\pi, a)$ is called a Bayes action. In order to demonstrate the calculation of $\rho(\pi, a_i)$, we use the middle value of the estimated overall site disruption probability bounds as a preliminary representative of $\pi(\theta_1)$. Thus

$$\pi\left(\theta_1\right) = \left(2.02 \times 10^{-5} + 6.57 \times 10^{-3}\right) / 2 = 3.3 \times 10^{-3} ,$$

and

$$\pi\left(\theta_2\right) = 1 - 3.3 \times 10^{-3}.$$

The Bayesian expected loss for a_i is:

$$\rho\left(\pi, a_1\right) = 3.3 \times 10^{-3} K_3,$$

and

$$\rho(\pi, a_2) = \left(1 - 3.3 \times 10^{-3}\right) K_2 + 3.3 \times 10^{-3} K_1.$$

The Bayes action would depend on the numerical values of K_1, K_2, and K_3. It is beyond the scope of this paper to assign values to these constants, but this is an important consideration for further study.

Minimax Nonrandomized Action

This section is devoted to the implementation and evaluation of decision-theoretic analysis based on the minimax principle. The essence of the minimax principle is to try and protect against the worst possible state of nature. The one situation in which this is clearly appropriate is when the state of nature is determined by an intelligent opponent who desires to maximize your loss. You can then expect the worst possible state of nature to occur, and should plan accordingly. Statistical problems, on the other hand, involve a "neutral" nature, and it is not clear why the minimax principle is useful. The most frequently given justification for minimax analysis in such a problem is a possible desire for conservative behavior.

The minimax nonrandomized action minimizes $\sup_\theta L(\theta, a)$. In this case,

$$\begin{aligned}
\sup_\theta L(\theta, a_1) &= \max\{0, K_3\} = K_3 \\
\sup_\theta L(\theta, a_2) &= \max\{K_1, K_2\} = K_2 \\
\inf_a \sup_\theta L(\theta, a) &= \min\{K_2, K_3\} = K_2
\end{aligned}$$

Thus, the minimax nonrandomized action is a_2: do not build the repository. Note that this decision is based only on the order of K_1, K_2, and K_3 and not on their magnitudes. Perhaps the greatest use of the minimax principle is in situations for which no prior information (i.e., the probability of site disruption) is available. There is then no natural decision principle by which to proceed, and the minimax principle is often suggested as a good choice.

CONCLUSION

In assessing the suitability of any nuclear-waste-disposal site, the risk associated with the disposal system must be evaluated. This is commonly done by means of a performance assessment. A performance assessment is a complex analysis that requires the expertise and input of many different scientists. Many critical issues associated with the assessment of Yucca Mountain can not be resolved by data collection alone. Inherent uncertainties associated with the geologic system and with predicting performance for thousands of years require substantial input of expert judgment. Such input, for example, could be that of a hydrologist determining the applicability of a given theoretical ground-water flow model to the unsaturated zone around Yucca Mountain, that of a metallurgist in extrapolating short-term corrosion data to probable waste package behavior over 10,000 years, or that of a manager weighing the effects of unresolved uncertainties upon repository licensing. This type of judgment is used extensively by scientists, engineers, and managers in their day-to-day activities. The volcanic modeling aspect of the performance-assessment methodology is only a small part of the effort. The calculation of the loss matrix required for the decision analysis needs knowledge from a variety of disciplines. The purpose of this article is to introduce methodologies widely used in volcanic modeling and decision science in the hopes that more scientists will become interested in addressing such issues and in formulating appropriate statistical techniques that can be used to solve problems such as the one addressed in this manuscript.

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Table 1. Results of the sensitivity analysis for the proposed Yucca Mountain Repository site based on the data of Quaternary volcanism

Model	Recurrence rate (min, max)	Hazard		
		Classical $p = 1.1 \times 10^{-3}$	Classical $p = 8 \times 10^{-2}$	Bayesian
HPP	$(4.38 \times 10^{-6}, 6.25 \times 10^{-6})$	$(4.81 \times 10^{-5}, 6.87 \times 10^{-5})$	$(3.49 \times 10^{-3}, 4.99 \times 10^{-3})$	$(2.33 \times 10^{-3}, 3.33 \times 10^{-3})$
WP-HPP	$(5.83 \times 10^{-6}, 8.23 \times 10^{-6})$	$(6.40 \times 10^{-5}, 9.06 \times 10^{-5})$	$(4.65 \times 10^{-3}, 6.56 \times 10^{-3})$	$(3.10 \times 10^{-3}, 4.38 \times 10^{-3})$
WP	$(5.83 \times 10^{-6}, 8.23 \times 10^{-6})$	$(6.41 \times 10^{-5}, 9.06 \times 10^{-5})$	$(4.65 \times 10^{-3}, 6.57 \times 10^{-3})$	$(3.10 \times 10^{-3}, 4.38 \times 10^{-3})$

Table 2. Results of the sensitivity analysis for the proposed Yucca Mountain Repository site based on the data of Pliocene and younger volcanism

Model	Recurrence rate (min, max)	Hazard		
		Classical $p = 1.1 \times 10^{-3}$	Classical $p = 8 \times 10^{-2}$	Bayesian
HPP	$(1.83 \times 10^{-6}, 3.33 \times 10^{-6})$	$(2.02 \times 10^{-5}, 3.67 \times 10^{-5})$	$(1.47 \times 10^{-3}, 2.66 \times 10^{-3})$	$(9.77 \times 10^{-4}, 1.78 \times 10^{-3})$
WP-HPP	$(3.41 \times 10^{-6}, 5.67 \times 10^{-6})$	$(3.75 \times 10^{-5}, 6.24 \times 10^{-5})$	$(2.72 \times 10^{-3}, 4.53 \times 10^{-3})$	$(1.82 \times 10^{-3}, 3.02 \times 10^{-3})$
WP	$(3.41 \times 10^{-6}, 5.67 \times 10^{-6})$	$(3.75 \times 10^{-5}, 6.24 \times 10^{-5})$	$(2.72 \times 10^{-3}, 4.53 \times 10^{-3})$	$(1.82 \times 10^{-3}, 3.02 \times 10^{-3})$

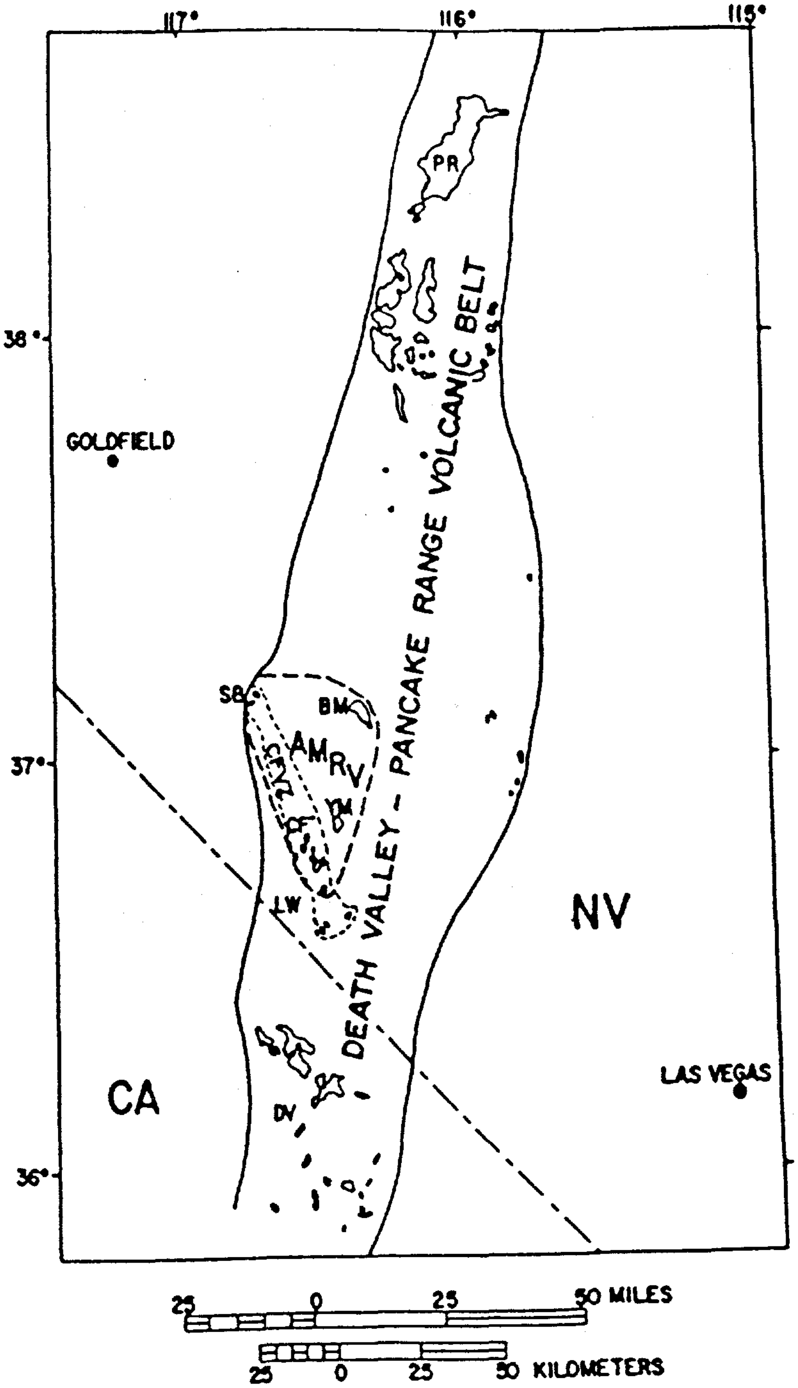

Fig. 1. The proposed area of most recent volcanism (AMRV) is outlined by a heavy dashed line and includes the Lathrop Wells cone (LW), Sleeping Butte cones (SB), Buckboard Mesa center (BM) and volcanic centers within Crater Flat (CF). For comparison the Crater Flat Volcanic Zone (dashed line) and the Death Valley-Pancake Range Volcanic Belt (solid line) are shown. PR = Pancake Range. YM = proposed drift perimeter at Yucca Mountain. DV = Death Valley. (Source: Smith et al. 1990, figure 2)

