LLC 4/25/94

DCS

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Attend the Nuclear Waste Technical Review Board meeting on probabilistic seismic and volcanic hazard estimation. 20-5702-441

DATE/PLACE: March 8-9, 1994, Holiday Inn, Burlingame, California

AUTHORS: Brittain E. Hill, Charles B. Connor

PERSONS PRESENT: CNWRA: C.B. Connor, B.E. Hill, R.B Hoffmann; NRC: K.I. McConnell, J.S. Trapp, S. McDuffie, A.K. Ibrahim, J. Clark, G.V. Giese-Koch, A.J. Murphy; NWTRB and its consultants; ACNW: Paul Pomeroy; DOE and its subcontractors; State and Counties representatives for Nevada.

DISTRIBUTION:

CNWRA	NRC	SwRI
W. Patrick	M. Knapp	S. Rowe
J. Latz	~~W. Brown~~ S Fortuna	
Directors	~~[illegible]~~	
Element Managers	B. Meehan	
GS Element Staff	L. Kovach	
	P. Justus	
	S. McDuffie	
	K. McConnell	
	J. Trapp	

Delete all distribution
except: CF
NUDOCS Full Text
NRC PDR

NH15
0/1

486.1
WM-11

9404110362 940323
PDR WASTE
WM-11 PDR

CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Attend the Nuclear Waste Technical Review Board meeting on probabilistic seismic and volcanic hazard estimation. 20-5702-441

DATE/PLACE: March 8-9, 1994, Holiday Inn, Burlingame, California

AUTHORS: Brittain E. Hill, Charles B. Connor

PERSONS PRESENT: CNWRA: C.B. Connor, B.E. Hill, R.B Hoffmann; NRC: K.I. McConnell, J.S. Trapp, S. McDuffie, A.K. Ibrahim, J. Clark, G.V. Giese-Koch, A.J. Murphy; NWTRB and its consultants; ACNW: Paul Pomeroy; DOE and its subcontractors; State and Counties representatives for Nevada.

BACKGROUND:

The Nuclear Waste Technical Review Board meeting was convened to examine the current state of probabilistic seismic (PSHA) and volcanic (PVHA) hazards assessment at the candidate Yucca Mountain repository site. The NWTRB is aware of differences in hazards assessment models between the DOE and other groups, and is especially interested in how these differences may be significant or change in the future.

SUMMARY OF THE MEETING:

The meeting agenda is attached as appendix A, and handouts for PVHA presentations are attached as appendix B. PSHA presentations are summarized in a trip report by R.B. Hoffmann (CNWRA).

Tuesday, March 8:

Frank Perry (LANL) presented an update on volcanic investigations in the Yucca Mountain region (YMR). Much of the information presented was different than contained in the Preliminary Draft Status Report on Volcanism by Crowe et al. (1993). The current volcanism hypothesis is that Lathrop Wells has had at least 4 distinct periods of activity between about 100 ka and 10 ka (i.e., polycyclic eruptions). Small geochemical variations, which cannot be explained by simple crystal fractionation, are used to delineate these eruptive cycles. Polycyclic activity also is being proposed for Black Cone, Red Cone, and at Sleeping Butte. New Ar-Ar dates for the Quaternary volcanoes in the YMR are being determined. These dates apparently cluster at about 1 Ma for the Crater Flat volcanoes. Pliocene Crater Flat units cluster at about 3.7 Ma, and the basalt in the Amargosa drill-hole is about 3.8 Ma and thus contemporaneous with Crater Flat. Perry concluded that "the next eruption in the region will probably again be at Lathrop Wells."

C. Allin Cornell (Stanford University) presented an overview on approaches to probabilistic hazards assessment, which focused on some of the hazards associated with these assessments. He stressed the need to rigorously determine the uncertainties in both the data and the models. Expert elicitation is useful in constraining and evaluating model uncertainties, but the problems are usually multidisciplinary and require broad participation. He concluded that it is necessary to do a state-of-the-art job in analyzing hazards and uncertainties, even if the resulting models are highly complex.

Bob Budnitz (Future Resources Associates; no handout) gave an overview on the application of probabilistic hazard assessment to design of critical facilities. He stressed the linkage necessary between the hazards and design groups and the requirement for two-way communication between these groups. For Yucca Mountain, there is a problem in determining the hazard associated with seismicity. The large variations in the current design of the repository and waste package makes it difficult to assess the fragility of the system to seismic hazards. In essence, there is no way to effectively determine what level of seismicity constitutes a hazard until the design criteria are constrained.

Wednesday, March 9, 1994:

Bruce Crowe (LANL) provided a synopsis of probabilistic volcanic risk assessment for the YMR. Much of the presented material apparently originates from a revision to the Volcanism Status Report of Crowe et al. (1993). Relative to seismic hazards, PVHA is considerably more advanced for the YMR and the parameters used in probability models are better constrained. In spite of evidence to the contrary (e.g., Smith et al., 1990; Connor and Hill, 1993), a fundamental assumption in his PVHA models is that the "volcanic record [at the YMR] is too limited for robust calculations, statistical significance, goodness of fit", and although "multiple models are possible, they cannot be proven or disproven with the record." Thus the homogeneous Poisson model is appropriate for the YMR. It is important to note that, in contrast to the models presented in Crowe et al. (1993), the probability for direct igneous disruption of the candidate repository site is estimated to be at or greater than 10^{-8} per year for over 70 percent of the proposed models. Crowe also emphasized the need for expert judgment in the PVHA program, which was well received by the NWTRB. Crowe was encouraged by Mike Sheridan (SUNY Buffalo) to publish these results in the geologic literature. Leon Reiter (NWTRB) and Bob Budnitz observed that although the mean or median of the proposed values may be representative, it may not adequately represent the range of behavior in the system.

Kevin Coppersmith (Geomatrix) presented as quick overview of the use of expert judgment in PVHA, as part of Crowe's presentation. Expert judgment and peer review will be an important part of the DOE volcanism program, although the procedures are still being developed. He noted that although "the analysis of data by Bruce Crowe et al. is itself 'expert judgment' ... it is probable that there are other knowledgeable experts outside the YM project who can provide their interpretations of the available data as well."

Jeanne Nesbit (DOE) discussed the overall use of PVHA, which includes consideration of the consequences of igneous activity on repository performance. A preliminary finding is that based on the "limited" volcanic effects considered in the Total System Performance Phase I (1991), consequences of volcanism alone do not exceed regulatory release limits. Volcanism research will continue to examine the consequences of igneous activity in detail. The revised Crowe et al. (1993) report will be submitted to DOE in FY94, and the decision to submit a volcanism topical report will be made in FY95. Nesbit emphasized that independent technical review is an accepted part of the YM program, and that peer review and expert elicitation are being considered. Nesbit reiterated Crowe's statement that the probability of magmatic disruption of the candidate repository is at or greater than 10^{-8} per year.

Keith McConnell (NRC) provided an overview of the regulatory basis for PVHA and an outline of the general acceptance criteria for igneous activity in the YMR. In summary, the final determination of when "enough" studies have been done is when the potential effects of igneous activity on repository performance, including uncertainty, can be fully examined. McConnell also provided examples of how the DOE has made progress towards an acceptable PVHA, but that significant problems exist and that many critical investigations need to be completed in order to determine a robust PVHA.

Chuck Connor (CNWRA) presented a synopsis of current CNWRA PVHA models. Connor explained how volcanoes in the YMR cluster and thus require spatially nonhomogeneous probability models. He gave an overview of the near-neighbor nonhomogeneous Poisson probability model (Connor and Hill, 1993), which results in an annual probability of direct repository disruption between 3×10^{-8} and 1×10^{-8}. Initial results from a spatio-temporal homogeneous Markov model support the idea that future volcanism is most likely to occur in the Crater Flat region. All PVHA models need to incorporate geologic data, such as structural control on volcano location, and that these models need to be tested at other volcanic fields besides the YMR.

Carl Johnson (State of Nevada) was unable to attend the meeting. His remarks were presented by Dave Tillson. In summary, volcanism is a high-priority problem because of its proximity to the candidate repository site. Johnson does not believe that there is a consensus on volcanic system models, and that although all researchers agree that there are Quaternary volcanoes in the YMR, the processes that could "trigger" volcanic eruptions in the future are unknown. He also maintains that the volcanic system must be understood before the repository can be designed and evaluated for potential risks.

Gene Smith (UNLV) and C.H. Ho (UNLV) gave an overview of alternate geologic models to those presented by DOE and its affiliates. Smith's presentation focused on the difficulties in defining what constitutes a volcanic "event", especially in light of new data that suggests Red Cone and possibly Black Cone are polycyclic volcanoes. He reiterated many of the points in Smith et al. (1990) about defining hazard zones on the basis of structural control. The 1975 Tolbachik eruption was presented as an example of the type of explosive mafic eruption that could occur in the YMR, and that detailed research is needed on the volatile content of mafic magmas. Ho provided further variations of the Weibull model (Smith et al., 1990). By using different recurrence rates and variations in the timing of volcanic eruptions, he calculates that the probability of direct disruption of the candidate repository site can range from 2×10^{-9} to 6.6×10^{-7} per year.

Peter Wallmann (Golder Associates) presented the results of Monte Carlo simulations of dike emplacement for the YMR. By defining various areas that encompass the candidate repository site and assuming a homogeneous distribution of dike initiation points within these areas, Wallmann simulated dike propagation using variations in dike orientation, length, and emplacement depth. He then recalculates volcano recurrence rate to account for the past occurrences of volcanism that only occur within the defined zones. The resulting probabilities for direct repository disruption then tend to cluster around 10^{-8} per year, even for the hazard zone defined by Smith et al. (1990). But these calculations were made using a very low recurrence rate. Riefer questioned Wallman's use of low recurrence rate.

Mike Sheridan (SUNY Buffalo) provided some general remarks on PVHA. One method that has been used in the past for PVHA on single volcanoes is to examine the repose time and volume of eruptions as indicators for future eruptions. He recommends that models for the YMR are put into a larger framework and tested at larger volcanic fields, and that some determination should be made about the minimum eruption volume necessary for repository disruption. He also favors expert judgment to evaluate volcanological issues in the YMR.

George Thompson (Stanford University) made several comments about the possible relationships between igneous intrusion and faulting. He noted that strain can be accommodated through either faulting or the emplacement of intrusions such as dikes. The Crater Flat area produces relatively few earthquakes, which may be due to dike emplacement. He recommends that detailed geophysical studies, such as aeromagnetic or seismic reflection surveys, be performed in Crater Flat to look for intrusions without obvious surface manifestations.

Following the presentations, the speakers were invited to join in a round-table discussion of the material presented during the meeting. Most of the discussion, and certainly the liveliest, involved the probability of volcanic disruption of the repository. Crowe asked Connor several questions, which involved the effect of defining volcanic events differently. If the Crater Flat alignment were one event, how would the nonhomogeneous Poisson model change? Connor said that he had not calculated the impact of using the Crater Flat alignment as a single event. Connor added that the recurrence rate would decrease, because the number of events during the Quaternary would be fewer. However, the area affected by a single volcanic event would increase substantially, because this area term would have to include the entire Crater Flat alignment. Connor stated that the net change in probability might not be large.

Another question Crowe asked Connor concerned the use of Miocene vents in the calculation of the nonhomogeneous Poisson probability model, the implication being that the inclusion of these vents somehow skews the results, and may increase the degree of clustering. Connor pointed out that the clustering persists in the Crater Flat area because volcanism has persisted there since the Pliocene. Two additional points should be made, however. First, tests for spatial clustering for volcanoes in the YMR have been made using all volcanoes since 10 Ma, all younger post-caldera basalts, and only Quaternary volcanoes. Spatial clustering occurs in all of these age groups. Second, the nonhomogeneous Poisson model used by the CNWRA is robust with respect to changes in the pattern of volcanism through time. If the data were available, the distribution of all Tertiary volcanoes could be used in the model and the probability of distribution near Crater Flat, and the repository site, would not change. This is because a six near-neighbor model is used, which accurately describes Quaternary volcanic recurrence rates. Miocene volcanoes, especially those located >50 km away from the repository, have an almost negligible effect on probability calculations. Young volcanoes located relatively close to the proposed repository site control the probability distribution. Following these questions there was discussion about the general application of probability, the meaning of the E1 term, and the comparative lack of probability model development in PSHA. John Trapp commented that the proposed use of expert judgement was excellent and may lead to some progress in PVHA.

Close to the end of the roundtable discussion, Connor asked about the criteria used for discarding a model from consideration, pointing out that because volcanoes cluster in the YMR, homogeneous Poisson models are not appropriate. Crowe indicated that there are programmatic reasons for keeping a model once it is proposed. In addition, Peter Wallmann suggested that he would incorporate nonhomogeneous models into future calculations, but was unable to at the present because of budgetary considerations. This indicates two things. First, currently there do not appear to be any scientific criteria for evaluating the utility of specific probability models in the DOE volcanism program. As a result, the DOE will continue to use homogeneous Poisson models despite ample evidence that spatially nonhomogeneous models are more robust. Second, if there are programmatic reasons for keeping all proposed models, then there is no basis for rejection of UNLV models by the DOE despite numerous objections related to assumptions made in this model raised at the meeting.

OTHER ACTIVITIES:

In addition to the NWTRB meeting, Hill, Connor, McConnell, Trapp, and McDuffie met informally with Paul Pomeroy (ACNW) to discuss the February ACNW meeting on volcanism. Hill and Connor were able to give a quick synopsis of volcanism research at the CNWRA and show how this research directly supports performance assessment work and provides the NRC with critical, pre-licensing technical assistance. Hill and Connor further explained the technical basis for conducting research at historically active basaltic volcanoes, and how this research directly relates to the development and assessment of igneous activity models for the YMR.

IMPRESSIONS AND CONCLUSIONS:

There was little technical discussion of PSHA during the meeting, which focused primarily as a synopsis of DOE-sponsored structural geology studies and conceptual PSHA methodologies. The PVHA presentations further emphasized that there is significant disagreement about what methods are valid in PVHA. Objections to the homogeneous Poisson model were acknowledged by several NWTRB members and consultants and the proposed CNWRA models were not refuted. Many of the criticisms of DOE-PVHA previously raised by NRC and CNWRA staff were not addressed in these presentations.

The probability models proposed by Ho and coworkers at UNLV have been the source of much disagreement at previous meetings. These models need to be explained, because they result in probabilities of direct repository disruption that are significantly greater than the worst-case models proposed by Crowe and coworkers. Two basic elements of Ho's model are that regional recurrence rate must be evaluated using a nonhomogeneous method, such as the Weibull-Poisson method, and that this regional recurrence rate must be multiplied using a prior distribution in order to determine the probability of volcanic disruption of the candidate site. Uncertainty in estimates of the regional recurrence rate and uncertainty in the prior distribution results in uncertainty in disruption probabilities. Allin Cornell indicated in his talk that nonhomogeneous methods are quite useful in assessing hazard, but questioned the use of the Weibull-Poisson method. However, most discussion of Ho's model involved his use of the prior term. One prior term Ho used was π (0, 8/56), where π has a uniform random distribution. This means that the probability of volcanic disruption of the repository, given a volcanic event in the region, is somewhere between 0, the best case scenario, and 8/56, the worst case scenario. The ratio, 8/56, is the repository area divided by the area of a NE -trending structural zone extending from Lathrop Wells through the repository site. The "most likely" probability of disruption must lie somewhere between these bounds. Alternatively, we may know nothing geologically significant about this prior, so its distribution becomes π (0,1). In this case to probability of disruption of the repository is somewhere between 0 and the regional recurrence rate.