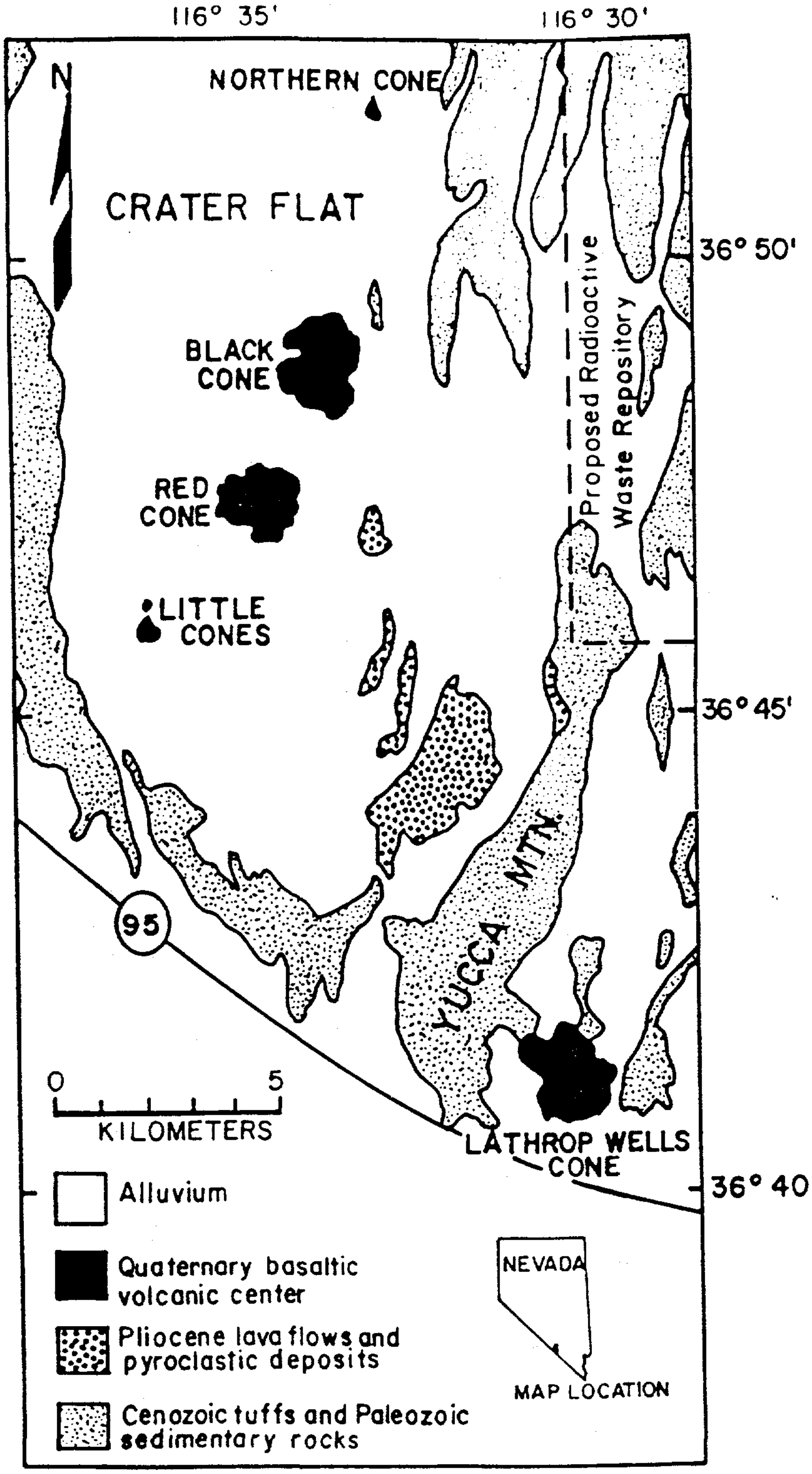

Fig. 2. Generalized geologic map of Crater Flat volcanic field area and boundary of proposed radioactive waste repository; inset map shows location of the Crater Flat volcanic field. (Source: Wells et al. 1990, figure 1)

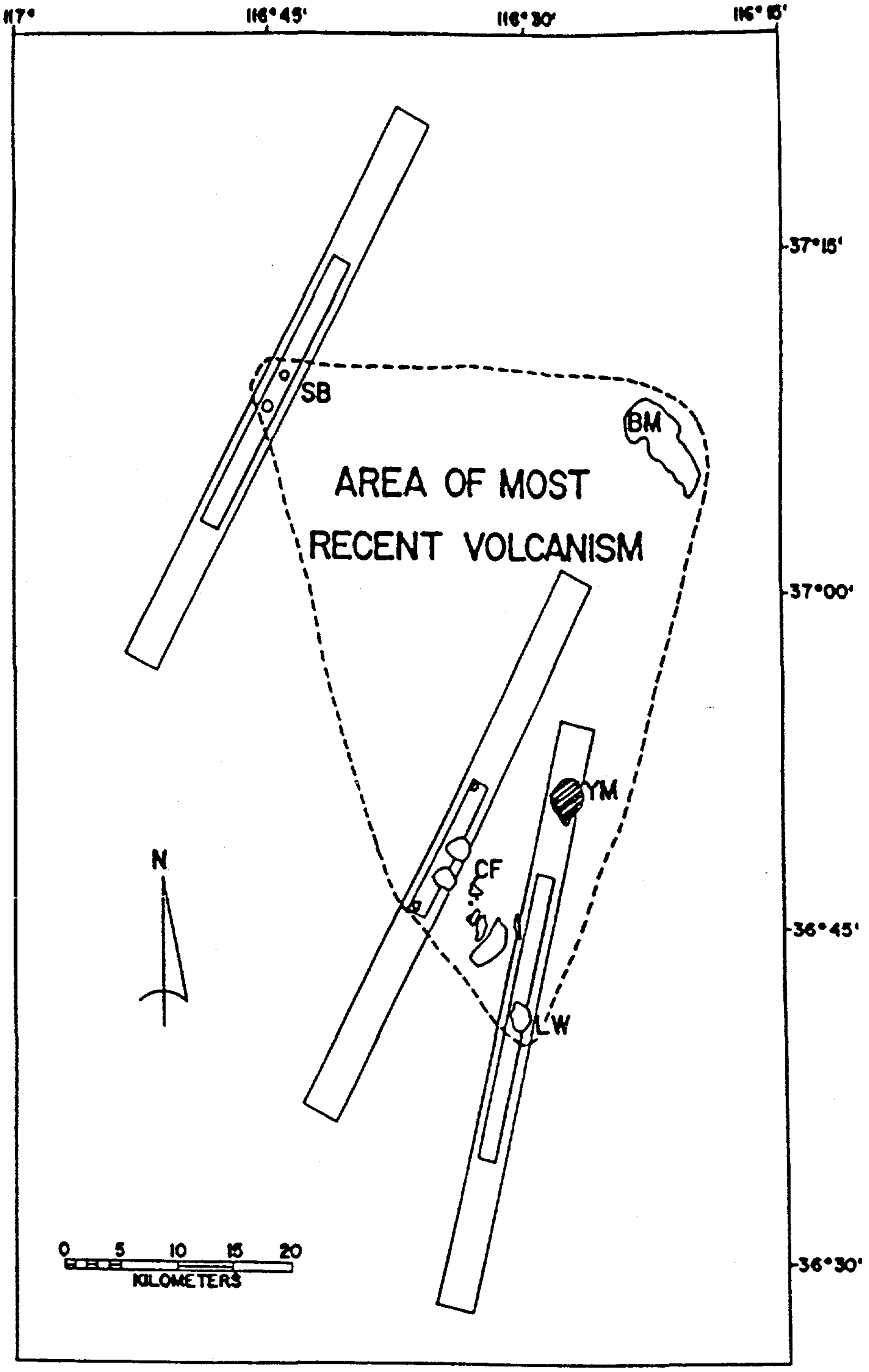

Fig. 3. Map outlining the AMRV (dashed line) and high-risk zones (rectangles) in the Yucca Mountain (YM) area that include Lathrop Wells (LW), Sleeping Butte cones (SB), Buckboard Mesa center (BM), volcanic centers within Crater Flat (CF). (Source: Smith et al. 1990, figure 7)

APPENDIX 2

Article (3): Quantitative Comparison of Two Volcanic Repose Time Series

Quantitative Comparison of Two Volcanic Repose Time Series

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ABSTRACT

Volcanism, because it recurs, must represent a hierarchy of simultaneously unique-nonunique patterns. Even though no two growth histories, nor even any two eruptive events, are identical, there are strong resemblances between various volcanic styles that can be classified. Numerical and graphical attractor patterns add insight to such classifications. In this paper, we propose a test to quantatively compare two volcanic repose times series. Two examples are provided to show the applications.

STATISTICAL METHOD

Let $t_1, \cdots, t_n$ be the first n successive times of eruptions of a volcano. These times are measured from the beginning of the observation period (cumulative length of time over which the eruptions occur), so $t_1 < t_2 < \cdots < t_n$. Ho (1991) considers a nonhomogeneous Poisson process (NHPP) with intensity function $\lambda(t) = (\beta/\theta)\,(t/\theta)^{\beta-1}$ for $\beta, \theta > 0$. The parameters β and θ are sometimes referred to as shape and scale parameters, respectively. Because $\lambda(t)$ is the failure rate for the Weibull distribution, the corresponding process has been called the Weibull process (WP). This model is also known in the literature as a Power Law process. A WP is appropriate for three types of volcanoes: increasing-recurrence-rate ($\beta > 1$), decreasing-recurrence-rate ($\beta < 1$), and constant-recurrence rate ($\beta = 1$). This generalized model can be considered a goodness-of-fit test for an exponential model ($\beta = 1$)of the volcanic inter-event times, which is equivalent to a homogeneous Poisson model of the events. In a simulation study, Bain et al. (1985) conclude that the test which is derived as an optimal test for the WP also is rather powerful as a test of trend of general NHPP's. In other words, the test is "robust" against other model assumptions. This is the rationale of our choice of a WP to amend a simple Poisson model which neglects the time trend of the volcanic activities. The following theoretical results (for proof see Bain and Engelhardt, 1991, Chap 9) are useful for this study:

1. Let $S = \sum_{i=1}^{n-1} \ln(t_n/t_i)$, then the maximum likelihood estimators for β is
$$\hat{\beta} = n/S.$$

2. Under the null hypothesis $H_0 : \beta = 1$, $2S \sim \chi^2(2n-2)$. Therefore, a size α test of $H_0 : \beta = 1$ against $H_A : \beta \neq 1$ is to reject H_0 if $2S \leq \chi^2_{\alpha/2}(2n-2)$ or $2S \geq \chi^2_{1-\alpha/2}(2n-2)$, where $\chi^2_{\alpha/2}(2n-2)$ is the $100\alpha/2$ percentile of a chi-square distribution with $2n-2$ degrees of freedom.

Suppose now that independent volcanic repose time series of sizes n_1 and n_2 are observed, and two Weibull processes with shape parameters β_1 and β_2 are assumed respectively for each process. Let S_1 and S_2 be the corresponding test statistics as described in (1), then the overall time trends of these two volcanic processes can be quantitatively compared using the following test.

3. Let $F = (n_2 - 1)S_1/(n_1 - 1)S_2$, then under the null hypothesis $H_0 : \beta_1 = \beta_2$, $F \sim F(2n_1 - 2, 2n_2 - 2)$. And, a size α test of $H_0 : \beta_1 = \beta_2$ against $H_A : \beta_1 \neq \beta_2$ is to reject H_0 if $F \leq F_{\alpha/2}(2n_1 - 2, 2n_2 - 2)$ or $F \geq F_{1-\alpha/2}(2n_1 - 2, 2n_2 - 2)$, where $F_{\alpha/2}(2n_1 - 2, 2n_2 - 2)$ is the $100\alpha/2$ percentile of an F-distribution with $2n_1 - 2$ and $2n_2 - 2$ degrees of freedom.