Similar disruption probabilities arise through the application of other spatially homogeneous Poisson models, primarily because of the need to define areas, within which volcanoes are expected to have a uniform random distribution. In the worst-case model presented by Crowe, the annual probability of disruption is about 7.5×10^{-8}. Although this value is substantially higher than worst case scenarios that have previously been generated using the homogeneous Poisson model [Crowe et al., 1982, for example, have a worst case model of 4.5×10^{-8}, and this was retained as a worst case value as recently as 1993 (Crowe et al., 1993)], it does not actually represent a worst case scenario using a homogeneous Poisson model. To illustrate this point, a simple polygon with an area, A, of about 200 km² can be arbitrarily defined to encompass Lathrop Wells, the Crater Flat alignment, and the repository site. Six cinder cones that are about 1 Ma or younger are found within this area. Using a recurrence rate of six cinder cones per million years, and a repository area of 6 km², the annual probability of volcanism occurring within the repository site is 1.8×10^{-7}. This illustrative example treats volcanoes as points, does not include terms for intrusion geometries, or attempts to account for possible indirect effects of volcanism, all of which would increase the annual probability of disruption. It is possible to double the area of the polygon to 400 km², and still have probabilities of disruption in excess of those currently proposed as worst case by the DOE ($P[\,a = 6\ \text{km}^2, A = 400\ \text{km}^2, \lambda = 6 \times 10^{-6}\ \text{v/yr}, t = 1\ \text{yr}] = 9 \times 10^{-8}$). These values are comparable to those proposed by Ho as worst-case probabilities, but are five to ten times greater than probabilities proposed by the CNWRA using spatially and temporally nonhomogeneous Poisson models and regional recurrence rates between four and ten volcanoes per million years.

The primary cause of the disparity between worst-case models, such as those proposed by Ho and exemplified by the calculations using $A \leq 400$ km², and spatially and temporally nonhomogeneous models we use at the CNWRA, lies in the use of area terms in Ho's, and in all spatially homogeneous Poisson, models. As the area, A, becomes small, the probability of disruption becomes implausibly large. Similarly, when A is selected to be very large, the probability of disruption approaches 0. This best-case scenario is equally implausible. The probability of disruption is strongly controlled by the selection of these area terms in Poisson models. This selection process is justified only if there is a strong mechanistic basis for the selection of areas. As in seismology, this basis is currently lacking in volcanology. Furthermore, at the present time there appears to be little hope of convergence among various groups about the geological or geophysical basis for the selection of different area terms. As a result, the DOE approach has been to develop a series of models based on a variety of area terms. Because effectively an infinite number of area terms could be used, it is not really possible to place objective constraints on this distribution of models. For example, it seems difficult to discount spatially homogeneous Poisson models based on worst case scenarios, such as Ho's model, if the selection of any area term is a subjective process.

The spatially and temporally nonhomogeneous Poisson models and Markov models in use at the CNWRA do not depend on an area term, A. In other words, the probability of volcanism at the repository site does not depend on the area over which a probability surface is calculated. This circumvents many difficulties inherent in the homogeneous Poisson solution. These models also take into account the fact that volcanoes in the YMR cluster in time and space. Allin Cornell, in his presentation about seismic models, concluded that spatially nonhomogeneous models are preferable, especially where data sets are limited. His position that nonhomogeneous models are preferable is closely reflected in CNWRA model development.

A point raised by several speakers is that nothing is lost by using nonhomogeneous methods. This can be proven for the CNWRA models, in which a nonparametric estimate of $\lambda_r\,(x,y)$ is found using varying numbers of near-neighbors:

$$\lambda_r(x,y) = \frac{m}{\sum_{i=1}^{m} u_i t_i} \tag{1}$$

where near-neighbor volcanoes are determined as the minimum, $u_i t_i$, t_i is the time elapsed since the formation of the i^{th} nearest-neighbor volcano, and u_i is the area of a circle whose radius is equal to the distance from point (x,y) to the i^{th} nearest-neighbor volcano, with $u_i \geq 1$ km^2.

The relationship between $\lambda_r(x,y)$ and homogeneous Poisson models, in which the recurrence rate is a constant over time and within a specified, large area, can be illustrated by describing the behavior of $\lambda_r(x,y)$ when a completely spatially and temporally random process is sampled. Modifying equation (1) slightly:

$$z_i = u_i t_i \tag{2}$$

$$\lambda_r(x,y) = \frac{m}{\sum_{i=1}^{m} z_i} = \frac{1}{E(Z)} \tag{3}$$

where $E(Z)$ is the expected value of z. If volcanoes form as the result of a completely spatially and temporally random process, $E(Z)$ can be thought of as the expected time and area within which n volcanoes will form, and z must have a gamma density distribution. Therefore the probability density function for z is:

$$f_z(z) = \frac{\lambda^n}{(n-1)!} z^{n-1} e^{-\lambda z} \tag{4}$$

where λ is the average recurrence rate within some specified area and over some specified time interval. The expected value of z, given this probability density function, becomes:

$$E(Z) = \frac{\lambda^n}{(n-1)!} \int_0^\infty z^n e^{-\lambda z} dz \tag{5}$$

$$E(Z) = \frac{\lambda^n}{(n-1)!} \frac{n!}{\lambda^n+1} = \frac{n}{\lambda} \tag{6}$$

In order to compare $E(Z)$ with the recurrence rate per unit area, as defined in equation 6, $E(Z)$ is evaluated for $n = 1$, that is, the expected time and area within which one new volcano will form. Combining equations 3 and 6,

$$\lambda_r(x,y) = \lambda \quad (7)$$

for completely spatially and temporally random distributions. This shows that the near-neighbor estimate of recurrence rate, $\lambda_r(x,y)$, becomes a constant equal to the average recurrence rate over some specified area if the underlying distribution is completely spatially and temporally random. The near-neighbor nonhomogeneous Poisson model is simply a general form of homogeneous Poisson models. A distinct advantage of near-neighbor nonhomogeneous Poisson models over homogeneous Poisson models is that regions within which λ is taken to be constant need not be defined.

Another topic that received considerable attention during the talks was the definition of a volcanic event. Smith pointed out that there are numerous ways to define an "event". For example, volcanic events may consist of individual cinder cones, eruptions, or magma batches. This definition is increasingly important because, as the work of Perry indicates, Lathrop Wells is likely polycyclic. This may mean that the next eruption in the region is most likely to occur at Lathrop Wells, rather than resulting in a new cone. The volcanological implications of polycyclic cinder cone volcanism are quite involved. The occurrence of polycyclic volcanism, for example, may increase the damage done to the repository, should a polycyclic center form within the repository block. However, there seems to be some uncertainty about the impact of polycyclic volcanism on probability models. Most models developed to date, including CNWRA models, use the distribution of cinder cones, at least for the Quaternary, as the basic data. These models determine the probability of a new cone forming, rather than the probability of eruptions occurring. Assuming polycyclic volcanism is frequent in the YMR, the probability of additional eruptions occurring is much higher than the probability of a new cone forming. The possibility of renewed eruptions at Lathrop Wells does not alter the probability of a new cone forming elsewhere as long as the probability model is based on the distribution of cinder cones.

One of stated goals of this meeting was to determine whether "enough is enough" with regard to development of volcano and seismic probability models. In other words, has there been sufficient investigation of these issues to make further model development unnecessary? It seems clear that volcanism probability models have not reached sufficient development in several respects:

- All speakers agreed that "load" terms associated with volcanism have not been considered in sufficient detail. These include indirect effects of volcanism and development of a probability distribution function (PDF) for volcano explosivity. Without incorporation of these load terms, probability models will not be complete.

- Uncertainty has not been accounted for to a sufficient degree. This uncertainty includes the precision of model parameters such as the regional recurrence rate and geochronological uncertainty, and in the accuracy of volcanological models.

- A full range of probability models has not yet been considered. Although many DOE investigators likely disagree with this statement, comments by some consultants to the NWTRB suggest that they may concur with the CNWRA position that it is important to consider a broad range of probability models.

Cornell addressed the use of a full range of models in his overview talk. He pointed out that (i) a full range of models is often retained, and (ii) a stochastic model should be as complicated as the scientific information requires. In light of these comments, the continuing development of probability models in volcanism is justified.

PENDING ACTIONS:

Dr. Pomeroy indicated that the ACNW may want to meet with Connor and Hill again to clarify the role of volcanism research in NRC activities. Such a meeting would likely be informal.

RECOMMENDATIONS:

The CNWRA should continue PVHA activities as planned. These activities include (i) continued development of a comprehensive range of spatially and temporally nonhomogeneous probability models, (ii) assessment of uncertainty in data sets used in these models, (iii) investigation of the consequences of volcanic activity. Finally, it should be noted that emphasis is shifting from questions about probability to questions about the impact of volcanism on PA models. It will be important to clearly place the probability of volcanism in a PA context, perhaps using a CCDF, in future meetings about PVHA.

PROBLEMS ENCOUNTERED: None Significant.

REFERENCES:

Connor, C.B., and B.E. Hill. 1993. Estimating the probability of volcanic disruption of the candidate Yucca Mountain repository using spatially and temporally nonhomogeneous poisson models. *Proceedings, American Nuclear Society Focus '93 Meeting*. La Grange Park, IL: American Nuclear Society.

Crowe, B.M., M.E. Johnson, and R.J. Beckman. 1982. Calculation of the probability of volcanic disruption of a high-level nuclear waste repository within southern Nevada, USA. *Radioactive Waste Management and the Nuclear Fuel Cycle* 3: 167-190.

Crowe, B.M., F.V. Perry, and G.A. Valentine. 1993. *Preliminary Draft: Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project*. Los Alamos National Laboratory Report: Los Alamos, NM: Los Alamos National Laboratory.

Smith, E.I., T.R. Feuerbach, and J.E. Faulds. 1990. The area of most recent volcanism near Yucca Mountain, Nevada: implications for volcanic risk assessment. *Proceedings of the First International High Level Radioactive Waste Management Conference*. La Grange Park, IL: American Nuclear Society: 81-90.

SIGNATURES:

Brittain E. Hill March 21, 1994

Brittain E. Hill Date
Research Scientist

Charles B. Connor March 22, 1994

Charles B. Connor Date
Senior Research Scientist

CONCURRENCE SIGNATURES AND DATA:

H Lawrence McKague 3/22/94

H. Lawrence McKague Date
Manager, Geologic Setting

3/23/94

Budhi Sagar Date
Technical Director

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
1100 Wilson Boulevard, Suite 910
Arlington, VA 22209

Agenda
Meeting of the Panel on Structural Geology & Geoengineering

Probabilistic Seismic and Volcanic Hazard Estimation

March 8-9, 1994

**Holiday Inn Crowne Plaza
San Francisco Airport
600 Airport Blvd.
Burlingame, CA 94010
Tel: (415) 340-8500
Fax: (415) 340-0599**

Tuesday, March 8, 1994

8:30 A.M.	**Opening remarks** Clarence Allen Nuclear Waste Technical Review Board (NWTRB)
8:40 A.M.	**Update on seismic investigations** John Whitney U.S. Geologic Survey (USGS)
9:15 A.M.	**Update on volcanic investigations** Frank Perry Los Alamos National Laboratory (LANL)
9:50 A.M.	**Integrated structural model of the Yucca Mountain region** Chris Fridrich, USGS
10:15 A.M.	**BREAK (15 minutes)**
10:30 A.M.	**General comments on probabilistic approaches** C. Allin Cornell Stanford University
11:15 A.M.	**Systems perspectives** Robert Budnitz Future Resources Associates
12:00 P.M.	**LUNCH**

Tuesday, March 8 - Continued

1:30 P.M.	**Department of Energy (DOE) topical report on seismic hazard** Richard Quittmayer Woodward-Clyde
2:10 P.M.	**Use of probabilistic seismic hazard assessment (PSHA) in the Yucca Mountain program** Tim Sullivan, DOE
2:30 P.M.	**PSHA case histories** Kevin Coppersmith Geomatrix
2:55 P.M.	**Comments by the Nuclear Regulatory Commission (NRC)** Keith McConnell, NRC
3:15 P.M.	**BREAK (15 minutes)**
3:30 P.M.	**Comments from the state of Nevada** Carl Johnson Agency for Nuclear Projects
3:50 P.M.	**How good is PSHA?** Steve Wesnouski University of Nevada — Reno
4:20 P.M.	**How good is PSHA?** Paul Pomeroy Advisory Committee on Nuclear Waste
4:50 P.M.	**General comments on PSHA** Keiiti Aki University of Southern California
5:30 P.M.	**Recess until Wednesday**

Wednesday, March 9, 1994

8:30 A.M.	**LANL report on volcanic hazard at Yucca Mountain** Bruce Crowe, LANL
9:30 A.M.	**Use of probabilistic volcanic hazard assessment (PVHA) in the Yucca Mountain program** Jeanne Nesbit, DOE
9:50 A.M.	**Comments by the NRC** Keith McConnell, NRC
10:10 A.M.	**BREAK (15 minutes)**
10:25 A.M.	**Models of volcanic hazard at Yucca Mountain** Charles Connor Center for Nuclear Waste Regulatory Analyses
11:00 A.M.	**Comments by the state of Nevada** Carl Johnson Agency for Nuclear Projects
11:20 A.M.	**Alternate geologic models: their significance with respect to the calculation of volcanic hazard at Yucca Mountain** Eugene Smith and C.H. Ho University of Nevada — Las Vegas
12:00 P.M.	**LUNCH**
1:15 P.M.	**Sensitivity studies on volcanic hazard at Yucca Mountain** Peter Wallmann Golder Associates
1:40 P.M.	**General comments on PVHA** Michael Sheridan State University of New York — Buffalo
2:30 P.M.	**Round-table discussion** Participants
4:00 P.M.	**Closing remarks** Clarence Allen, NWTRB

Update on Volcanism Investigations

Nuclear Waste Technical Review Board
Structural Geology and Geoengineering Panel

March 8-9, 1994
San Francisco, CA

Presented by:

Frank Perry
Los Alamos National Laboratory

Volcanism Studies

- **Characterization of Volcanic Features** (Frank Perry, PI)
  1. Geochronology studies
  2. Field Geologic studies
  3. Geochemistry studies
  4. Evolution of volcanic fields
  5. Volcanism drill holes

- **Probability of Magmatic Disruption of the Repository** (Bruce Crowe, PI)
  1. Location and timing of volcanic events
  2. Structural controls of basaltic volcanism
  3. Presence of magma bodies
  4. Probability calculations

- **Physical Processes and Effects of Magmatism** (Greg Valentine, PI)
  1. Eruptive effects
  2. Subsurface effects
  3. Dynamics of basaltic volcanism

Recent progress:

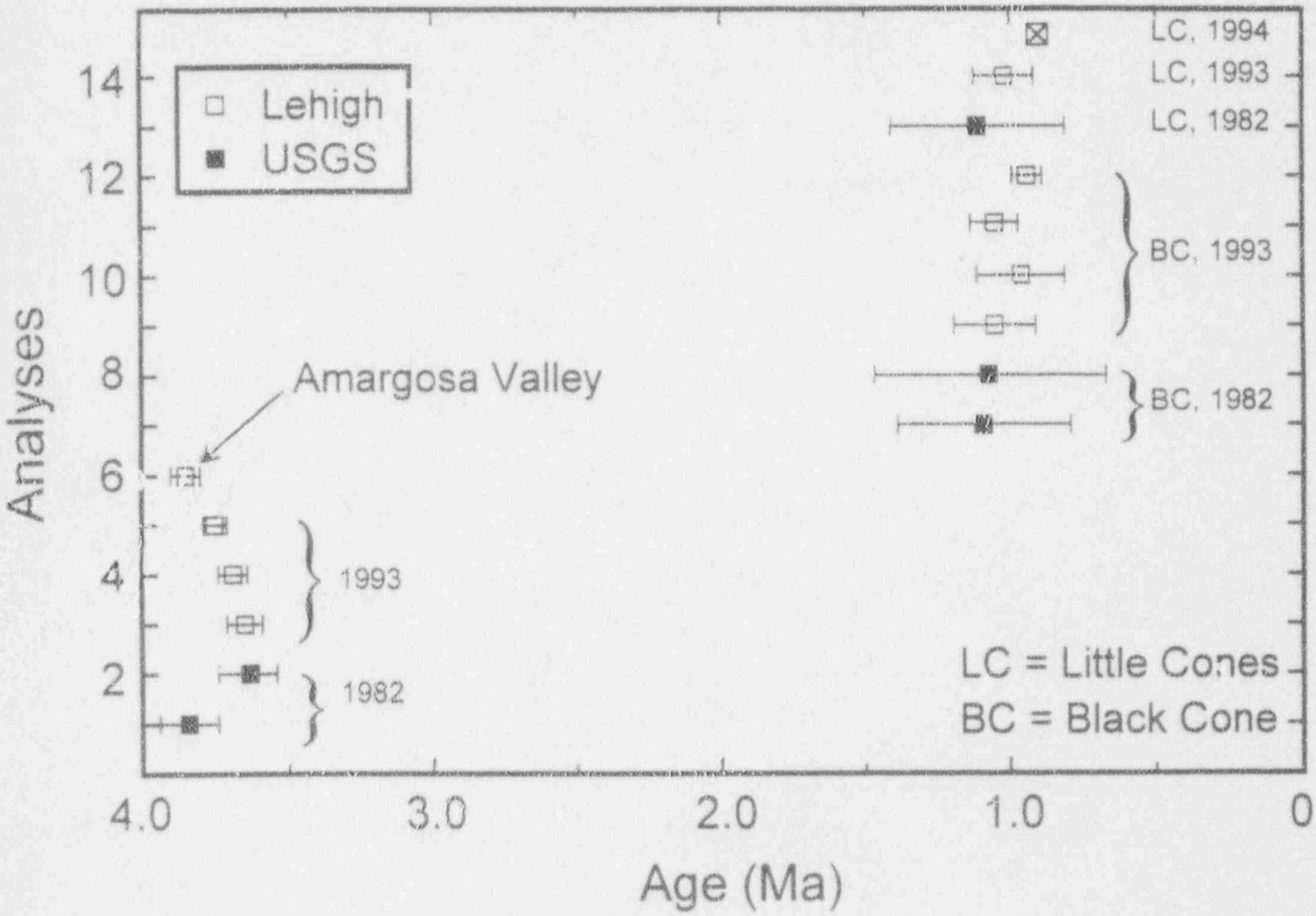
- **Regional geochronology well under way**
  1. Lehigh University and NM Bureau of Mines under contract for $^{40}Ar/^{39}Ar$
  2. 50% of post-Miocene centers and 1 aeromagnetic anomaly have been dated

- **Geochemical, geochronologic sampling continuing for rest of CFVZ, Buckboard Mesa**

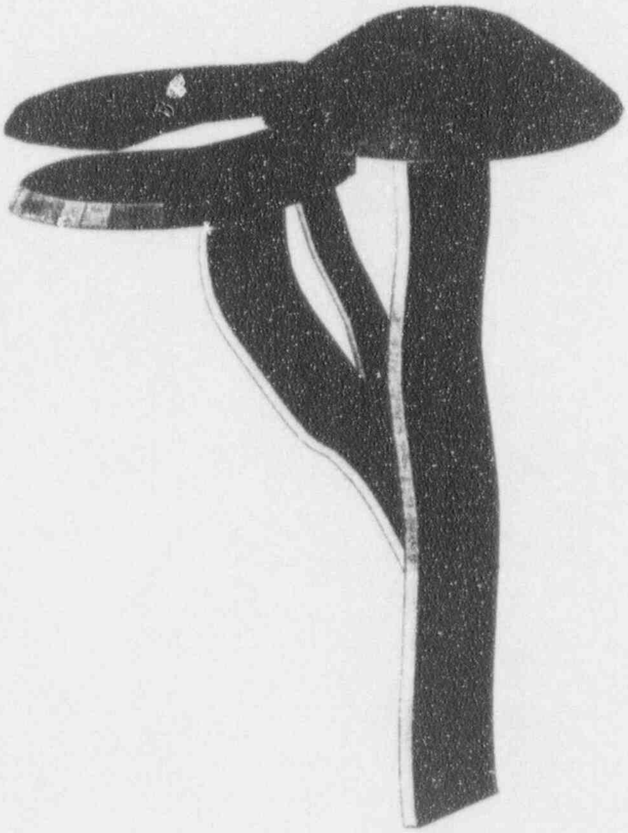
- **Work at Lathrop Wells in wrap-up phase**
  1. Four-episode polycyclic model established
  2. Minimum of 6-8 magma batches indicated by geochemistry
  3. Tuff sanidine separates being used to refine chronology

- **Magmatic effects studies underway**
  1. Field studies of analog centers at Paiute Ridge and Alkali Buttes complete
  2. Sensitivity studies begun for modeling liquid and vapor flow in the unsaturated zone in response to magmatic intrusion

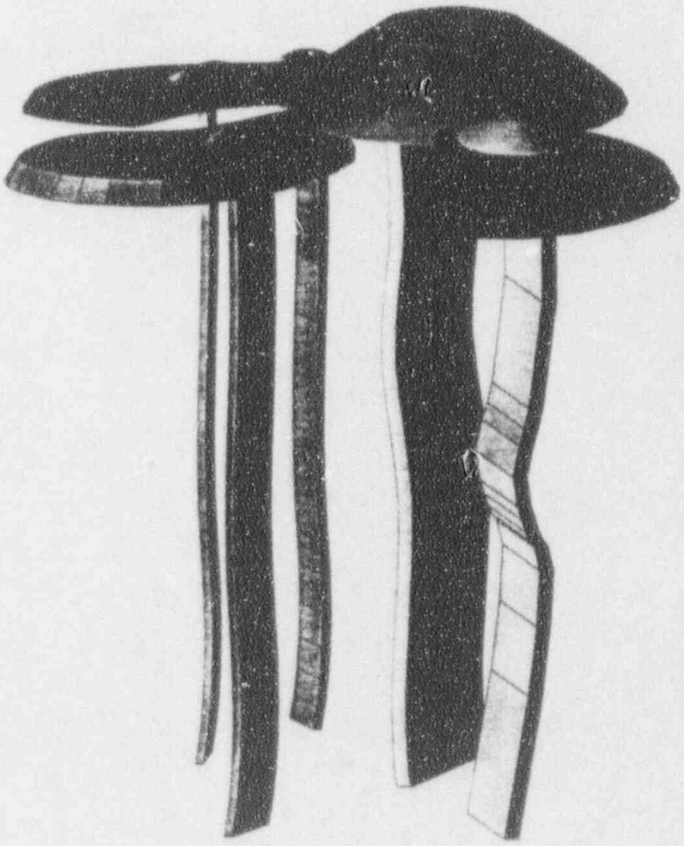
Crater Flat ages, comparison of Vaniman et al., 1982 dates (USGS), 1993 Lehigh dates, 1994 NMBM sanidine date