EMPIRICAL EXAMPLES

Case 1: Final Eruptions vs. Intermediate Eruptions of Mount Vesuvius

Vesuvius is one of the most studied volcanoes in the world because of its long recorded history and its easy accessibility. Carta et al. (1981) reproduced the pattern of activity (1631-1944) with a Markov chain of four states of activity (repose, persistent activity, intermediate eruption, and final eruption). A detailed chronology of the entire period 1631-1944 based on accounts of contemporaries was reconstructed by Scandone et al. (1993). The first set of two volcanic repose time series to be compared is based on (1) final eruptions (FE), and (2) intermediate eruptions (IE) classified by Scandone et al. (1993).

One more simplifying assumption must be made in treating eruptions as stochastic events in time. Although the onset date of an eruption is generally well-defined by the time when lava first breaks the surface, the duration is harder to determine because of such problems as slowly cooling flows or lava lakes and the gradual decline of activity. We adopt the same definition for repose time as defined by Klein (1982). We therefore, ignore eruption duration; instead, we take the onset date (in days) as most physically meaningful, and measure repose times from one onset date to the next. Thus, our definition of "repose time" differs from the classic one (a noneruptive period). Therefore, the data represent the dates over which the eruptions begin based on the record of Vesuvius reconstructed by Scandone et al. (1993).

Let the great eruption of December 15, 1631 be the beginning of the observation period. There are 21 FE and 78 IE. In this example, $n_1 = 21$, $n_2 = 78$, $\hat{\beta}_1 = 1.263$ and $\hat{\beta}_2 = 1.345$. Thus, $S_1 = 21/1.263 = 16.627$, $S_2 = 78/1.345 = 57.993$ and the degrees of freedom for the F-test are $2n_1 - 2 = 40$ and $2n_2 - 2 = 154$. The test does not reject $H_0 : \beta_1 = \beta_2$, since F$=$ 1.104 and the p-value is .656 (two-tailed). Thus, we conclude that the shape parameter, β, is statistically the same for volcanic activities of Vesuvius based on final eruptions or intermediate eruptions during the period of 1631-1944. Based on $\hat{\beta}$, the data suggest an increasing time trend in the volcanic activity through time for both data sets, but the difference is not significant.

Case 2: Hawaiian Volcanoes

Kilauea and Mauna Loa volcanoes are ideal for our next example because so much is known about the physical processes of these basaltic shield volcanoes. For instance, Klein (1982) concludes that the inverse relation between Kilauea and Mauna Loa volcanism means that both volcanoes appear to be competing, in some sense, for the same magma source. Therefore, the second set of two volcanic repose time series to be compared is based on (1) eruptions of Kilauea (1918-1981, Table 1 of Klein, 1982), and (2) eruptions of Mauna Loa (1832-1975), Table 2 of Klein, 1982).

Again, let each of the onset date of the first eruption listed on Tables 1 & 2 of Klein (1982) be the beginning of the observation period for Kilauea and Mauna Loa respectively. We then have $n_1 = 71$, $n_2 = 37$, $\hat{\beta}_1 = 1.701$ and $\hat{\beta}_2 = 0.999$. Thus, $S_1 = 41.740$, $S_2 = 37.037$ and the degrees of freedom for the F-test are 140 and 72. The test rejects $H_0 : \beta_1 = \beta_2$, since $F = 0.580$ with a two-tailed p-value of .006, slowing that the difference between these two volcanoes in terms of β is statistically significant. Separate hypothesis tests on $\beta = 1$ vs. $\beta \neq 1$ verify that, based on $\hat{\beta}$, Kilauea shows a signficantly increasing time trend while Mauna Loa remains approximately Poissonian during the observation periods.

CONCLUSIONS

Volcanic eruptions, intrusive events, and earthquakes are individually unique, but volcanism as a whole is a nonunique process in which repeated combinations of rate balances give rise to categorically similar patterns worldwide. Given sufficiently redundant information, pattern recognition and comparisons with the observed patterns become automatic. In this paper, we demonstrate a generalized method of quantitative description and comparisons of complex processes.

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APPENDIX 3

Significant aspects of my presentation and the round-table discussion in the meeting of the United States Nuclear Waste Technical Review Board's panel on structural geology and geoengineering, held on March 8-9, 1994 at San Francisco.

1. Theme of the meeting: Probabilistic Seismic and Volcanic Hazard Estimation

2. (a) In preparing the talk, I kept in mind the wishes of the meeting organizer, Dr. Leon Reiter, that it stay focused on the listed topics and that at least five minutes be allocated for questions.

   (b) Both Dr. E.I. Smith and I greatly appreciated that we were given a grand total of 40 minutes to present our paper.

3. The results of practice presentation with Dr. Smith led me to consider the probability that I could actually finish my talk in 15 minutes was less than 1. (In the words of the great mathematician Pierre Simon, Marquis de Laplace: "The most important questions of life are, for the most part, really only problems of probability.")

4. After a one and a half day bombardment of probabilities and enduring one "luxurious" hour of seeing my models mismatched, misinterpreted, and mishandled by a speaker, the nightmare finally began.

5. I laid out my first transparency approximately fifteen minutes before the scheduled lunch break. About twenty minutes later (using the extra time to show the remaining 50% of my transparencies), I noticed that the chairman was showing visible signs of imminent starvation, proving the truth of Blaise Pascal's statement to a friend: "I made this letter longer than usual, because I lacked the time to make it short."

6. The general mood was much more jovial after lunch.

7. (a) At the round-table discussion, I directed a question to Dr. Crowe: "What is your definition of E_1 in your conditional probability model (a copy of his model is enclosed),

$$P_r = P_r(E_3 \text{ given } E_2, E_1)P_r(E_2 \text{ given } E_1)P_r(E_1)?"$$

   His response was: "Recurrence rate of volcanic events."

   I then asked: "How can one put the probability on a parameter, which is a constant (not a random variable)?"

   I followed with an example: "Do you put probability (not probability distribution) on your current true weight?"

A strong voice with a loud laugh burst from a board member, "why not?!" He then said something I did not agree. Apparently, he had something else in his mind.

   (b) Among the comments that followed was one from a speaker who had just finished his talk moments before: "In geology, sometimes the values of the unknown parameters vary, so we can put the probability on them," (I expect even undergraduate students to understand the distinction between a parameter and an estimator). I then concluded my remarks with "Dr. Crowe assumes a simple Poisson distribution for the volcanic events (past and future). The assumed Poisson distribution has an unknown parameter, the recurrence rate, which needs to be estimated. In this case, E_1 should be the events of volcanic eruptions, not the recurrence rate."

8. In the debate on homogeneous vs. nonhomogeneous models, I gave the following example: Because the Weibull distribution generalizes the simple Poisson model, we are comparing the power of a motorcycle and a bicycle.

   I now have a better analogy: We are comparing the function of a fully automatic car with a stick-shift car which can be driven at low gear only.

9. Most of the speakers presented their probabilistic results using numbers like 10^{-8}/yr. I asked the board members to interpret these. Do they represent the probability (or risk, or hazard) of the first year? Do they remain constant every year for 10^4 years? The overall cumulative five-year disease-free survival rate after operation on lung cancer patients of 85 percent is meaningful. One board member agreed that 85% ÷ 5 (or 1- 85% ÷ 5) for a per year survival rate does not make sense. Another board member agreed with my suggestion that future presentations of risk assessments for Yucca Mountain be in the following format:

   The estimated probability of at least one site disruption for an isolation time of 10^4 years is about xx percent, which increases to yy percent if 10^5 years is the required isolation time.

   (There was one comment from a former speaker: "Because we have to constantly adjust our models, it is easier to present the result in terms of annual probability." He certainly forgot that even the probabilities derived from a simple Poisson process are not linear in time! Of course, in some cases they are approximately linear.)

10. The issue of deterministic analyses vs. probabilistic analyses were mentioned by several speakers in their presentations. During the roundtable discussion, the merits of both approaches were also raised. I made the following comment: "Because the phenomenon (site disruption event) is stochastic, the answer is necessarily probabilistic."

11. Right after Dr. Crowe's presentation, one board member asked: "How do you feel about after more than 10 years' study, your results of probability do not change at all (or much)?" Dr. Crowe's answer was not sufficiently interesting to bother remembering.

12. In my presentation, I concluded that the effects due to different counts of events reflect approximately 42% maximum change in the probability of site disruption (10^4 years) for each model. The effects due to assumptions of different models yield approximately 32%

maximum change for each data set. The combined effects (model and data) demonstrate that the estimated probability of direct site disruption by basaltic volcanism over the next 10,000 years varies from 2.02×10^{-5} to 6.57×10^{-3}. Is the difference in magnitude significant? I asked the audience to compare these figures in terms of the rates of income tax, provoking some laughter.

13. The risk zones, AMRV model, developed by Smith et al. (1990) was challenged by a board member. Nonetheless, until the geologists prove that it is false, my prior distribution, U(0, 8/75), remains valid. Interestingly enough, if I opt for a non-informative prior, U(0, 1), due to lack of geological information, the new calculation objectively increases the probability by 816% for the same isolation time (10^4 years).

In summary, although there were useful and interesting discussions with the participants, far too many showed an insufficient grasp of standard statistical concepts, which casts doubt on the quality of their analyses of the site characterization studies.

March 9, 1994
San Francisco, CA

Bruce Crowe
Los Alamos National Laboratory

Probabilistic Volcanic Risk Assessment

Conditional Probability Model (Crowe, 1994)
Magmatic Disruption

$$Pr_{dr} = Pr(E3 \text{ given } E2,E1)Pr(E2 \text{ given } E1)Pr(E1)$$

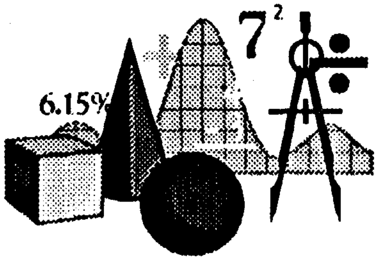
where

- E1: recurrence rate of volcanic events
- E2: probability a future event intersects a specified area
- E3: release of radionuclides to the accessible environment

E1: volcanic centers, volcanic clusters, intrusions, polycyclic episodes, cluster episodes

E2: repository, controlled area, waste isolation system (Yucca Mountain region)

E3: direct releases (eruptions), coupled releases



APPENDIX 4

A copy of the talk transparencies presented at the meeting of the United States Nuclear Waste Technical Review Board's panel on structural geology and geoengineering, held on March 8-9, 1994 at San Francisco. (This talk also highlights Article (1): Sensitivity in Volcanic Hazard Assessment for the Yucca Mountain High-Level Nuclear Waste Repository Site: The Model and the Data.)

Alternative Geologic Models: Their Significance with Respect to Calculation of Volcanic Hazard at Yucca Mountain

Presentation to the Nuclear Waste Technical Review Board (NWTRB)

March 8-9, 1994

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CVTS

Purpose

- Resolve problems regarding hazard assessment and consequence analysis
- Outline new and continuing research
- Demonstrate that these studies may make a difference.

CVTS

Outline

1. Geological studies
2. Volcanic hazard assessment

——— *CVTS*

Geological Studies

- Definition of a volcanic event
- Structural control of volcanism and area affected by future eruptions
- Explosivity of eruptions

——— *CVTS*

Definition of a Volcanic Event

- Definition is unclear
- Based on chemistry, field relations, geochronology, geographical distribution.
- Must develop a usable definition

——— *CVTS*

Volcanic Event

- A field of volcanoes formed at about the same time
- Eruption of chemically distinct magma batches
- Eruptions separated by a significant periods of time
- Count vents
- Count volcanic complexes

——— *CVTS*

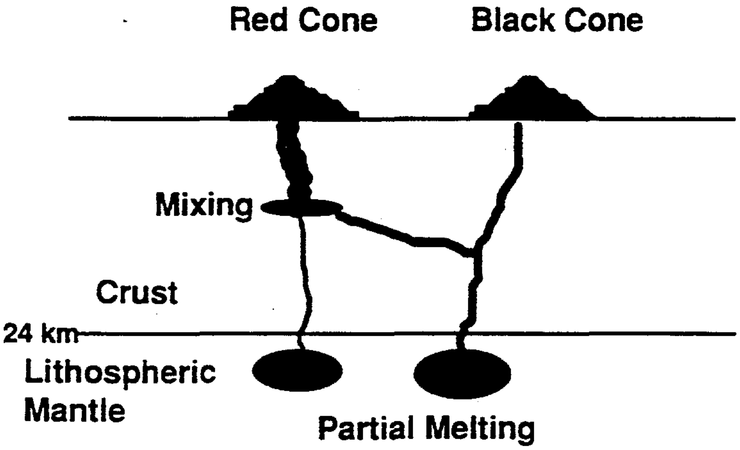
A field of volcanoes formed at about the same time

Three events:

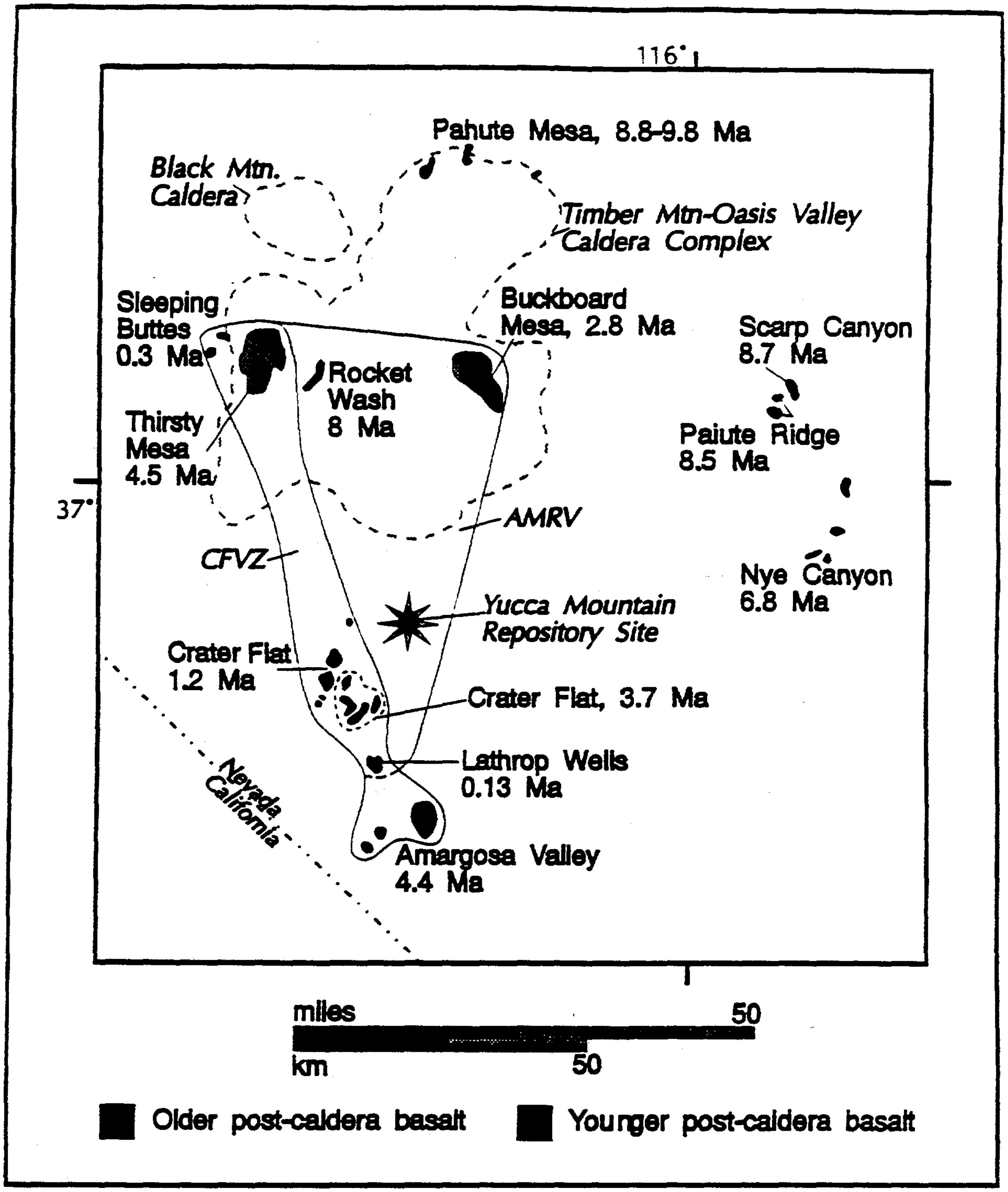
Lathrop Wells, 1.1 Crater Flat, 3.7 Crater Flat

CVTS

Crater Flat



CVTS



FROM:

CROWE (1990)
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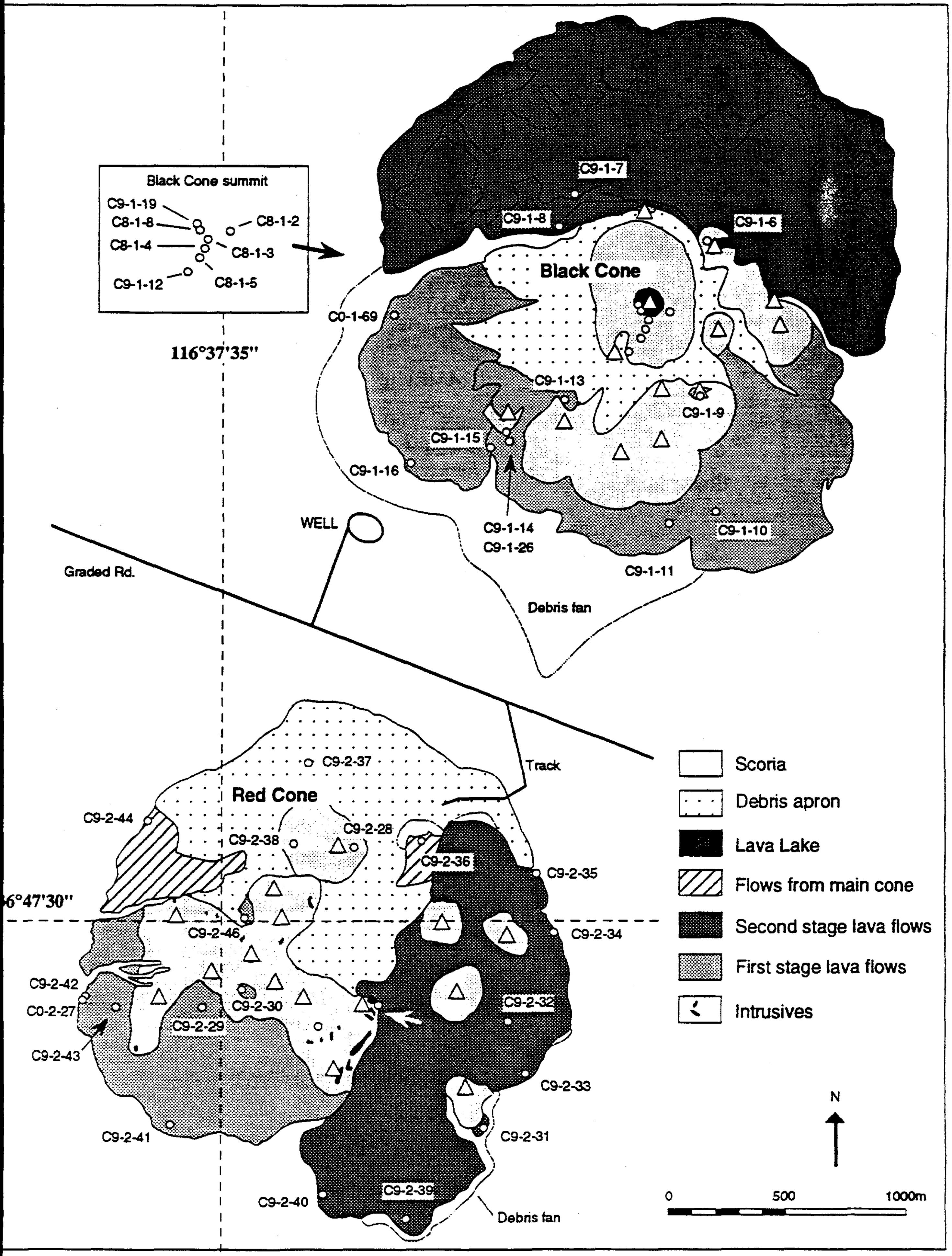
VANIMAN AND CROWE (1981)
CROWE AND PERRY (1991)
CROWE (1992, WRITTEN COMMUNICATION (NWTRB))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C9-1-6
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Debris fan
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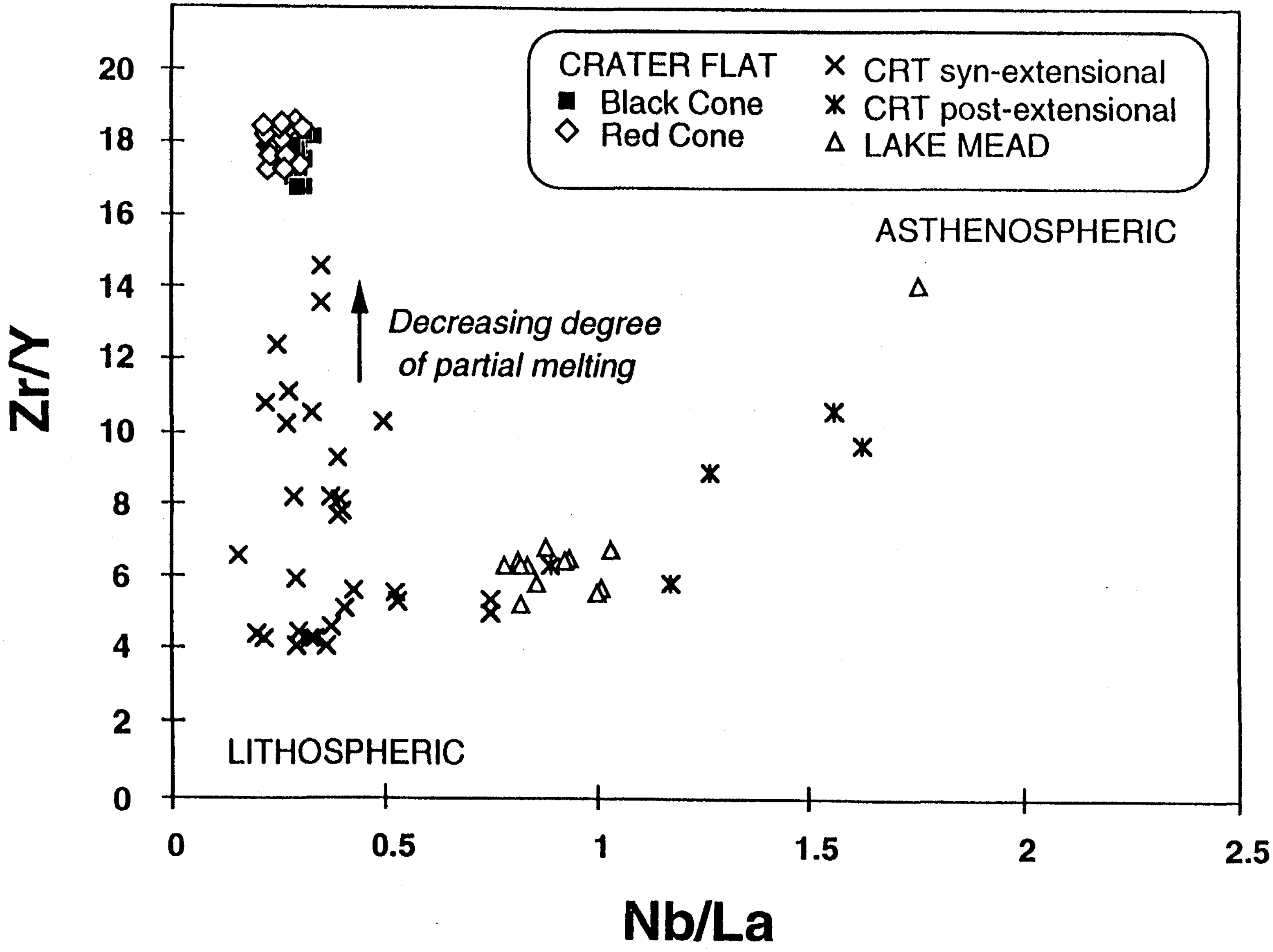
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◇ Red Cone
× CRT syn-extensional
✱ CRT post-extensional
△ LAKE MEAD
ASTHENOSPHERIC
LITHOSPHERIC
Decreasing degree of partial melting
Zr/Y
0
2
4
6
8
10
12
14
16
18
20
Nb/La
0
0.5
1
1.5
2
2.5