Monogenetic



Polycyclic

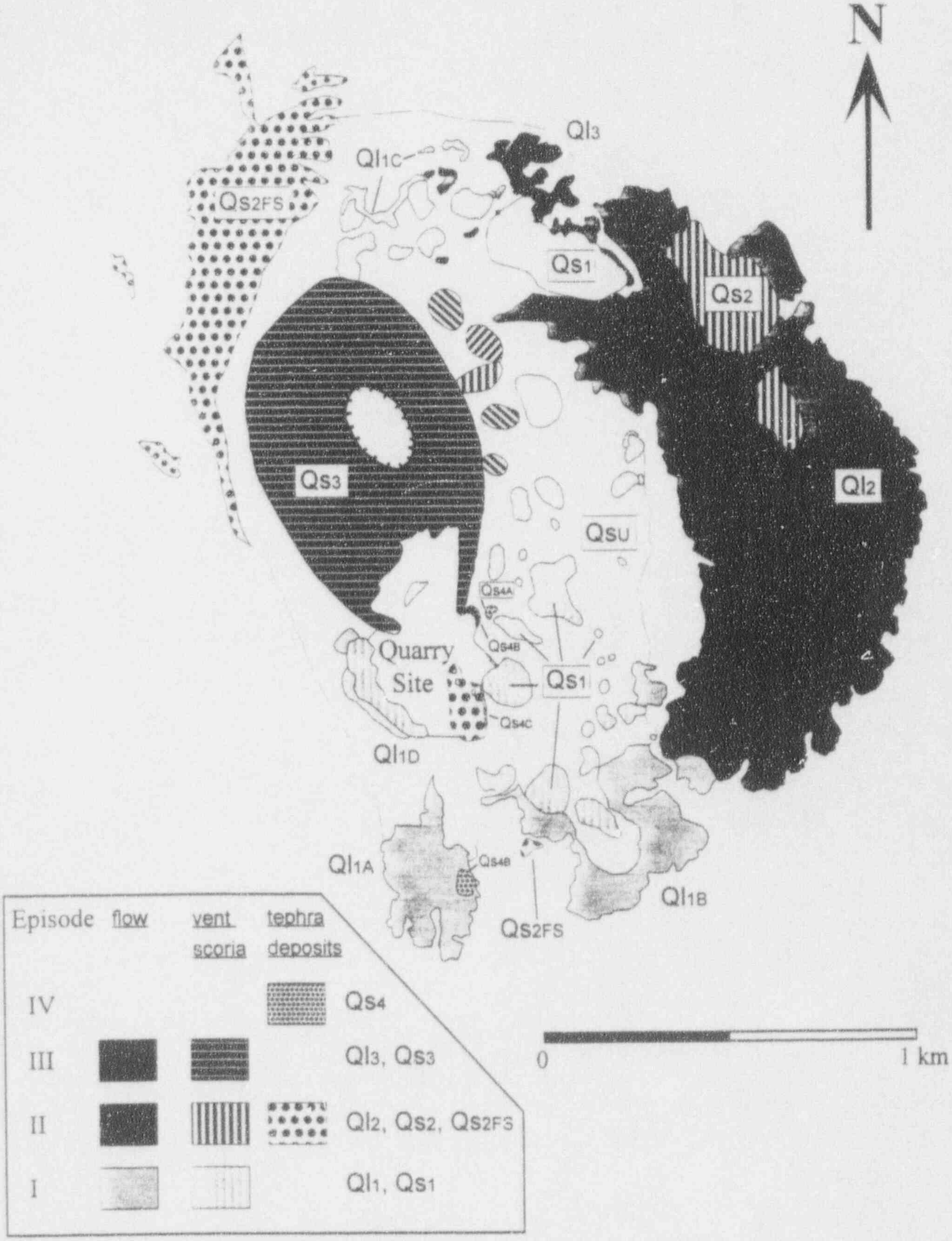


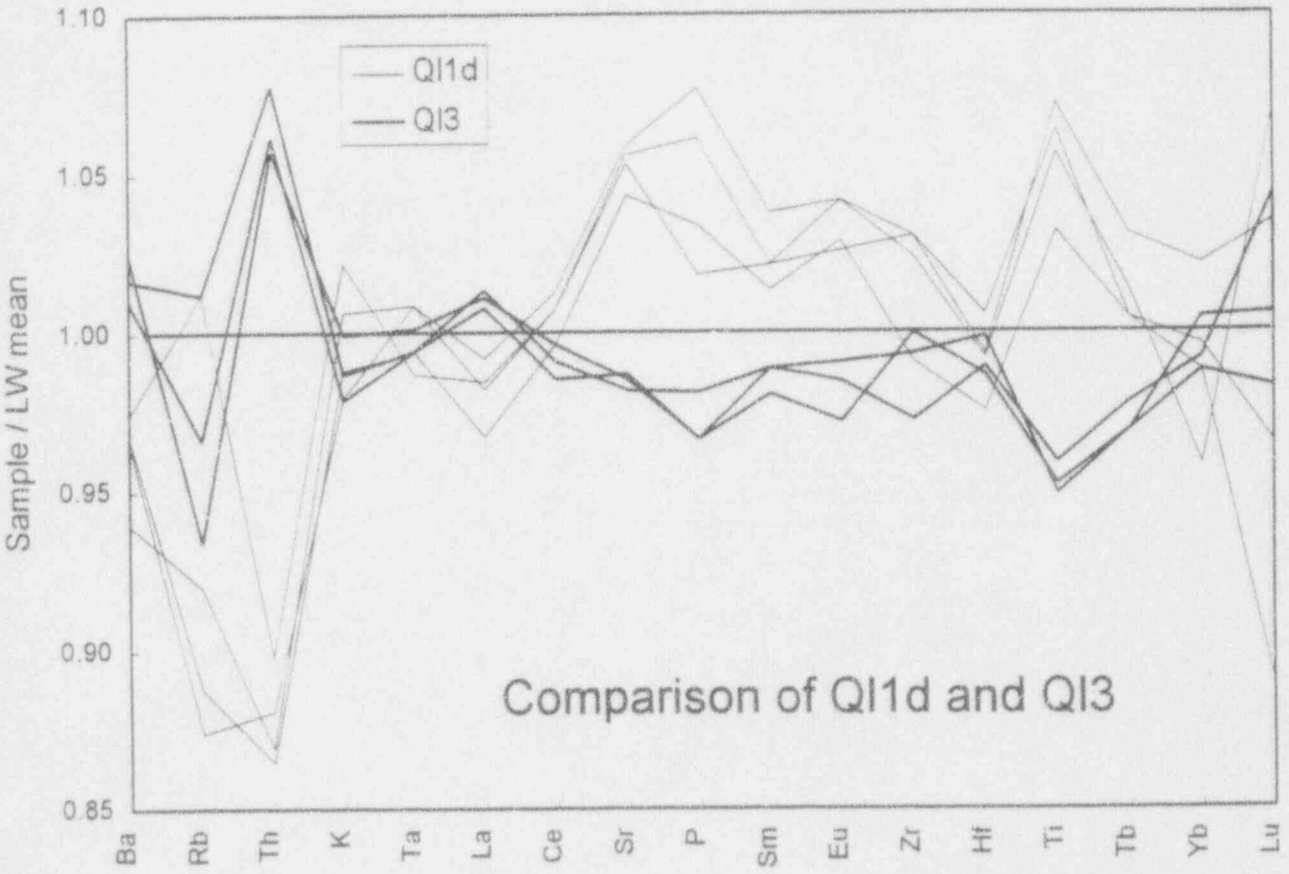
Polycyclic Volcanism at Lathrop Wells

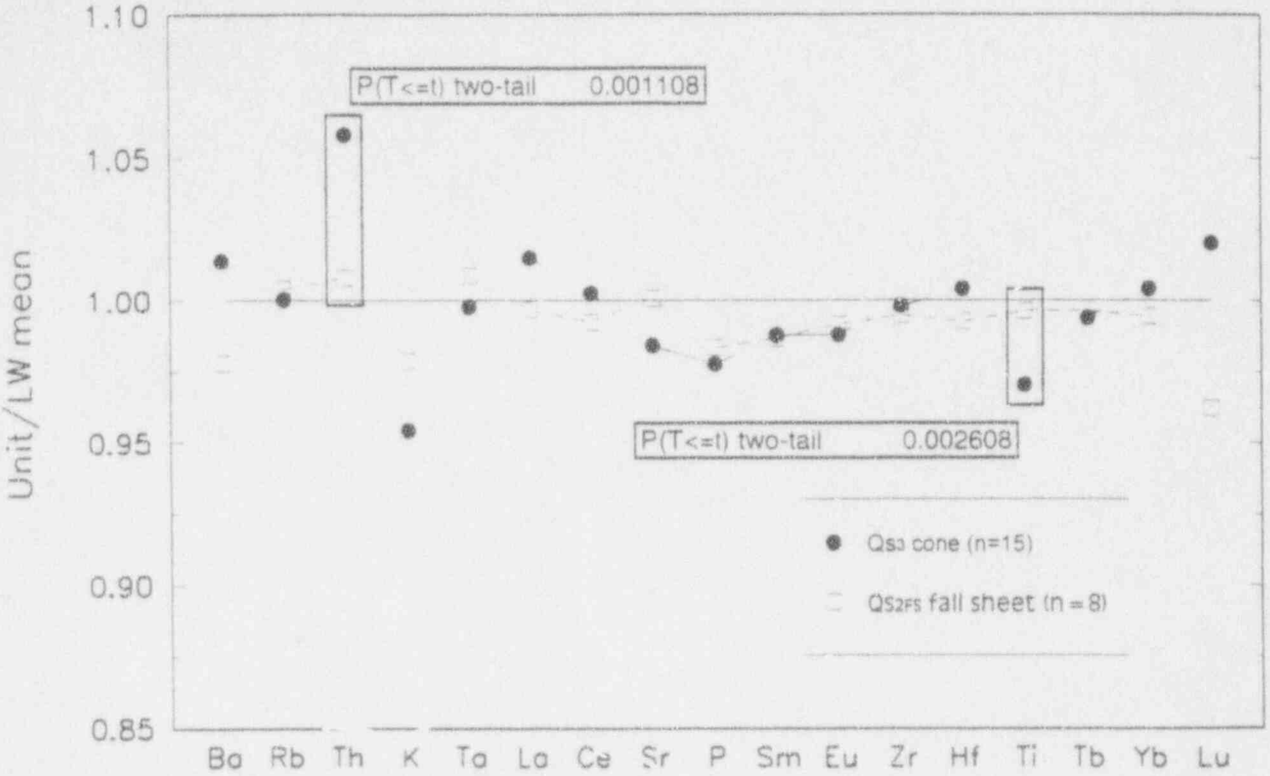
- Previously unrecognized class of volcano
- Field and geochronology studies indicate multiple, time-separate eruptive episodes
- Geochemistry indicates multiple, independent magma batches
- Holocene eruptions indicate center is probably still within a polycyclic period
- **Implications for volcanic risk assessment**

  1. Effects studies must consider multiple intrusive episodes
  2. Provides constraint on location of future volcanism (monogenetic volcanism: future eruption forms new volcano at unconstrained location)
  3. Disruption probability calculations that assume random distribution within event zones are conservative
  4. ***The most likely volcanic event in the Yucca Mountain region during the next 10,000 years is another eruption at the Lathrop Wells center***

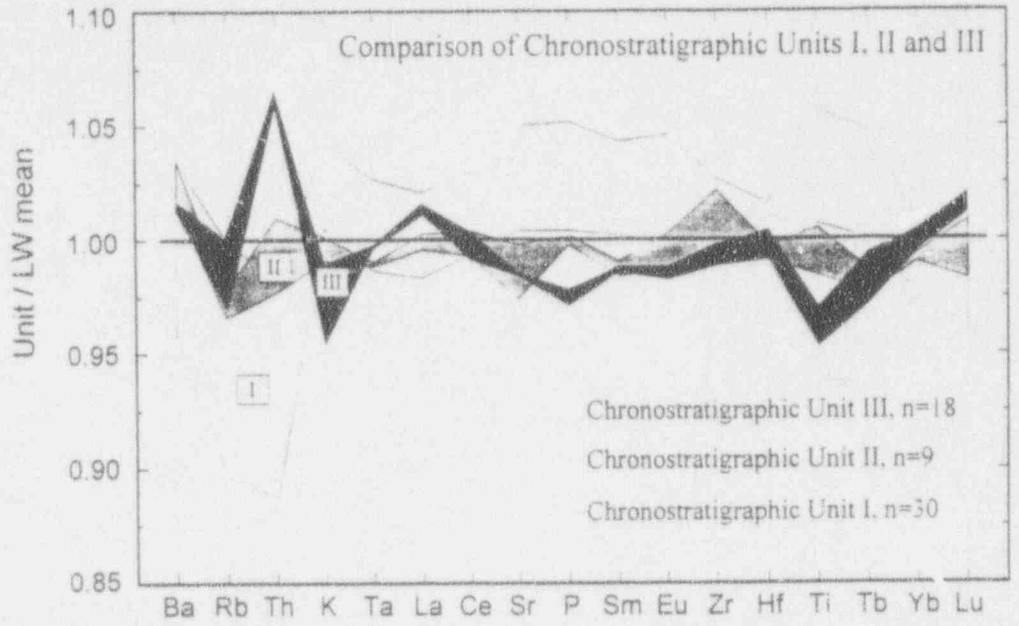
Lathrop Wells Volcanic Center

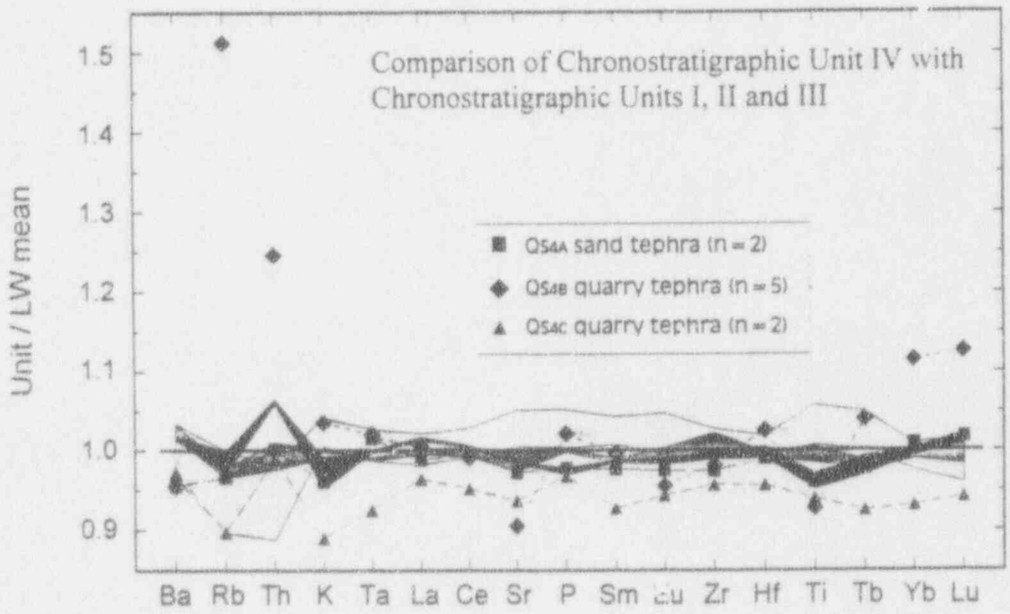


1.10
1.05
1.00
0.95
0.90
0.85
Sample / LW mean
QI1d
QI3
Comparison of QI1d and QI3
Ba
Rb
Th
K
Ta
La
Ce
Sr
P
Sm
Eu
Zr
Hf
Ti
Tb
Yb
Lu

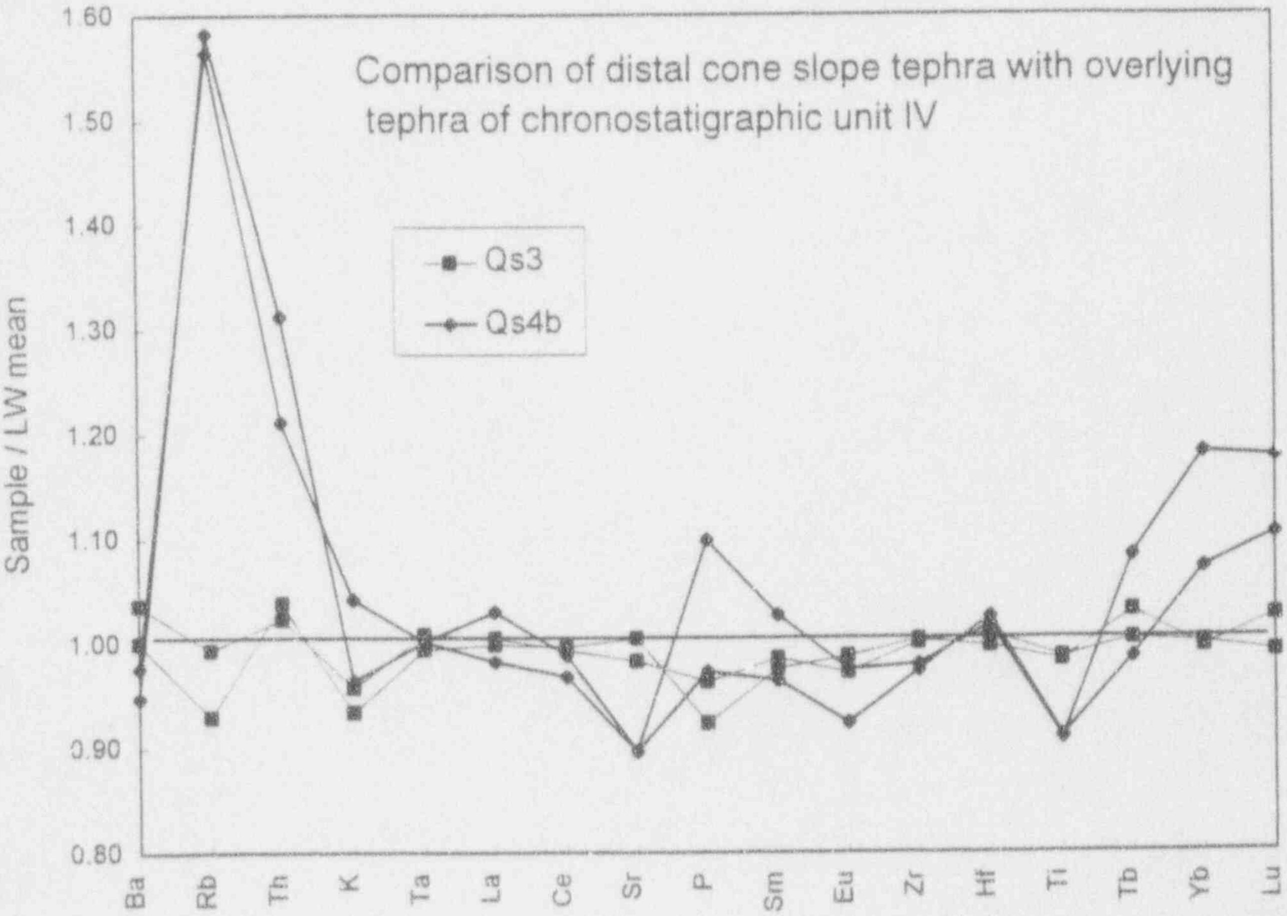

1.10
1.05
1.00
0.95
0.90
0.85
Unit/LW mean
P(T<=t) two-tail 0.001108
P(T<=t) two-tail 0.002608
● Qs3 cone (n=15)
Qs2FS fall sheet (n = 8)
Ba
Rb
Th
K
Ta
La
Ce
Sr
P
Sm
Eu
Zr
Hf
Ti
Tb
Yb
Lu

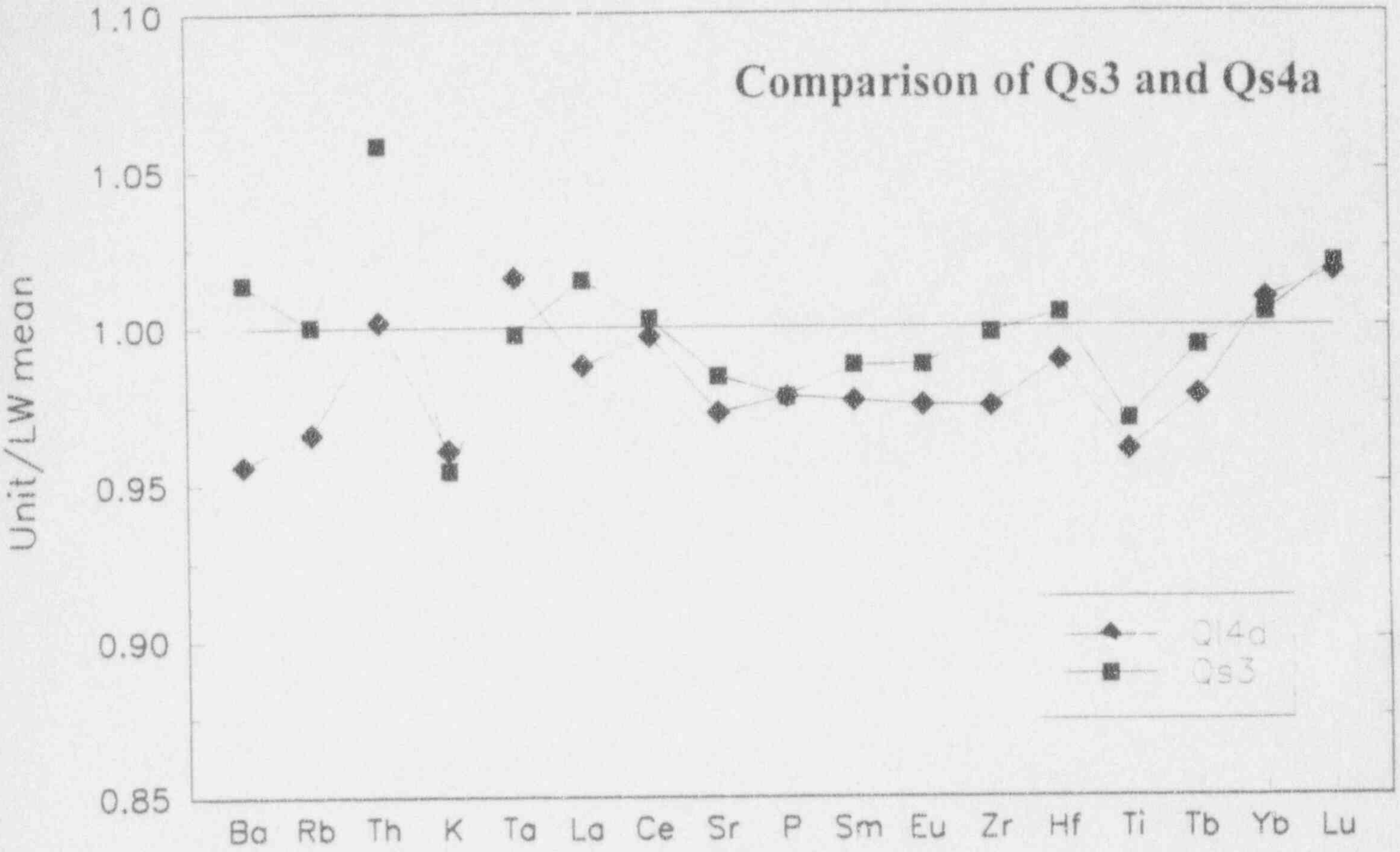
Geochemical Variations at the Lathrop Wells Volcanic Center



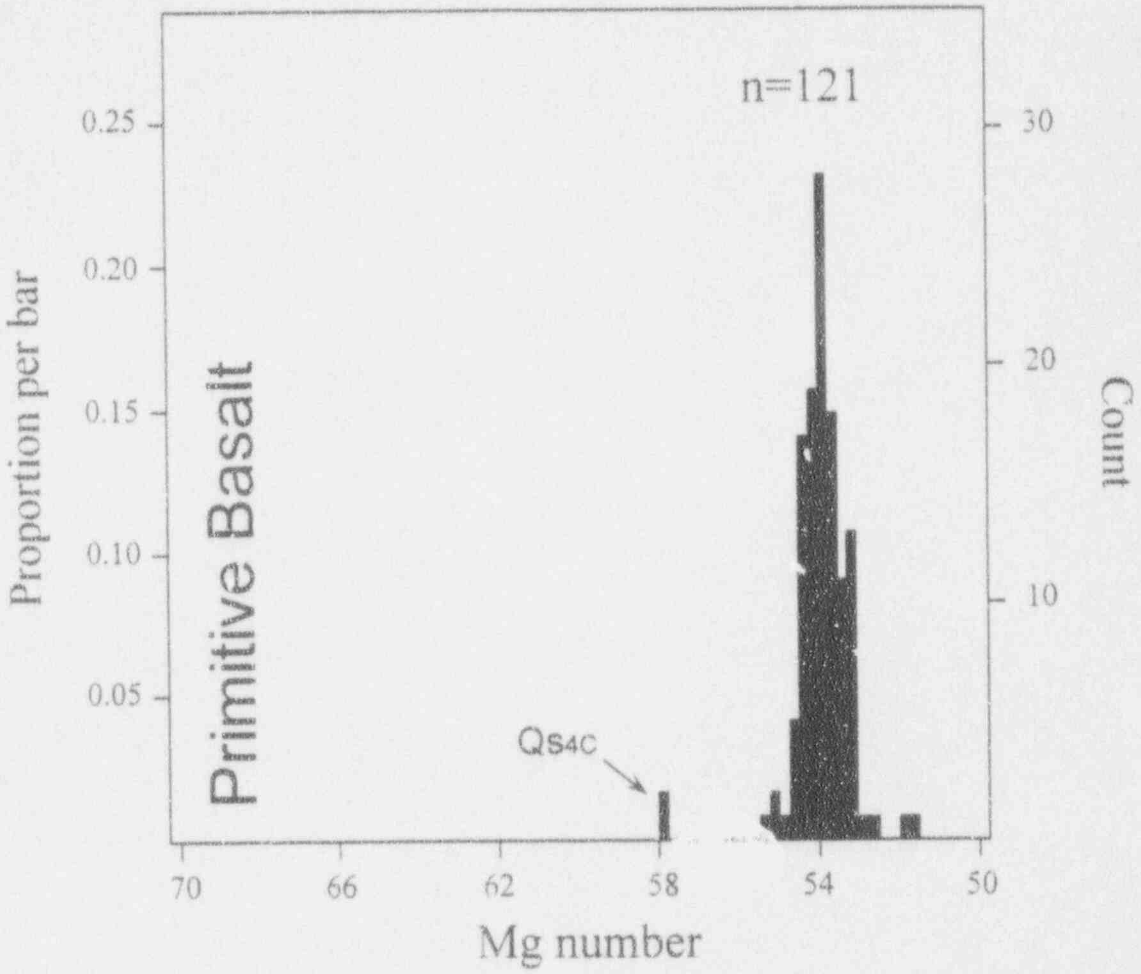


Four field photographs showing evidence of Holocene eruptions at the Lathrop Wells volcanic center.

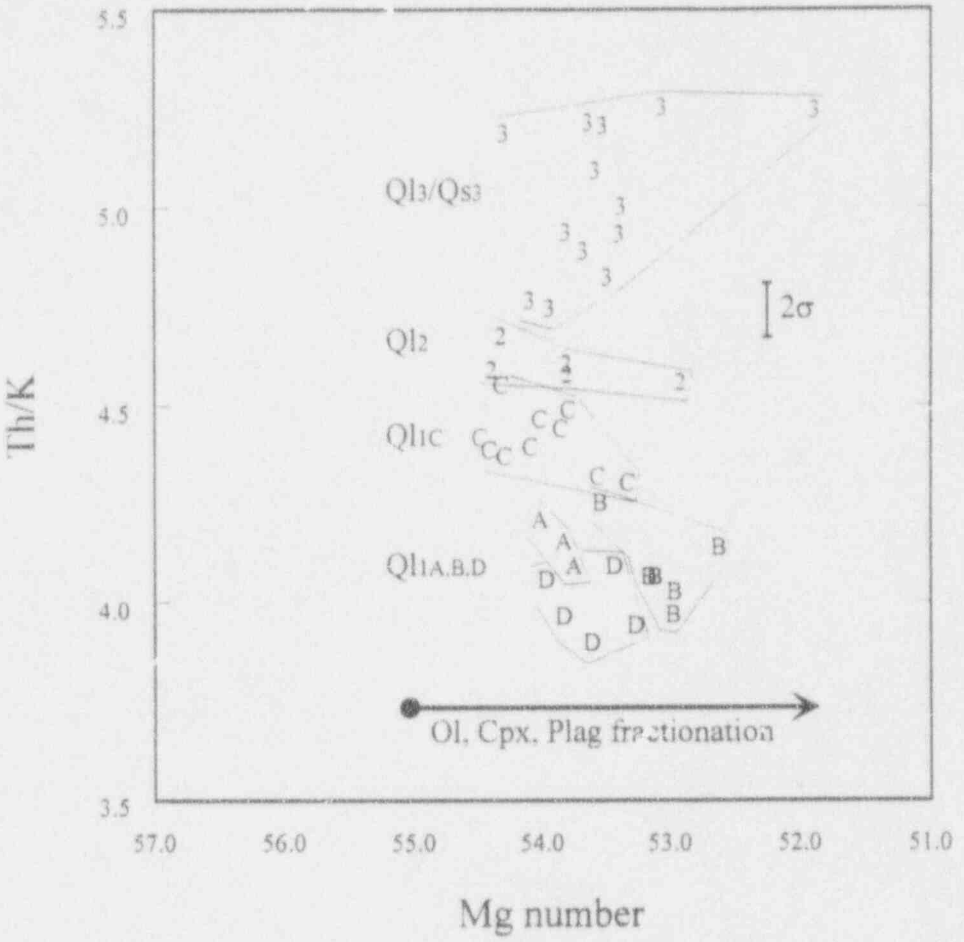

Comparison of distal cone slope tephra with overlying tephra of chronostatigraphic unit IV
Qs3
Qs4b
Sample / LW mean
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
Ba
Rb
Th
K
Ta
La
Ce
Sr
P
Sm
Eu
Zr
Hf
Ti
Tb
Yb
Lu

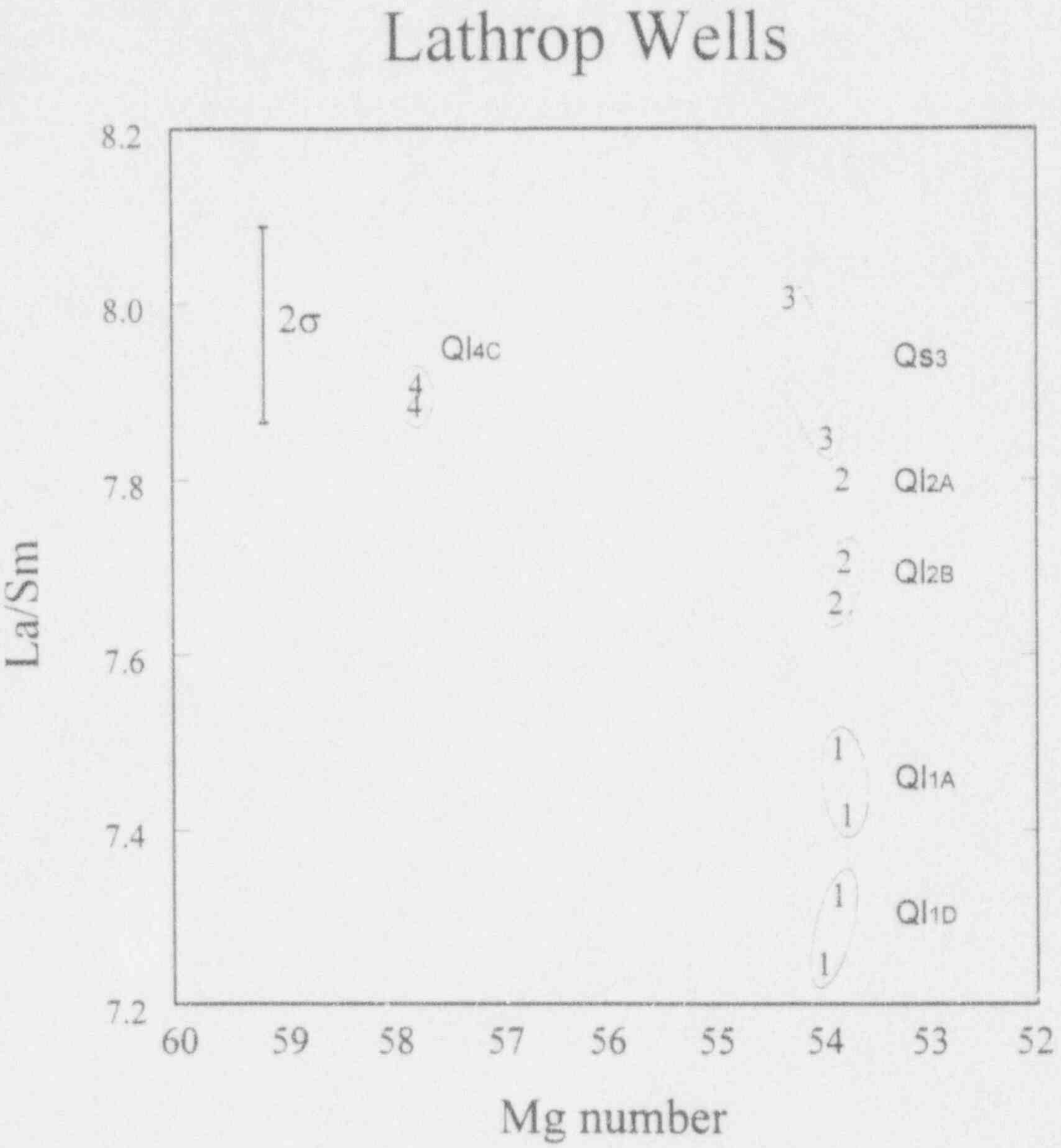

Comparison of Qs3 and Qs4a
Unit/LW mean
1.10
1.05
1.00
0.95
0.90
0.85
Ba
Rb
Th
K
Ta
La
Ce
Sr
P
Sm
Eu
Zr
Hf
Ti
Tb
Yb
Lu
Ql4a
Qs3

Lathrop Wells



Lathrop Wells




Lathrop Wells
8.2
8.0
7.8
7.6
7.4
7.2
La/Sm
2σ
Ql4C
4
4
3
Qs3
3
2
Ql2A
2
Ql2B
2
1
Ql1A
1
1
Ql1D
1
60
59
58
57
56
55
54
53
52
Mg number

FEAR model to calculate Mg# and trace-element composition of a basaltic magma

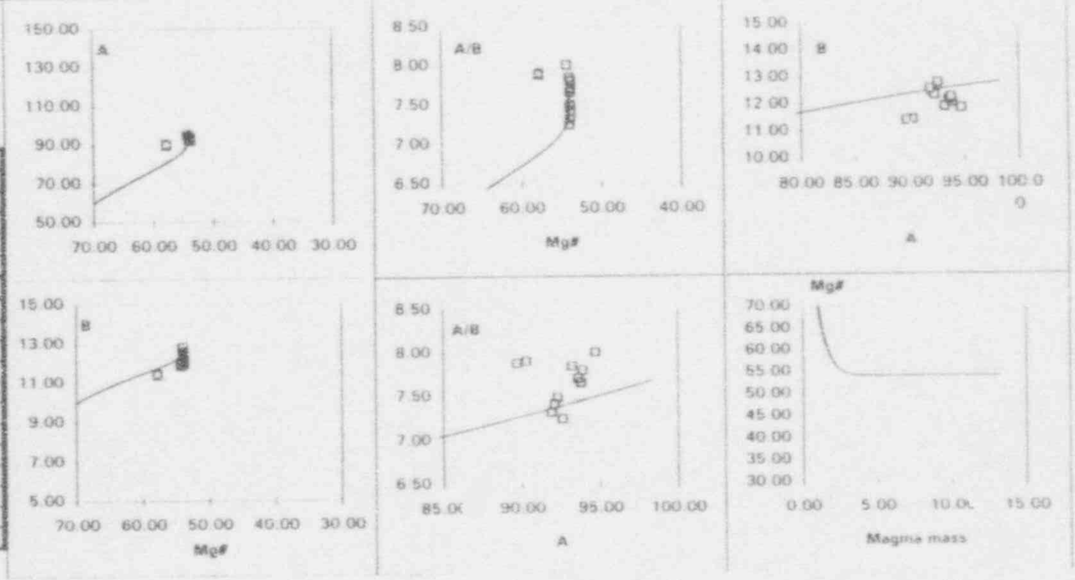
(Olivine and Clinopyroxene (Di-Hd) fractionation)