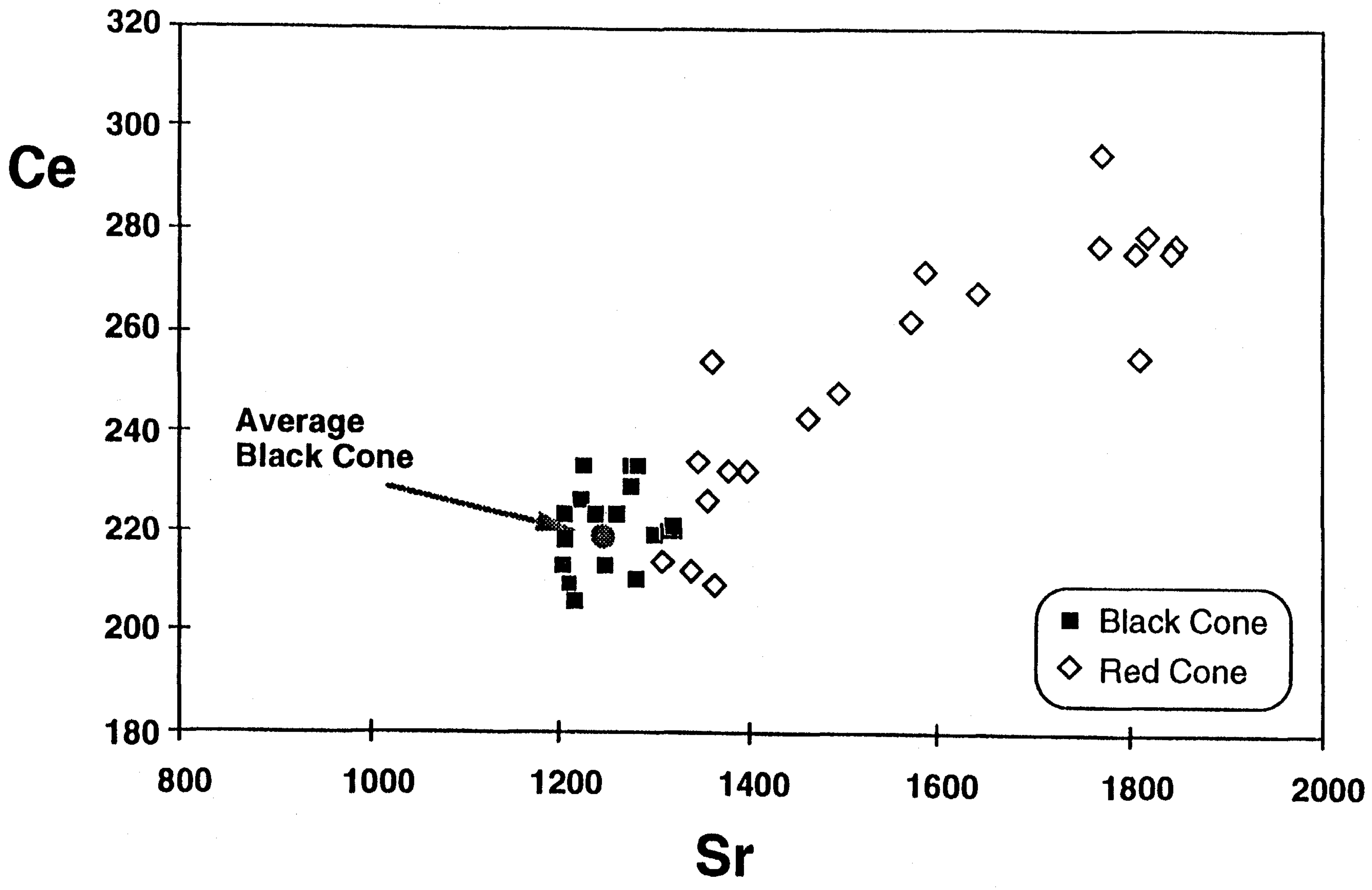
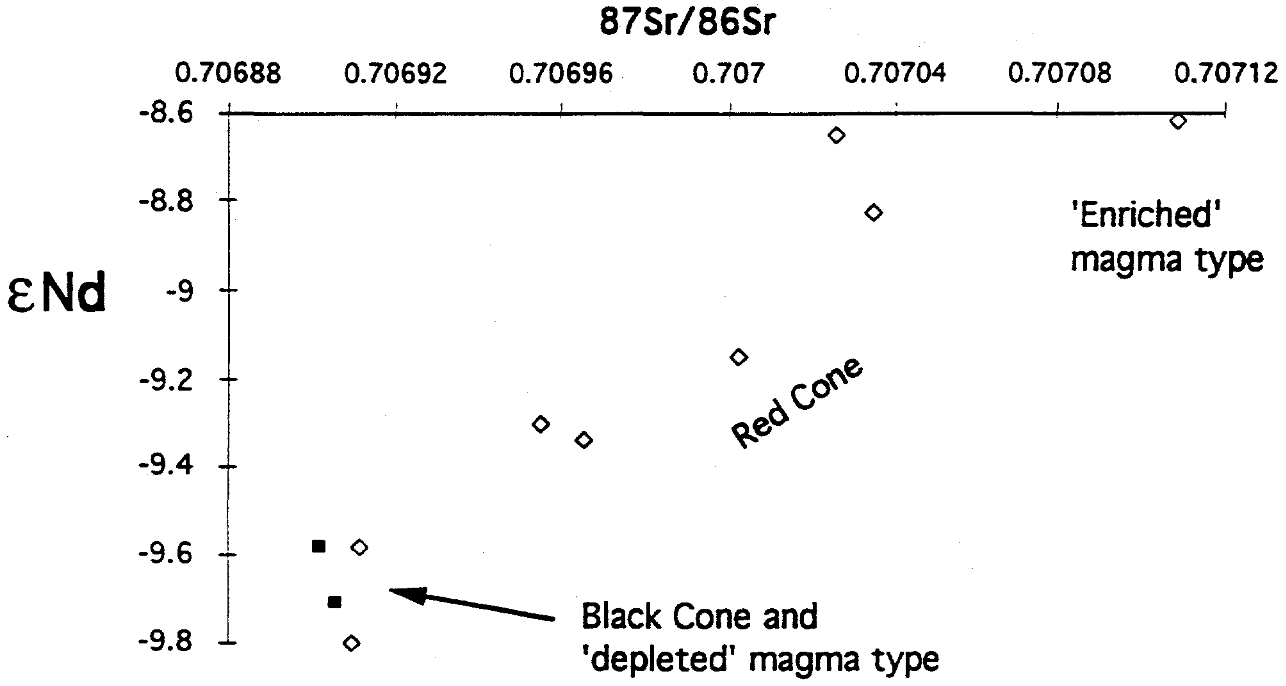
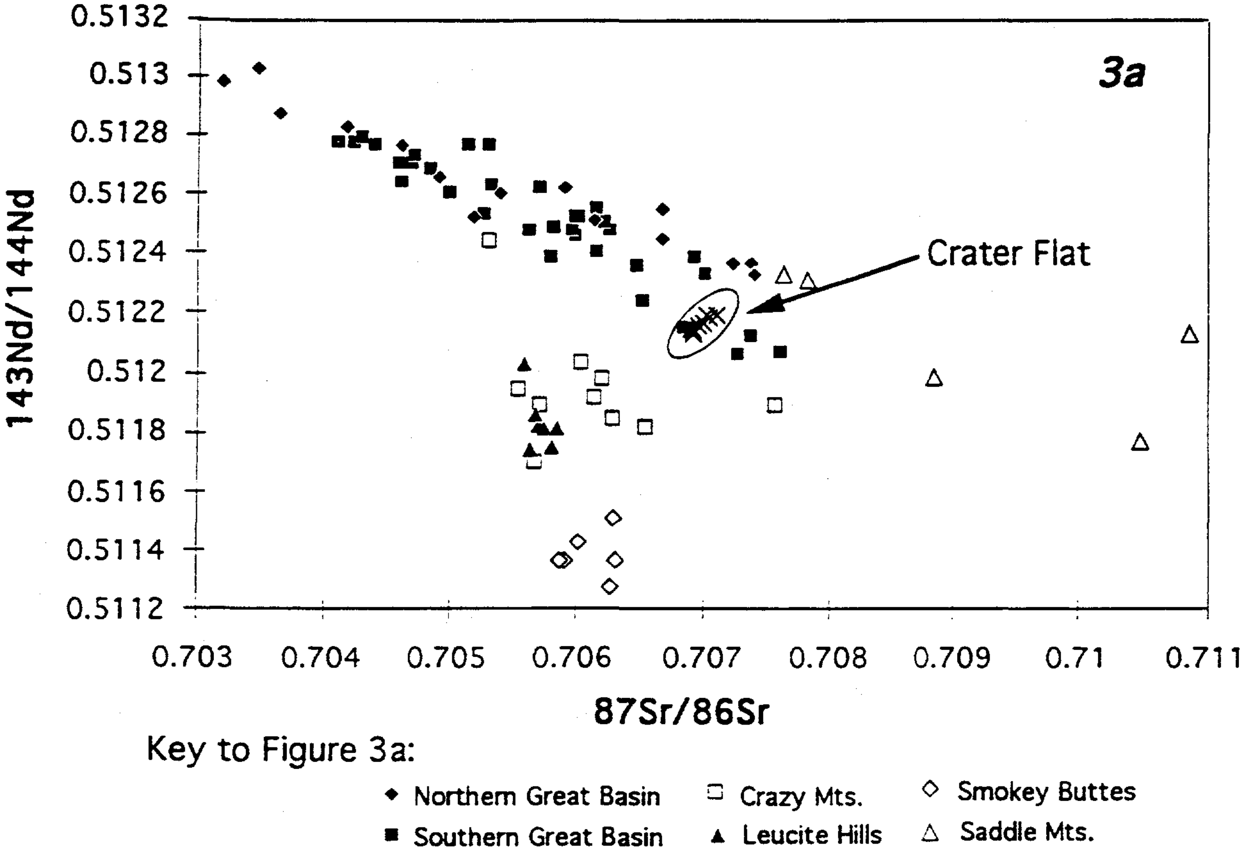