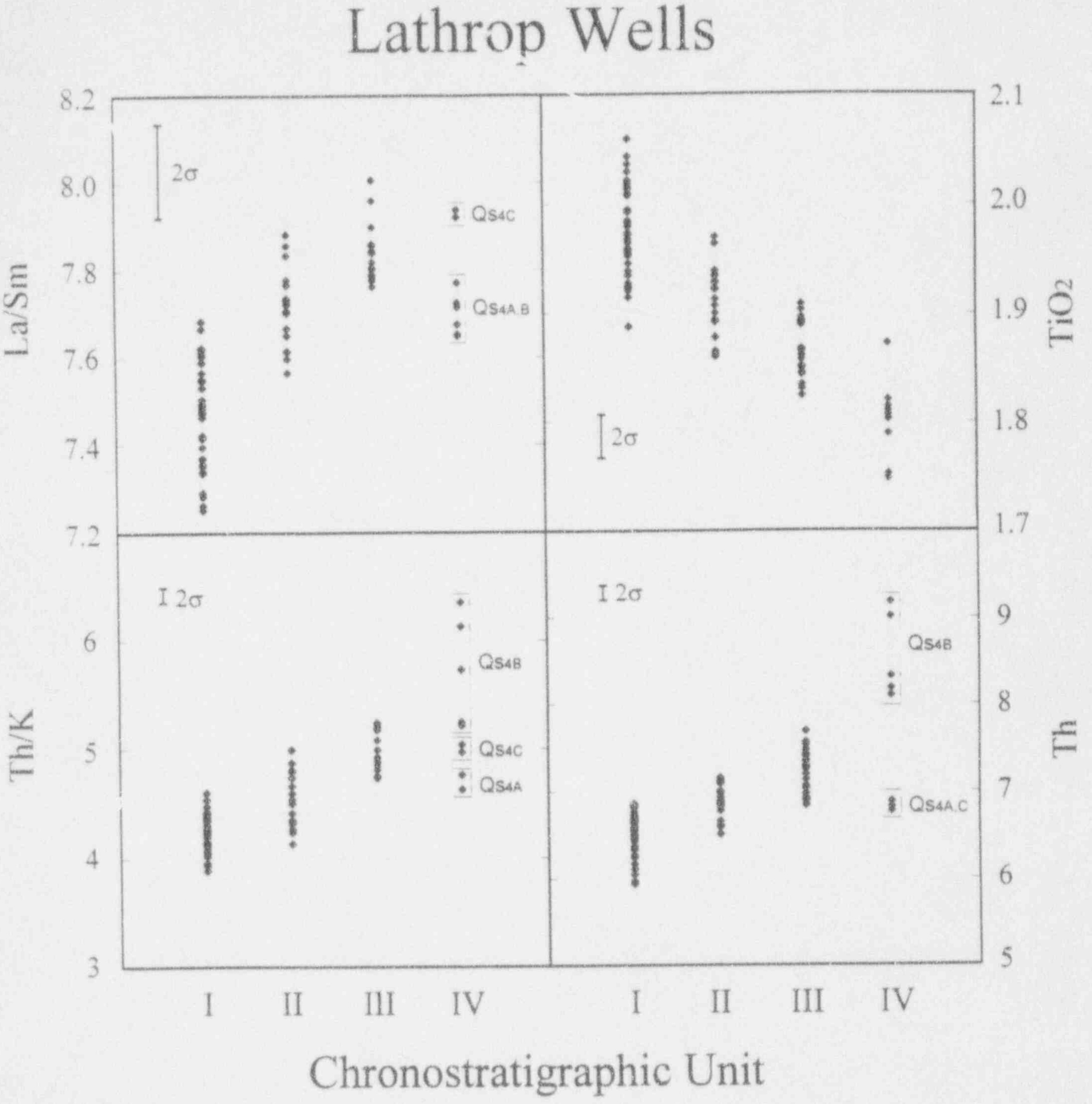
Element A is:	La	Element B is:	Sm
Assimilation rate	0.00		
Recharge rate	7.22		
Eruption rate	0.00		
Initial mass of magma	1.00		
crystallization increment	0.0050		
Mg# of magma	70.00		
MgO content of magma	14.00		
Mg# of recharging magma	70.00		
MgO content of recharging magma	14.00		
Mg# of assimilate	2.00		
FeO content of assimilate	2.00		
Conc. of element A in magma	60.00		
Conc. of element B in magma	10.00		
Conc. of element A in recharge	60.00		
Conc. of element B in recharge	10.00		
Conc. of element A in assimilate	60.00		
Conc. of element B in assimilate	10.00		
Prop. of Ol in xl assemblage	0.25		
Prop. of Cpx in xl assemblage	0.75		
Fe-Mg Kd for Olivine	0.32		
Fe-Mg Kd for Cpx	0.25		
Fe-Mg Kd for bulk	0.27		
D (A) for Olivine	0.0001		
D (B) for Olivine	0.0015		
D (A) for Cpx	0.1346	Bulk D (A)	0.1010
D (B) for Cpx	0.6693	Bulk D (B)	0.5024

	Magma	Recharge	Assim
FeO	10.70	10.70	2.00
MgO	14.00	14.00	0.02
Fe	0.1489	0.1489	0.0278
Mg	0.3474	0.3474	0.0006
Mg#	70.00	70.00	2.00

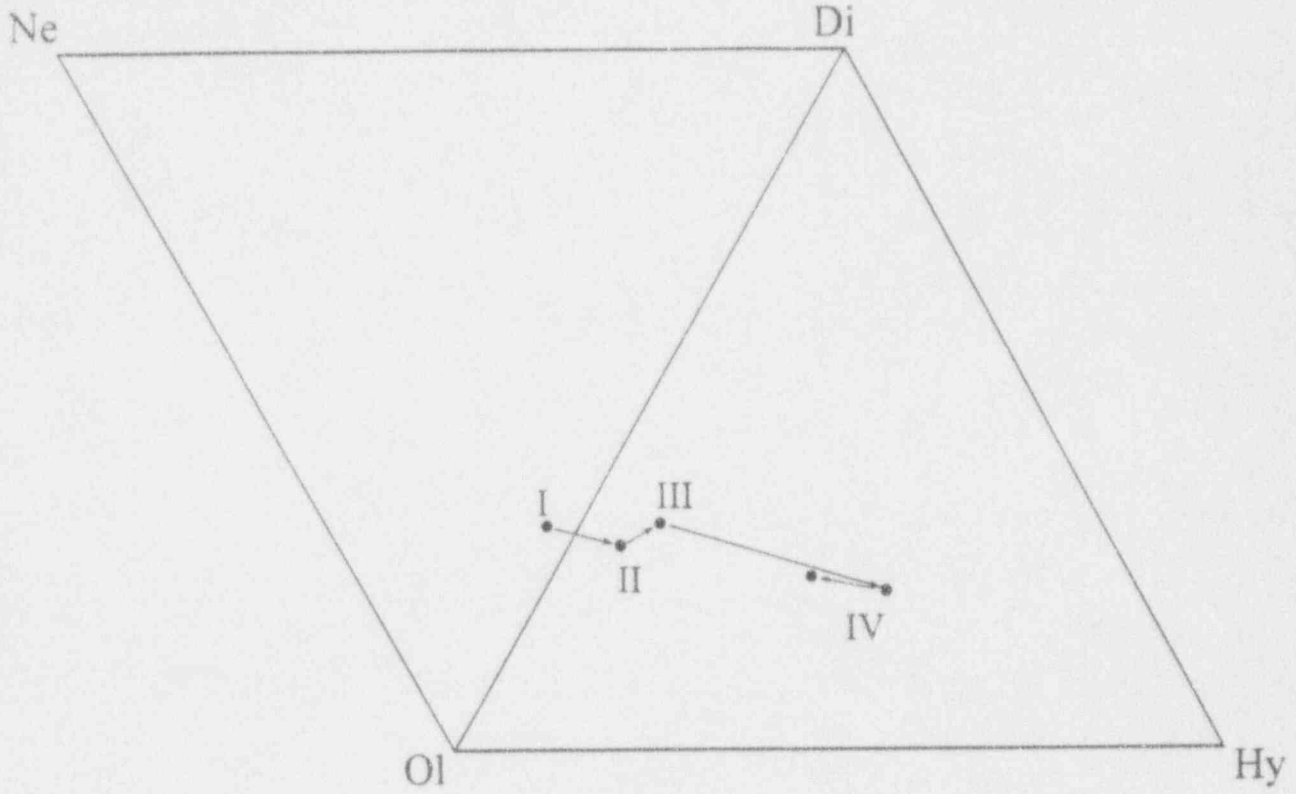
Partition coefficients

	Ol	Cpx
La	0.0001	0.1346
Nd	0.0002	0.4874
Sm	0.0015	0.6693
Pb	0.0010	0.0500
Rb	0.0006	0.0104
Th	0.0009	0.0467
Sr	0.0010	0.1199
Ni	21.1200	4.1153
Co	1.2542	1.7446
Sc	0.2457	6.3553
K	0.0006	0.0104

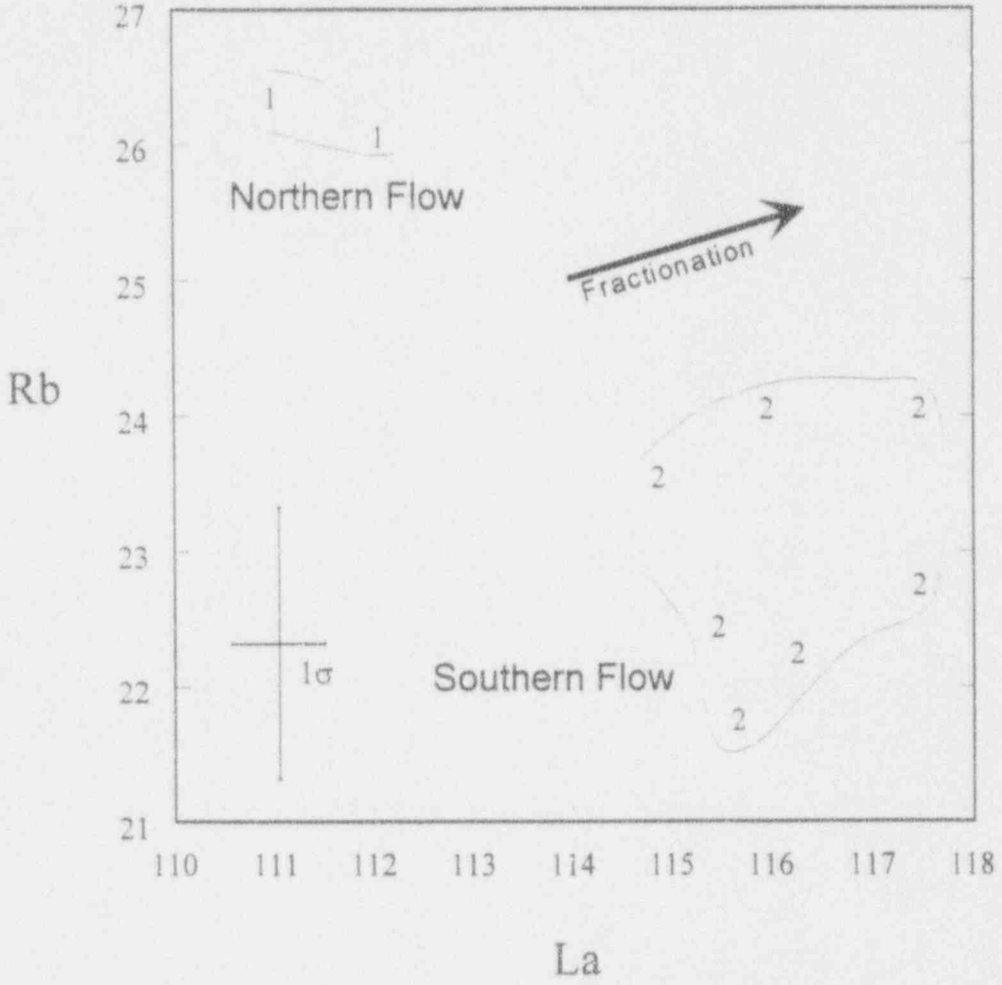



Lathrop Wells
La/Sm
8.2
8.0
7.8
7.6
7.4
7.2
2σ
Qs4C
Qs4A,B
TiO2
2.1
2.0
1.9
1.8
1.7
2σ
Th/K
6
5
4
3
I 2σ
Qs4B
Qs4C
Qs4A
Th
9
8
7
6
5
I 2σ
Qs4B
Qs4A,C
I
II
III
IV
I
II
III
IV
Chronostratigraphic Unit

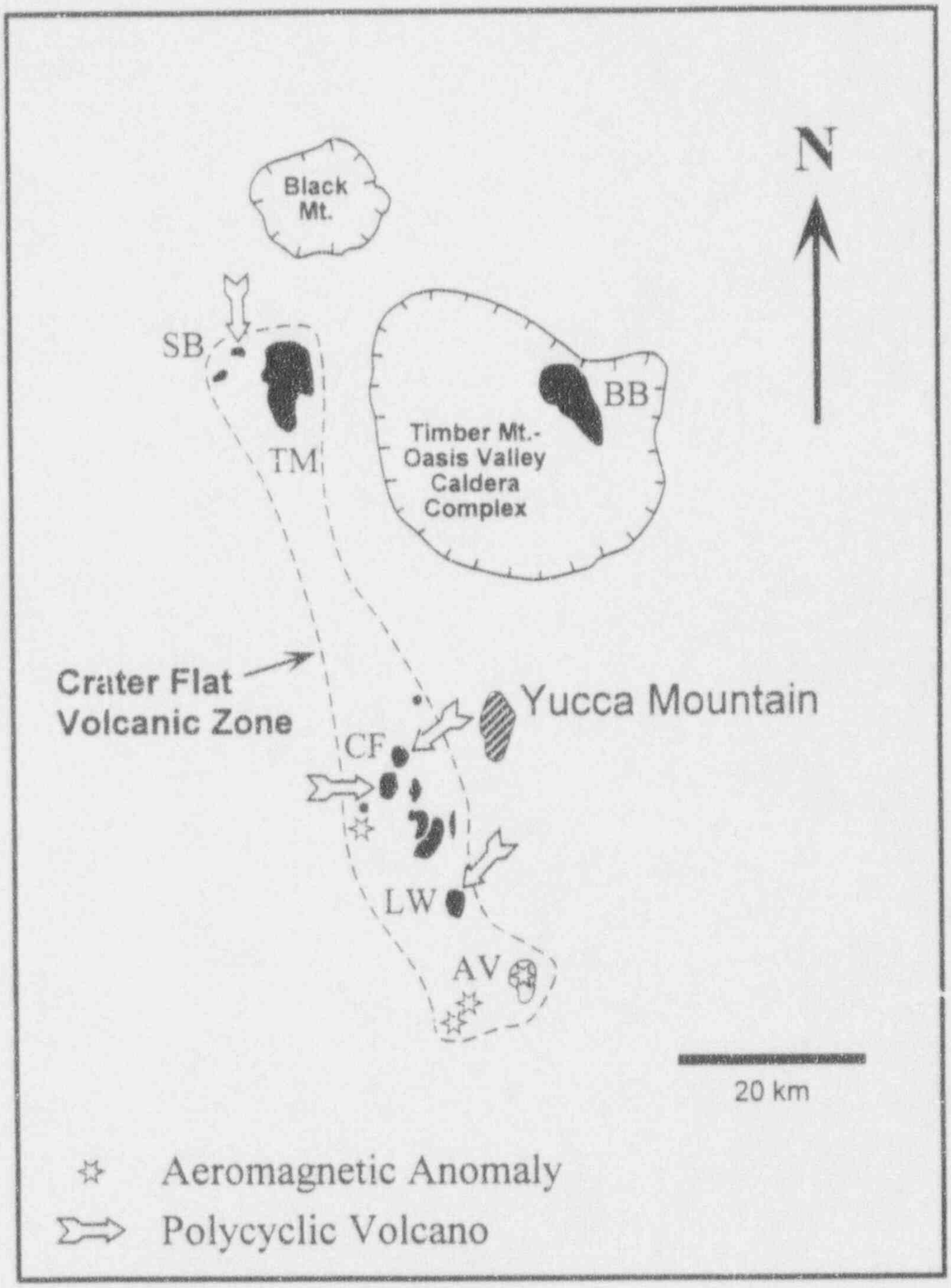
Lathrop Wells normative compositions



Black Cone


Rb
27
26
25
24
23
22
21
La
110
111
112
113
114
115
116
117
118
Northern Flow
Fractionation
Southern Flow
1σ
1
2

Post-Miocene Volcanic Centers of the Yucca Mountain Region



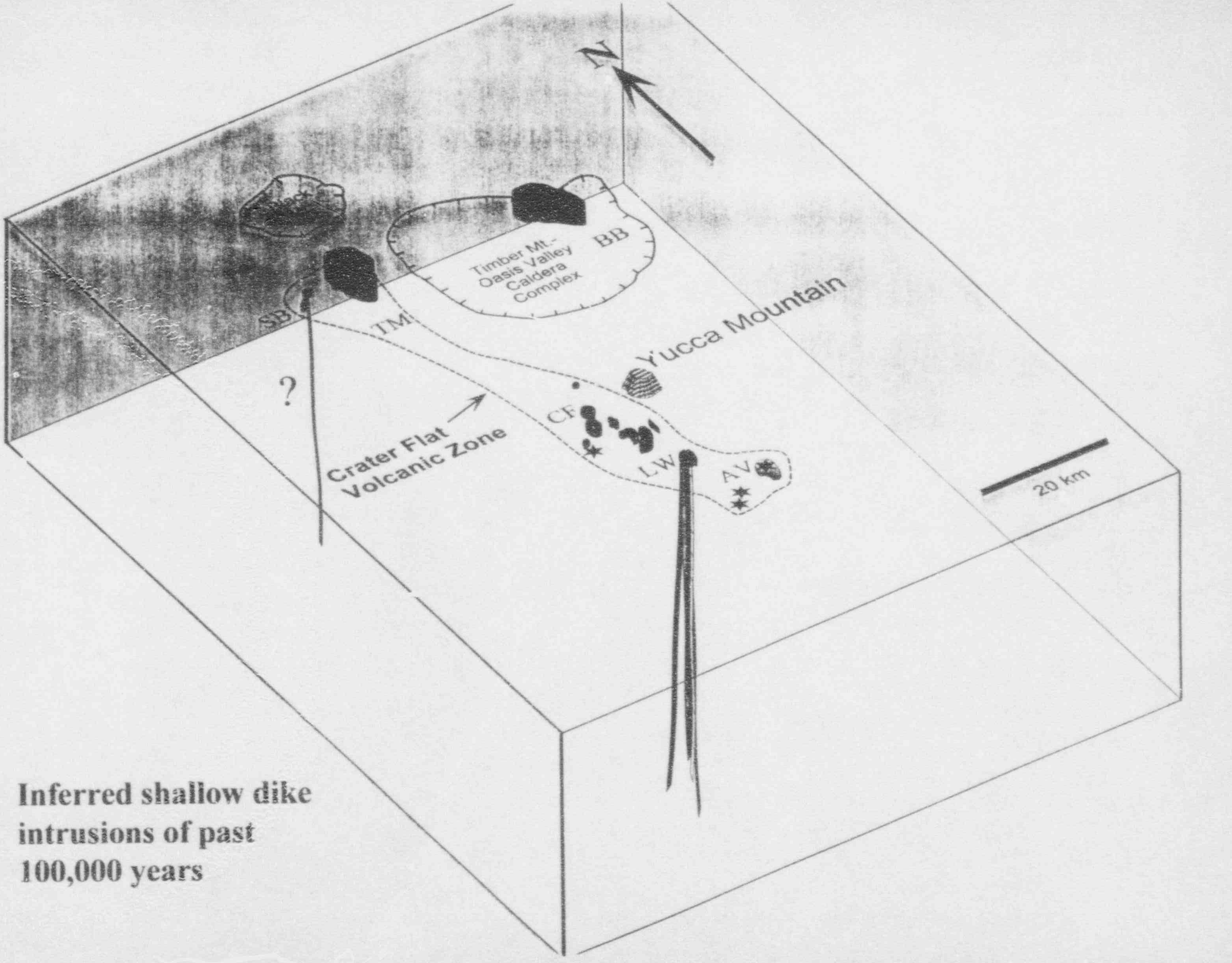
Summary of Quaternary polycyclic activity

- 1 Ma Crater Flat Centers
  - distributed polycyclic center?
  - ≥ 7 magma batches

- 0.3 Ma Sleeping Butte Centers
  - distributed polycyclic center?
  - chronology?
  - ≥ 2 magma batches

- ≤ 0.1 Ma Lathrop Wells Center
  - localized polycyclic center
  - ≥ 6 magma batches

The ~100,000 year pattern of repeated volcanism at Lathrop Wells, which has been maintained into the Holocene, indicates that the next eruption in the region will probably again be at Lathrop Wells.



Inferred shallow dike
intrusions of past
100,000 years

Necessary future work:

- **Evolution of Crater Flat volcanic zone**
    1. Geologic/geochemical model of magma production patterns through time
        - -is magmatism waxing or waning?
    2. Changes in volatile content, fractionation depth
        - -ascent mechanics, eruption styles
    3. Provides physical framework for probability models and effects studies

- **Magmatic effects studies**

- **Refine mechanism/duration of polycyclic volcanism**

- **Wrap up geochronology**

- **Correlate ashes in fault trenches to dated eruptive episodes at Lathrop Wells**

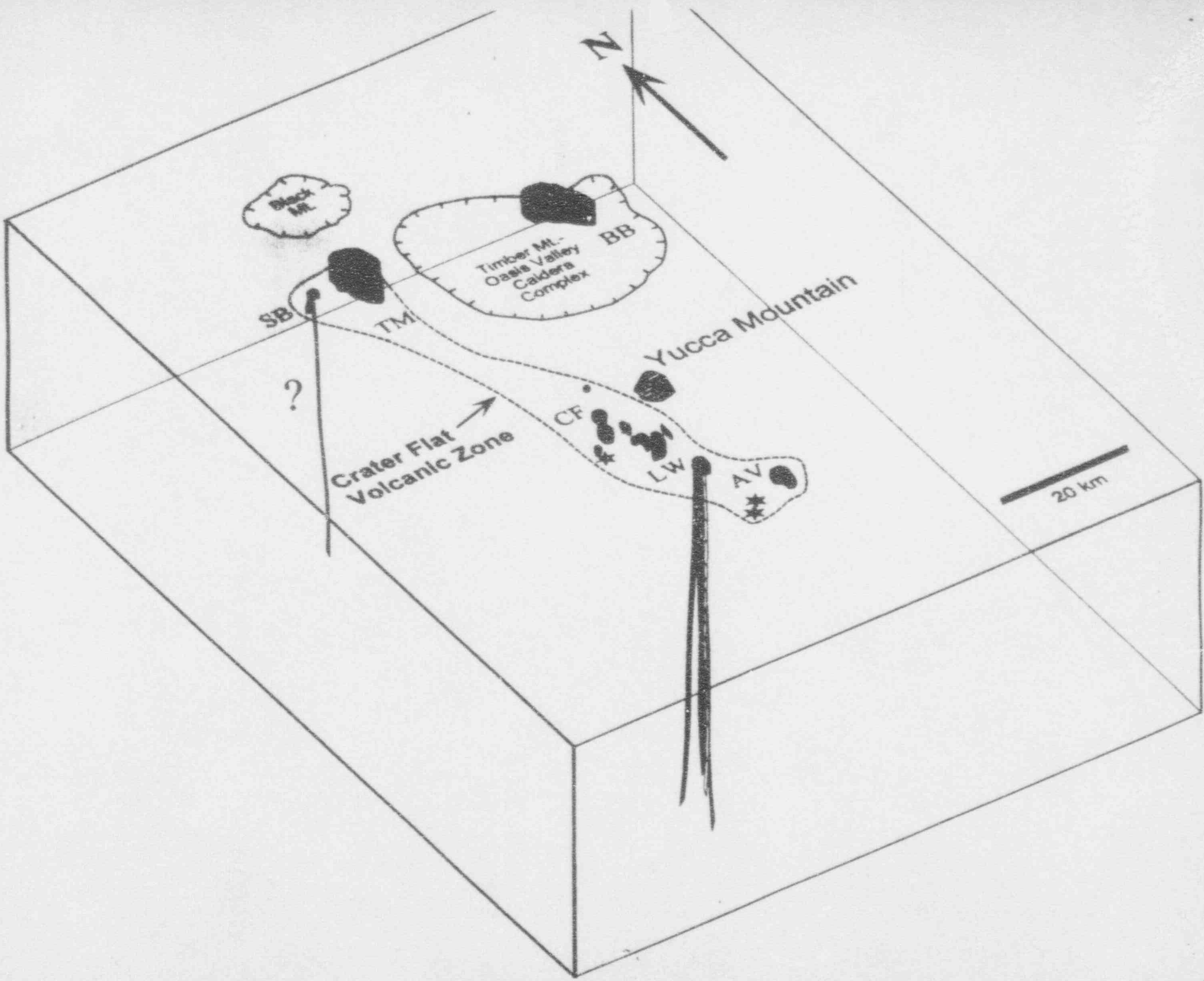
- **Volcanism drill holes**
    1. determine age and nature (intrusion/extrusion) of aeromagnetic anomalies

- **Revised probability studies**
    1. Probability of polycyclic volcanism

March 9, 1994
San Francisco, CA

Bruce Crowe
Los Alamos National Laboratory

Probabilistic Volcanic Risk Assessment


N
Black Mt.
Timber Mt.-
Oasis Valley
Caldera
Complex
BB
SB
TM
Yucca Mountain
?
CF
Crater Flat
Volcanic Zone
LW
AV
20 km

Conditional Probability Model
Magmatic Disruption

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

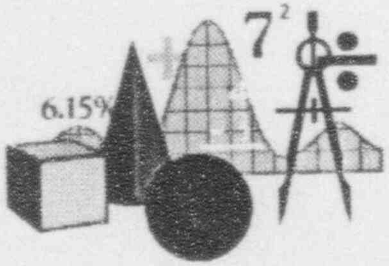
where

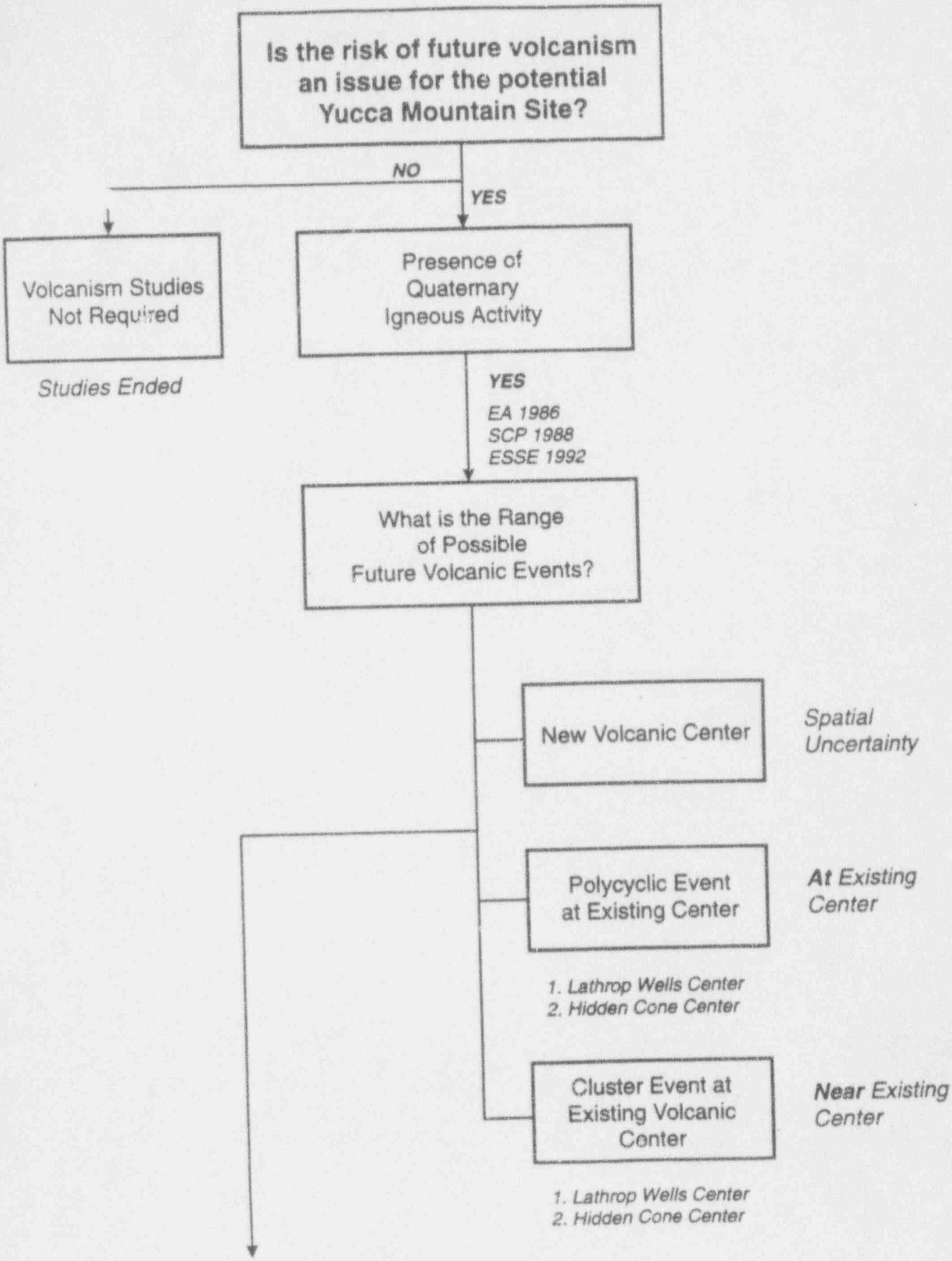
E1: recurrence rate of volcanic events
E2: probability a future event intersects a specified area
E3: release of radionuclides to the accessible environment

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

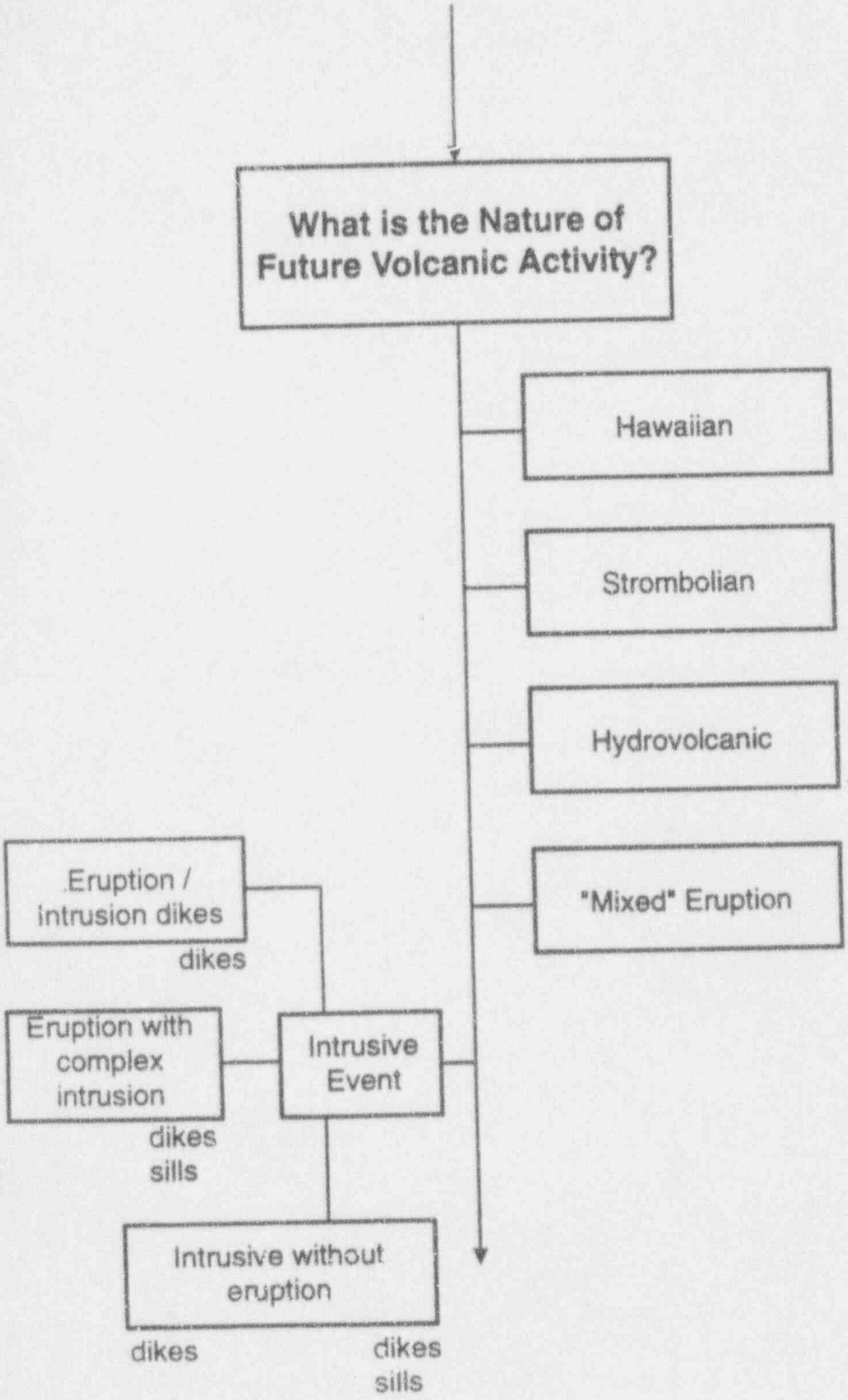
E2: repository, controlled area, waste isolation system (Yucca Mountain region)