Ce
320
300
280
260
240
220
200
180
800
1000
1200
1400
1600
1800
2000
Sr
Average
Black Cone
■ Black Cone
◇ Red Cone

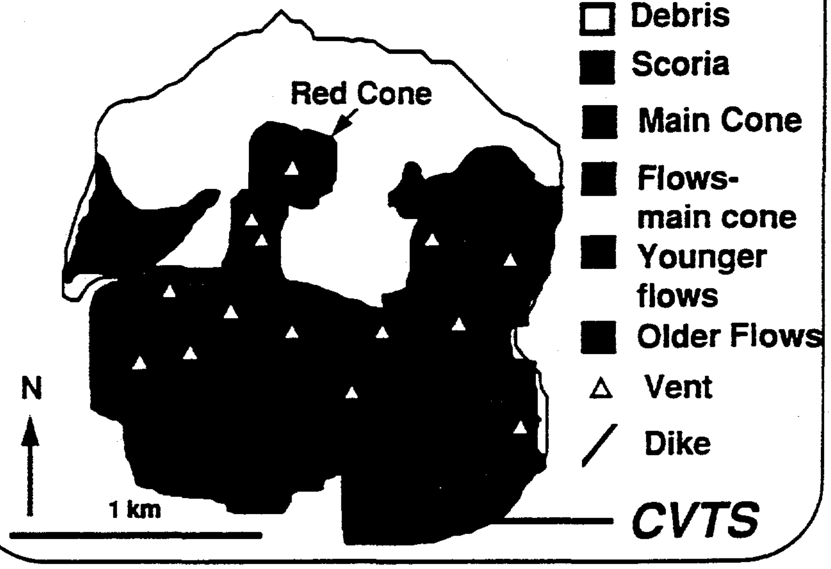
Figure 3. Sr and Nd isotope data for samples from Crater Flat.

3a. Comparison of Crater Flat data to samples from other volcanic fields in the western United States. Note that the Crater Flat samples fall within the trend defined by other basalts from the southern Great Basin.





Red Cone



CVTS

Eruptions separated by a significant periods of time

- Red Cone = 2 events
- Black Cone = 2 events

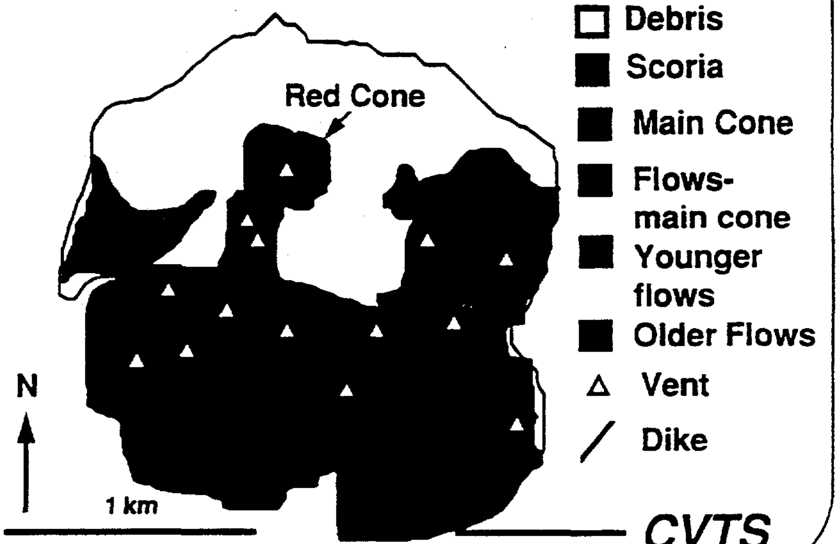
CVTS

Eruption of chemically distinct magma batches

- Black Cone and Red Cone = 2 events

CVTS

Red Cone



CVTS

Count vents

Red Cone = 14 events

——— *CVTS*

Count volcanic complexes

Red Cone = 1
Black Cone = 1

4 events in Crater Flat

——— *CVTS*

Summary

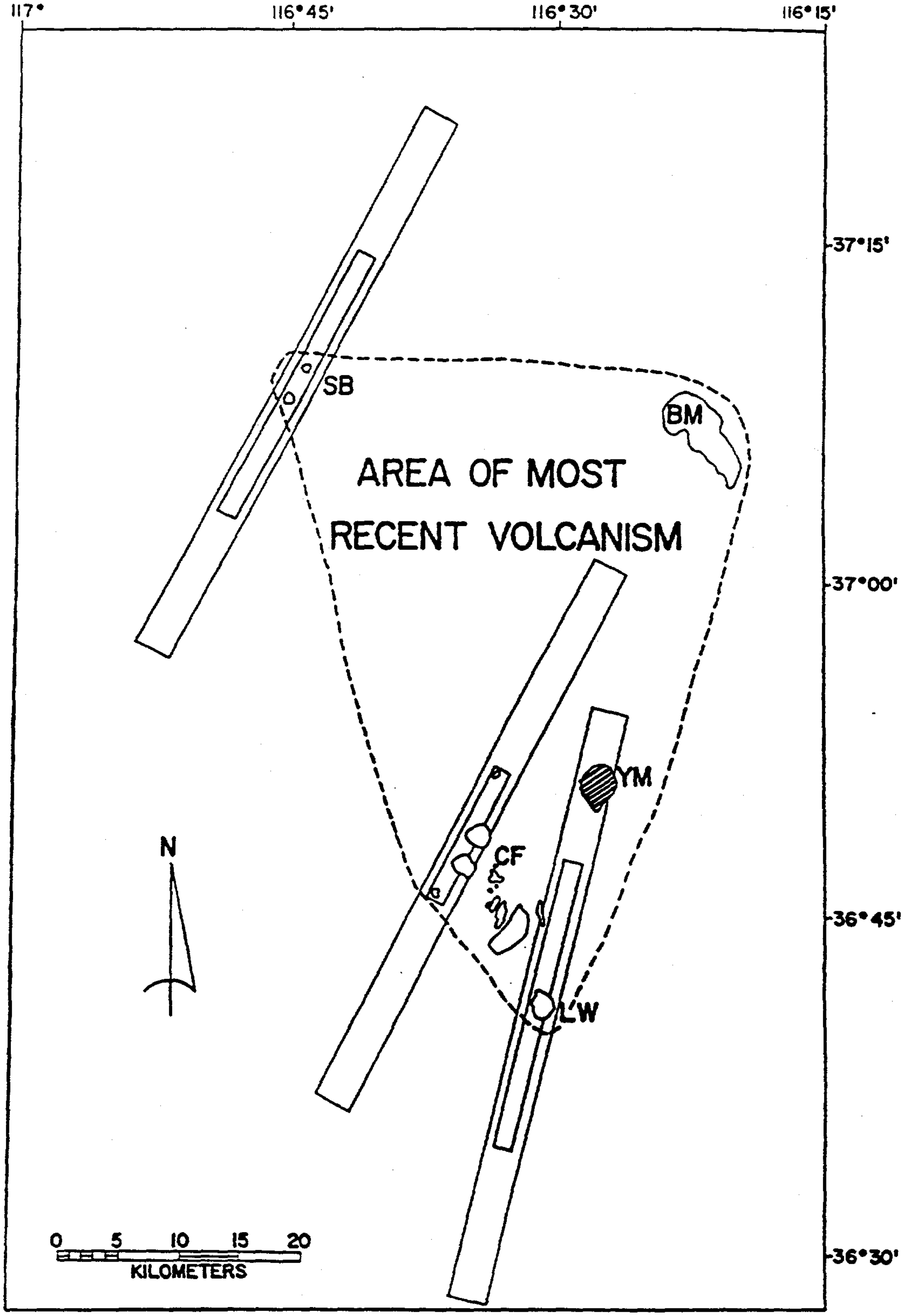
- **Red Cone**
  - –14 events-vent count
  - –2 events-chemistry
  - –2 events-time
  - –1 event-volcanic complex
  - –part of the Crater Flat event

——— *CVTS*

Area of Concern for Hazard Assessment

- **What is the area that may be affected by a future eruption?**
  - –Crater Flat zone
  - –Area of most recent volcanism
  - –Others

——— *CVTS*


117°
116°45'
116°30'
116°15'
37°15'
37°00'
36°45'
36°30'
SB
BM
AREA OF MOST RECENT VOLCANISM
YM
CF
LW
N
0 5 10 15 20
KILOMETERS

Structural Control

- **Which structures control magma emplacement in the uppermost crust?**
- **Formation of volcanic chains**
- **A single "volcanic event" may occur at more than one location.**

——— ***CVTS***

Consequence of Eruption

Cinder cone eruptions can be explosive (Plinian or subplinian)

For example Tolbachik in Kamchatka

——— ***CVTS***

Consequence of Eruption

- **Determine the explosivity of an eruption.**
- **Volatile content (especially H_2O) is an indication of explosivity.**

——— *CVTS*

Consequence of Eruption

- **Melt inclusions are quenched samples of magma (and volatile phases) at time of eruption.**
- **Melt inclusions occur in olivine phenocrysts in a wide variety of tectonic settings.**

——— *CVTS*

Consequence of Eruption

- Compare H_2O in primitive melts at Crater Flat and Lathrop Wells with data from volcanic centers with known eruptive type.
- Similar volatile contents would be an indication but not proof of similar eruptive mechanism.
- Support with geological data.

Summary

- Important data required for hazard assessment studies not yet available
  - volcanic event and area affected by volcanism still debated
- Cinder cones may erupt by a Plinian or subplinian mechanism

"The most important questions of life are, for the most part, really only problems of probability."

Pierre Simon, Marquis de Laplace
(the "Newton of France")

The enlightened individual
has learned
to ask not

"Is it so?"

but rather

"What is the probability
that it is so?"

To Quantify

The possibility of direct disruption of the repository by basaltic volcanism (an important factor in determining future public and environmental safety).

Related Issues

1. Modeling Assumptions:
    - homogeneous Poisson vs. nonhomogeneous Poisson
2. Eruptive History of Basaltic Volcanism:
    - monogenetic vs. polycyclic
3. Structural Controls on Basaltic Volcanic Activity:
    - northwest vs. northeast trend
4. Counts of Volcanic Events

BASIC MODELS

	Past	Future
1. HPP	Simple Poisson	Simple Poisson
2. WP-HPP	Weibull Process	Simple Poisson
3. WP	Weibull Process	Weibull Process

Probability of repository disruption *p*

Estimates of *p* listed in Table 7.1 of

Crowe et al. (1993) range from

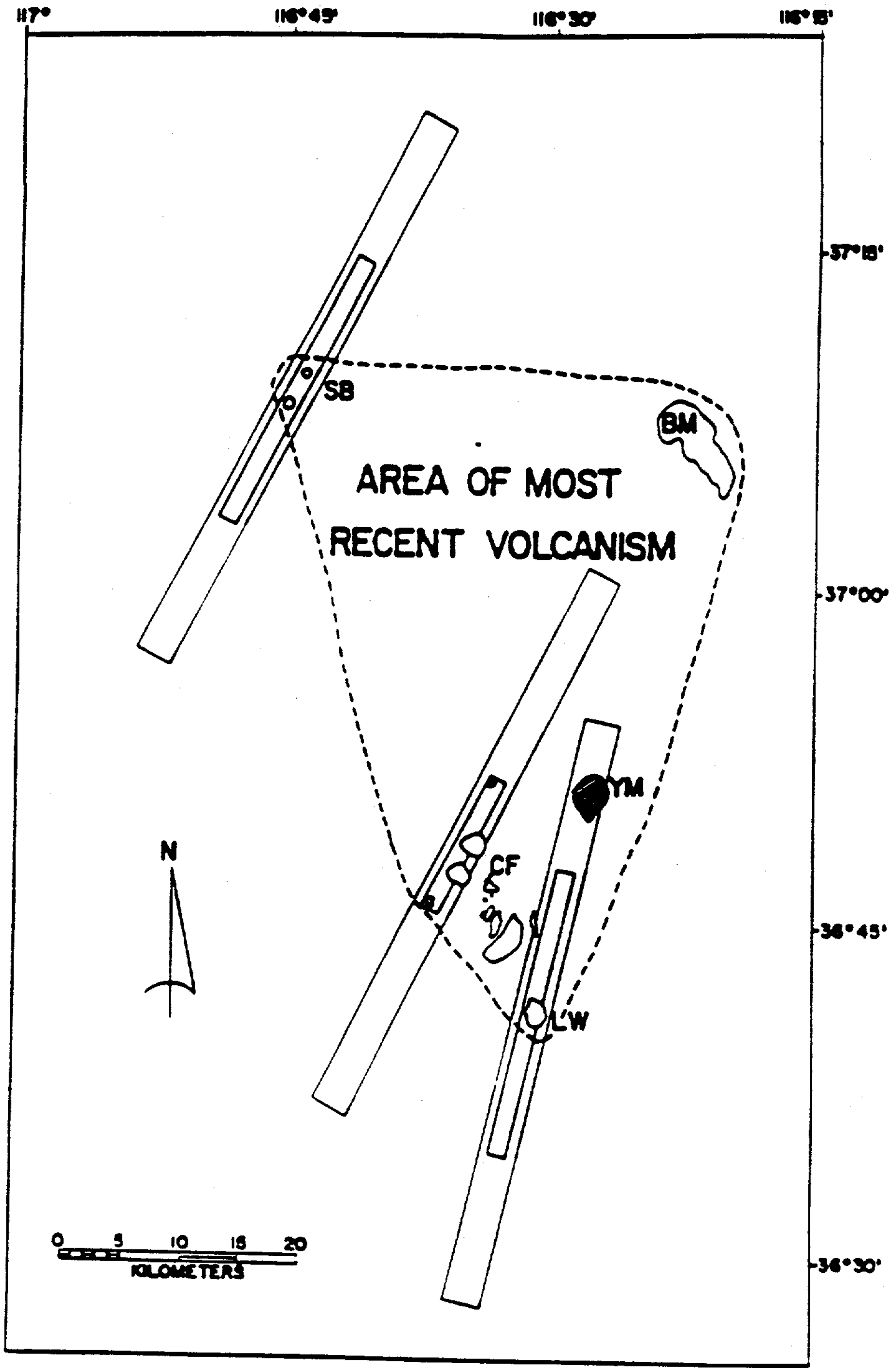
$$1.1 \times 10^{-3} \text{ to } 8 \times 10^{-2}$$

Two approaches for *p*

Classical — $p = 1.1 \times 10^{-3}$

Classical — $p = 8 \times 10^{-2}$

Bayesian — $p \sim U(0,8/75)$



Map outlining the AMRV (dashed line) and high-risk zones (rectangles) in the Yucca Mountain (YM) area that include Lathrop Wells (LW), Sleeping Butte cones (SB), Buckboard Mesa center (BM), volcanic centers within Crater Flat (CF). (Source: Smith et al., 1990a, fig. 7)

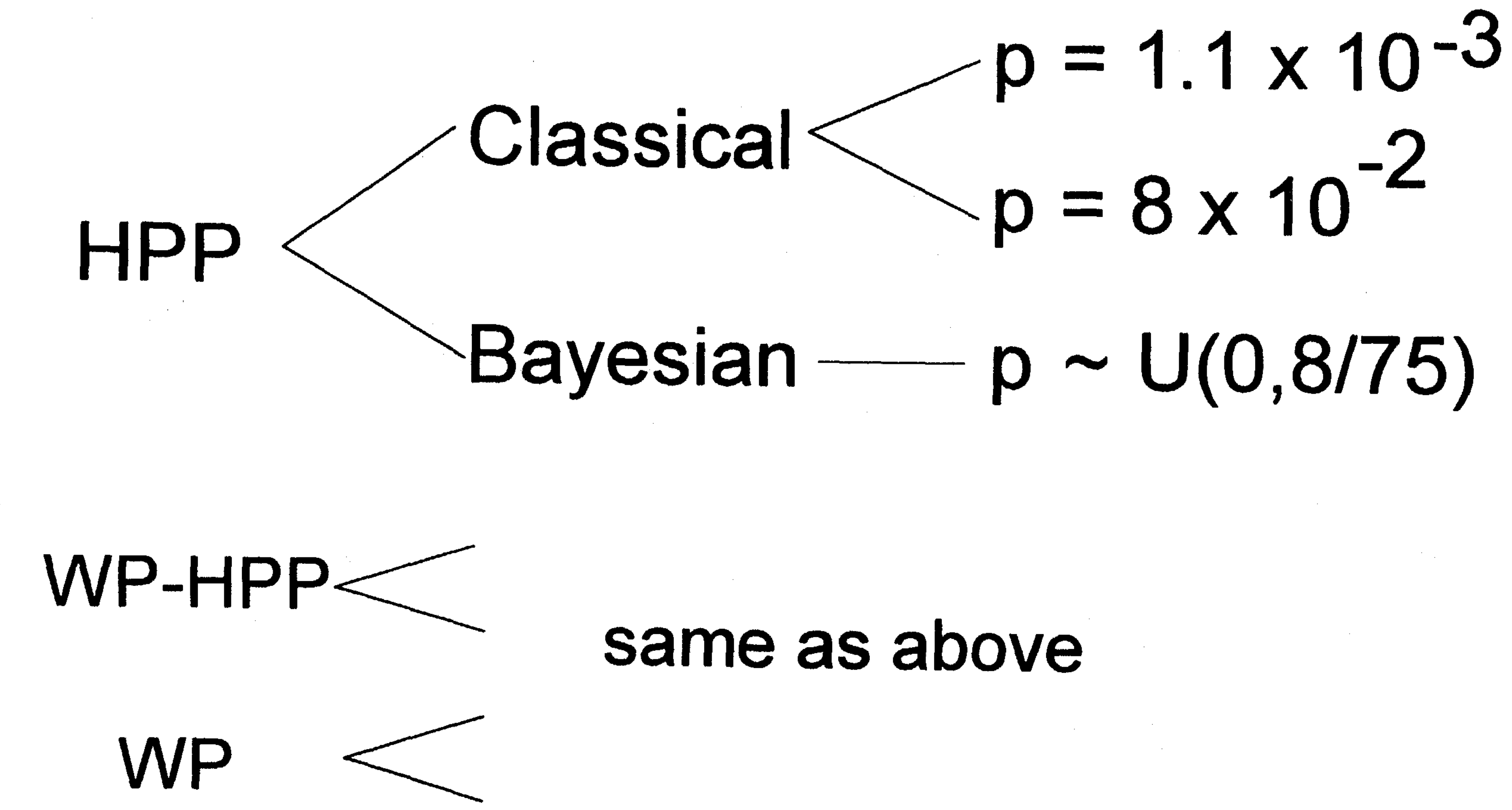
We have

1. $A = 75\ \mathrm{km}^2$ (= half of the rectangle)

2. $a = 8\ \mathrm{km}^2$ (area of the repository, Crowe et al, 1982)

3. $\pi(p) \sim U(0,8/75)$, which assumes 8/75 as the upper limit for p

Model Approach Parameter



HPP

Classical

$p = 1.1 \times 10^{-3}$

$p = 8 \times 10^{-2}$

Bayesian

$p \sim U(0,8/75)$

WP-HPP

WP

same as above

DATA (Crowe et al. 1993)

4.6 Ma, Thirsty Mesa (1 to 3 events)
4.4 , Amargosa Valley
3.7 , Crater Flat (1 to 5 events)
2.9 , Buckboard Mesa
1.1 , Crater Flat (4 to 6 events)
0.38 , Sleeping Butte (2 events)
0.1 , Lathrop Wells
0.01 , Lathrop Wells (remains controversial)

- **Post-6-Ma** (Pliocene and younger, 90 data sets)

4.6 (1 to 3), 4.4, 3.7 (1 to 5), 2.9, 1.1 (4 to 6), 0.38 (2), 0.1, 0.01 (0 to 1).

- **Quaternary, 6 data sets**

1.1 (4 to 6), 0.38 (2), 0.1, 0.01 (0 to 1)

Notes

Risk: probability of at least one disruptive event over the next 10,000 years $(= t_0)$ years

Model	Classical	Bayesian
HPP, WP-HPP	$1-\exp\{-\lambda p t_0\}$	$1-\int_p \exp\{-\lambda p t_0\}\pi(p)dp$
WP	$1-\exp\{-m(t_0)p\}$	$1-\int_p \exp\{-m(t_0)p\}\pi(p)dp$

1. How models and data affect calculation of volcanic risk?

2. Is the difference significant?

3. How important is the related future work?

1.• Recurrence rate and risk are higher based on the Quaternary data.

- Reason: length of the Pliocene period outweighs the greater number of events.

2.• (Instantaneous) recurrence rates produced by the WP are generally higher than rates obtained from the HPP, which shows that the volcanic trend is increasing.

Model	Recurrence rate (min, max)
HPP	$\left(4.38\times10^{-6}, 6.25\times10^{-6}\right)$
WP-HPP	$\left(5.83\times10^{-6}, 8.23\times10^{-6}\right)$
WP	$\left(5.83\times10^{-6}, 8.23\times10^{-6}\right)$

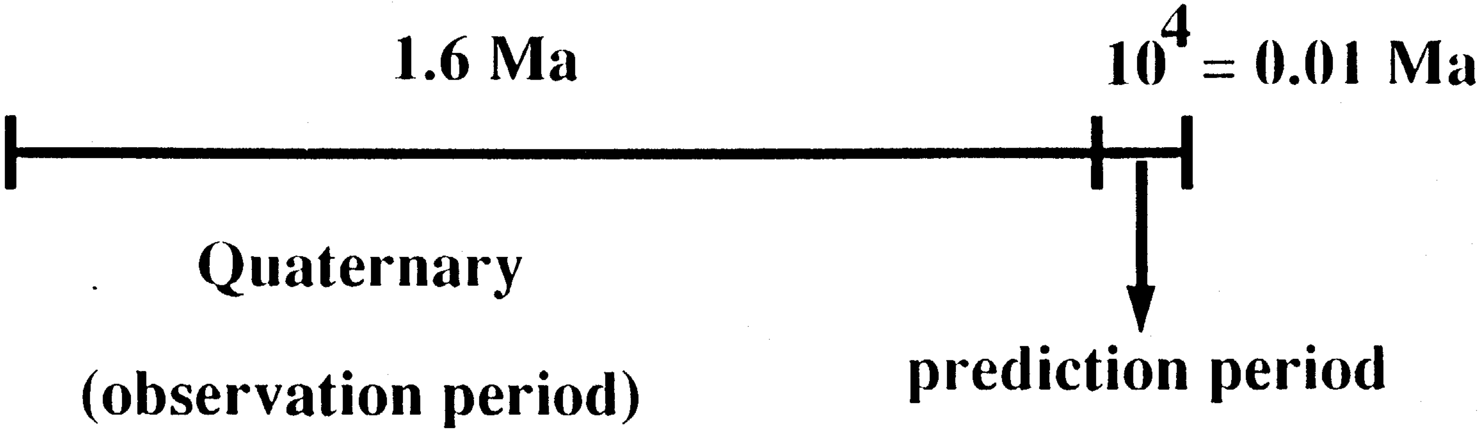
3.

- The classical approach using $p = 1.1 \times 10^{-3}$ and $p = 8 \times 10^{-2}$ yields the lowest and the highest values respectively for the risk.
- The Bayesian approach yields risks that are of the same order of magnitude as those calculated using the higher p.

Model	Risk Classical $p = 1.1 \times 10^{-3}$	 Classical $p = 8 \times 10^{-2}$	 Bayesian
HPP	$\left(4.81 \times 10^{-5}, 6.87 \times 10^{-5}\right)$	$\left(3.49 \times 10^{-3}, 4.99 \times 10^{-3}\right)$	$\left(2.33 \times 10^{-3}, 3.33 \times 10^{-3}\right)$
WP-HPP	$\left(6.40 \times 10^{-5}, 9.06 \times 10^{-5}\right)$	$\left(4.65 \times 10^{-3}, 6.56 \times 10^{-3}\right)$	$\left(3.10 \times 10^{-3}, 4.38 \times 10^{-3}\right)$
WP	$\left(6.41 \times 10^{-5}, 9.06 \times 10^{-5}\right)$	$\left(4.65 \times 10^{-3}, 6.57 \times 10^{-3}\right)$	$\left(3.10 \times 10^{-3}, 4.38 \times 10^{-3}\right)$

Model	Bayesian
HPP	$\left(2.33\times10^{-3},3.33\times10^{-3}\right)$
WP-HPP	$\left(3.10\times10^{-3},4.38\times10^{-3}\right)$
WP	$\left(3.10\times10^{-3},4.38\times10^{-3}\right)$

4\. • Results of both WP & WP-HPP models are almost identical.



1.6 Ma

$10^4 = 0.01$ Ma

Quaternary

(observation period)

prediction period

1. The projected time frame is about 0.6% of the OP
2. It is only 5% of the average repose time

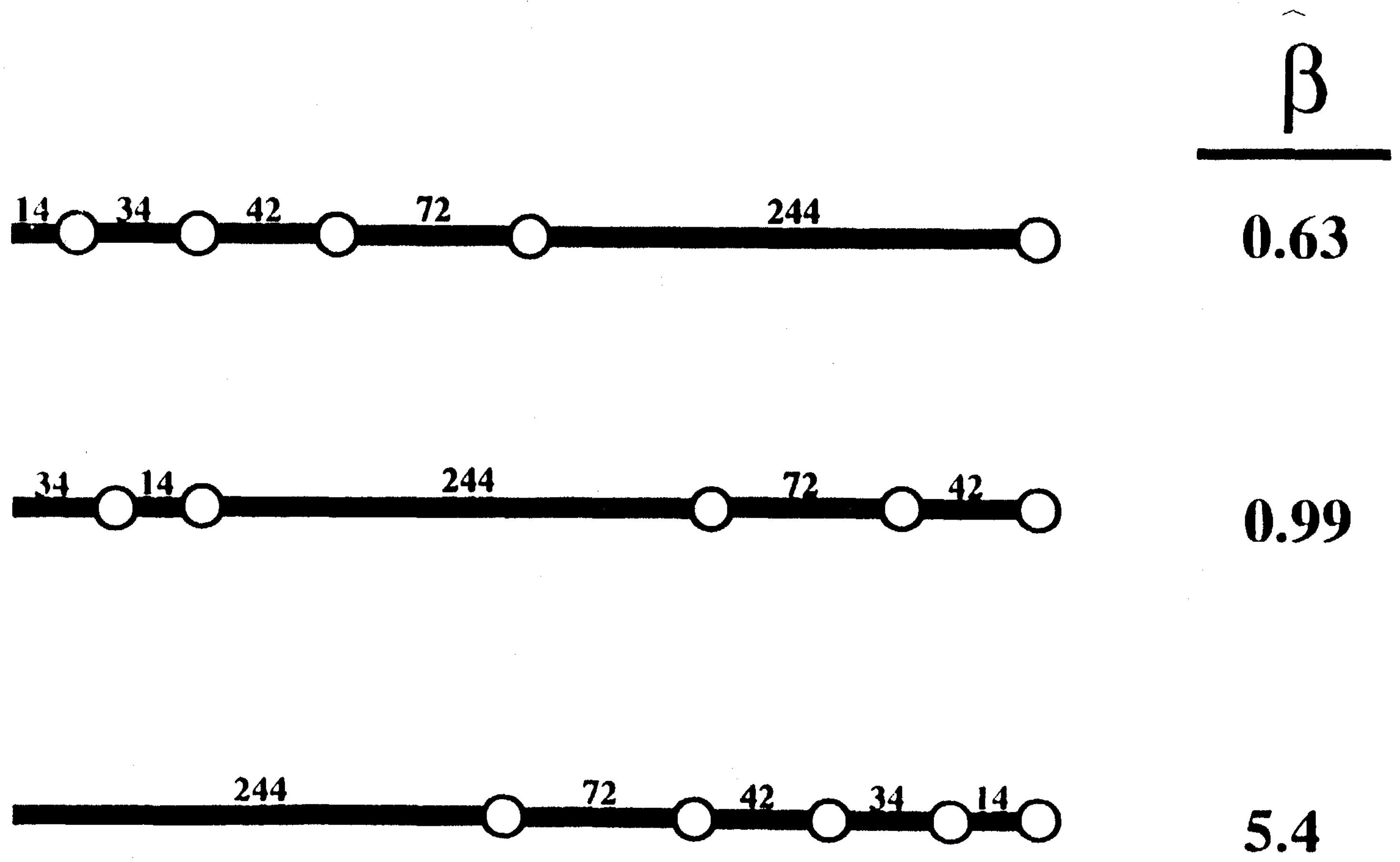
$\Downarrow$

Suggests switching from a NHPP to a predictive HPP model

5\.

- Inclusion of the potential youngest volcanic event at Lathrop Wells (= 10 ka) increases the risk.

- Should further young events be determined at Lathrop Wells or other sites in the AMRV, all risk values would increase, but those from the WP and WP-HPP models could change proportionally more than those from the HPP as the evidence of increasing trend is strengthened.


$\hat{\beta}$
14
34
42
72
244
0.63
34
14
244
72
42
0.99
244
72
42
34
14
5.4

6.• As expected, data with the least (most) count of events yield the lowest (highest) values of both recurrence rate and risk using the model of HPP.

- The data set which produces the lowest risk (WP and WP-HPP models only) is: 4.6, 4.6, 4.6, 4.4, 3.7, 2.9, 1.1, 1.1, 1.1, 1.1, 0.38, 0.38, 0.1 ($\hat{\beta} = 1.57$). The risk is actually higher if we only count one event for the Basalt of the Thirsty Mesa (= 4.6 Ma) and keep the same counts for the others (in this case, $\hat{\beta} = 2.05$).

- **Along the same line of argument, the data set which produces the highest risk is: 4.6, 4.4, 3.7, 2.9, 1.1, 1.1, 1.1, 1.1, 1.1, 1.1, 0.38, 0.38, 0.1, 0.01** $\left(\hat{\beta} = 2.43\right)$.

MAJOR RESULT

The estimated probability of direct site disruption by basaltic volcanism over the next 10,000 years is

$$2.02 \times 10^{-5} \text{ to } 6.57 \times 10^{-3}$$

What would be the effect of increasing the time period of concern for post-closure performance from 10,000 to 100,000 years?

It would increase the estimates to approximately

$$2.02 \times 10^{-4} \text{ to } 6.57 \times 10^{-2}$$

or

$$0.02\% \text{ to } 6.57\%$$

When is "enough is enough?"

What are the criteria for that
determination?

Question(s) to be answered:
Are probabilities 0.02% and
6.57% both acceptable?
i.e.,
Is the difference significant?

Model: WP

$p \sim U(0,8/75)$

Data	**Risk (10,000 years)**
$1.1 \times 6, 0.38 \times 2, 0.1, 0.01$	4.38×10^{-3}
$1.1 \times 6, 0.38 \times 2, 0.1, 0.02, 0.01, 0.01$	6.29×10^{-3}

Percentage change $= 43.6\%$

Model: WP

Data: $1.1 \times 6, 0.38 \times 2, 0.1, 0.01$

Prior	**Risk (10,000 years)**
$U(0,8/75)$	4.38×10^{-3}
$U(0,1)$	4.01×10^{-2}

Percentage change = 816%

The human mind is like a parachute; it works best when it is OPEN.

Deterministic (models)

v.s.

Probabilistic (models)

Power,

Mystery, and

Volcano

DEADLY SCIENCE

Volcanology is
tragically imprecise.