E3: direct releases (eruptions), coupled releases

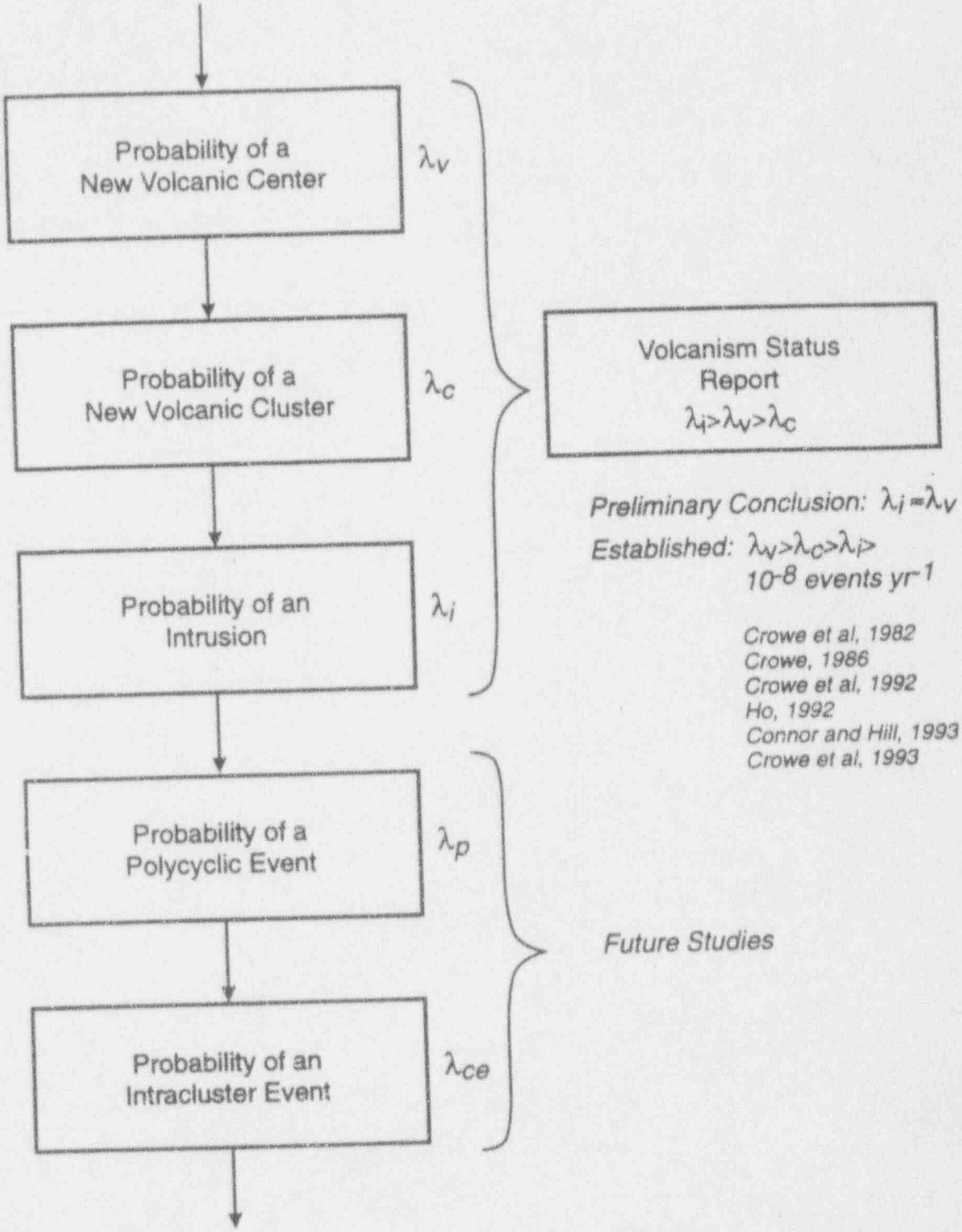




YMVOLCAN1.DOE.CD4/1-31-94



≈ 10% YMR
<< 10% Controlled Area,
Repository



Probability of a New Volcanic Center λ_v

Probability of a New Volcanic Cluster λ_c

Probability of an Intrusion λ_i

Volcanism Status Report

$\lambda_i > \lambda_v > \lambda_c$

Preliminary Conclusion: $\lambda_i \approx \lambda_v$

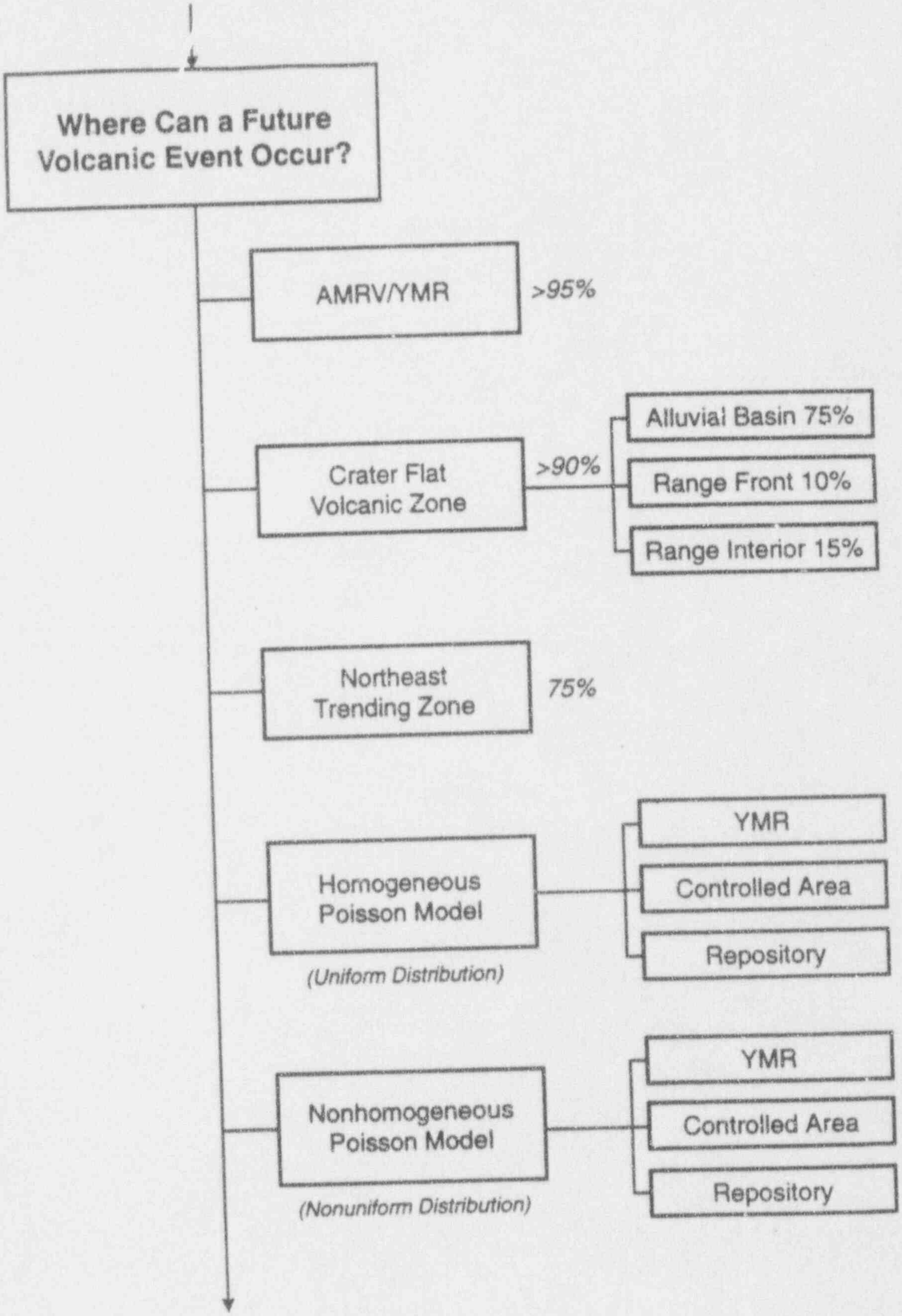
Established: $\lambda_v > \lambda_c > \lambda_i >$ 10^{-8} *events* yr^{-1}

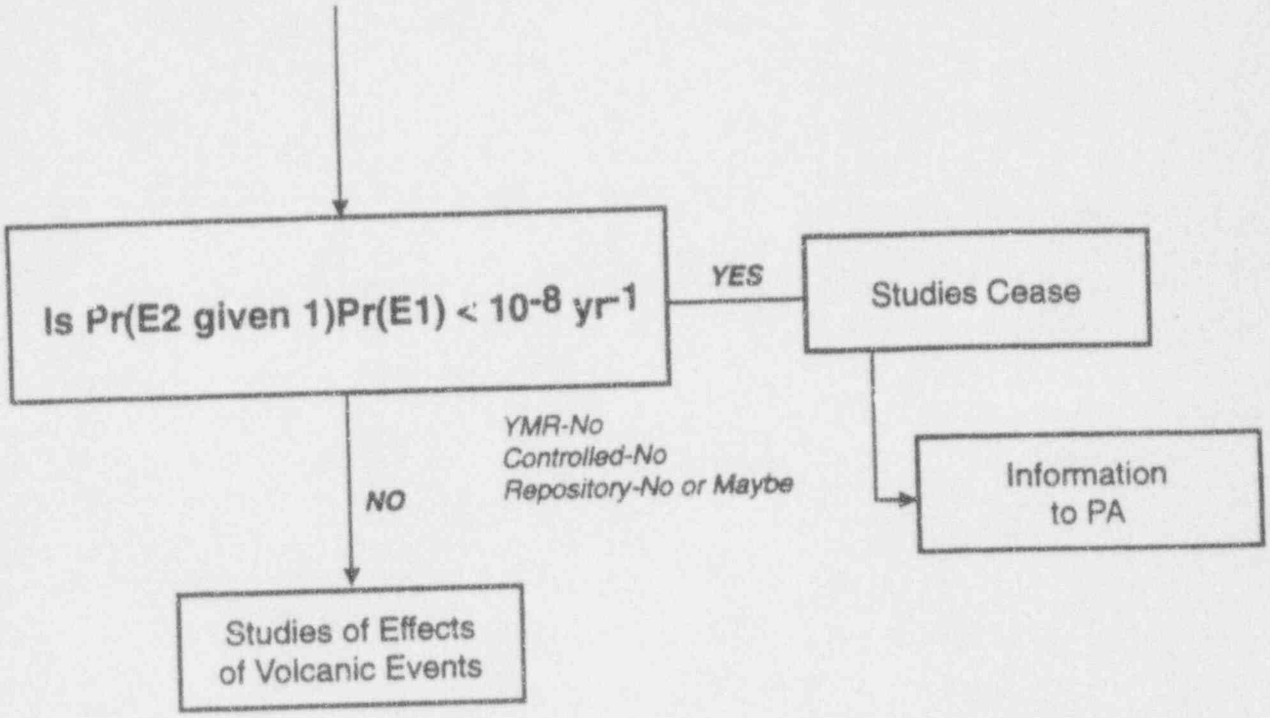
Crowe et al, 1982
Crowe, 1986
Crowe et al, 1992
Ho, 1992
Connor and Hill, 1993
Crowe et al, 1993

Probability of a Polycyclic Event λ_p

Probability of an Intracluster Event λ_{ce}

Future Studies


Where Can a Future Volcanic Event Occur?
AMRV/YMR
>95%
Crater Flat Volcanic Zone
>90%
Alluvial Basin 75%
Range Front 10%
Range Interior 15%
Northeast Trending Zone
75%
Homogeneous Poisson Model
(Uniform Distribution)
YMR
Controlled Area
Repository
Nonhomogeneous Poisson Model
(Nonuniform Distribution)
YMR
Controlled Area
Repository


Is Pr(E2 given 1)Pr(E1) < 10^{-8} yr^{-1}
YES
Studies Cease
Information to PA
NO
YMR-No
Controlled-No
Repository-No or Maybe
Studies of Effects of Volcanic Events

Volcanism Studies
Data Paradox

1. Limited number of Volcanic Centers in the Yucca Mountain Region

    7 Quaternary volcanic centers
    3 Time-space clusters

    12 Pliocene volcanic centers
    4-5 Time-space clusters

2. **Fundamental Assumption**

Volcanic record is too limited for robust calculations
statistical significance
goodness of fit

3. Risk assessment

    Volcanic record of the Yucca Mountain region
        forward projection for probability estimates
        mid-point estimates
    Analog volcanic fields
        bounds on rates of volcanic events
    Multiple Alternative Models
        recurrence models
        structural and spatial models
        distribution models

4. Multiple Models are Possible
        cannot be proven or disproven with record

***effect* on probability distribution**

Volcanic Event
Probability Model

1. Range of definitions

   one of the reasons for differences in probability estimates

   Cluster model: spatial and time related clusters of centers
   Center model: new volcanic center
   Event model: individual vents or fissures in a center

2. Polycyclic Volcanism

   episodes of volcanic activity at an ***existing*** volcanic center
   new concept: confusion in probability applications

   Polycyclic events have been included in center or cluster models

3. Polycyclic Volcanism

   emphasis of future probabilistic studies

4. Consistent Application of Defined Models

Volcanism Studies
RISK SIMULATION

1. Simulation Modeling is used to test significance, sensitivity

   ensure: all alternative models are included/evaluated
   occurrence probability
   risk

NOT UNDERESTIMATED

BUT . . . .

ALTERNATIVE MODELS MUST BE PLAUSIBLE PHYSICALLY

2. New Perspective: Probability Estimates
   - Previous Estimations:
     - ***probability bounds***
   - Review Organizations
     - ***worse or worst case emphasis***

3. Revised Estimates

   - Regulatory bounds
   - Analog bounds
   - Mid-point estimates: geologic record

unbiased probability distributions

4. DOE will assess distributions

   Regulatory perspective

Recurrence Models

Probability Estimates

1. Time-Series Data

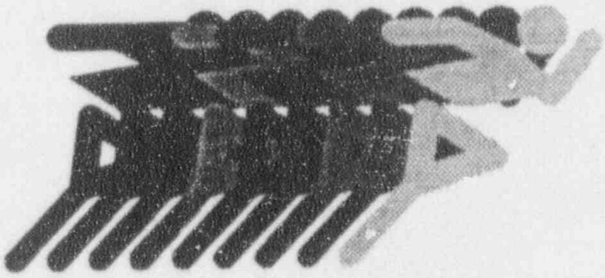
   Data too limited to be significant
   repose intervals

2. Homogeneous and Nonhomogeneous Poisson Models

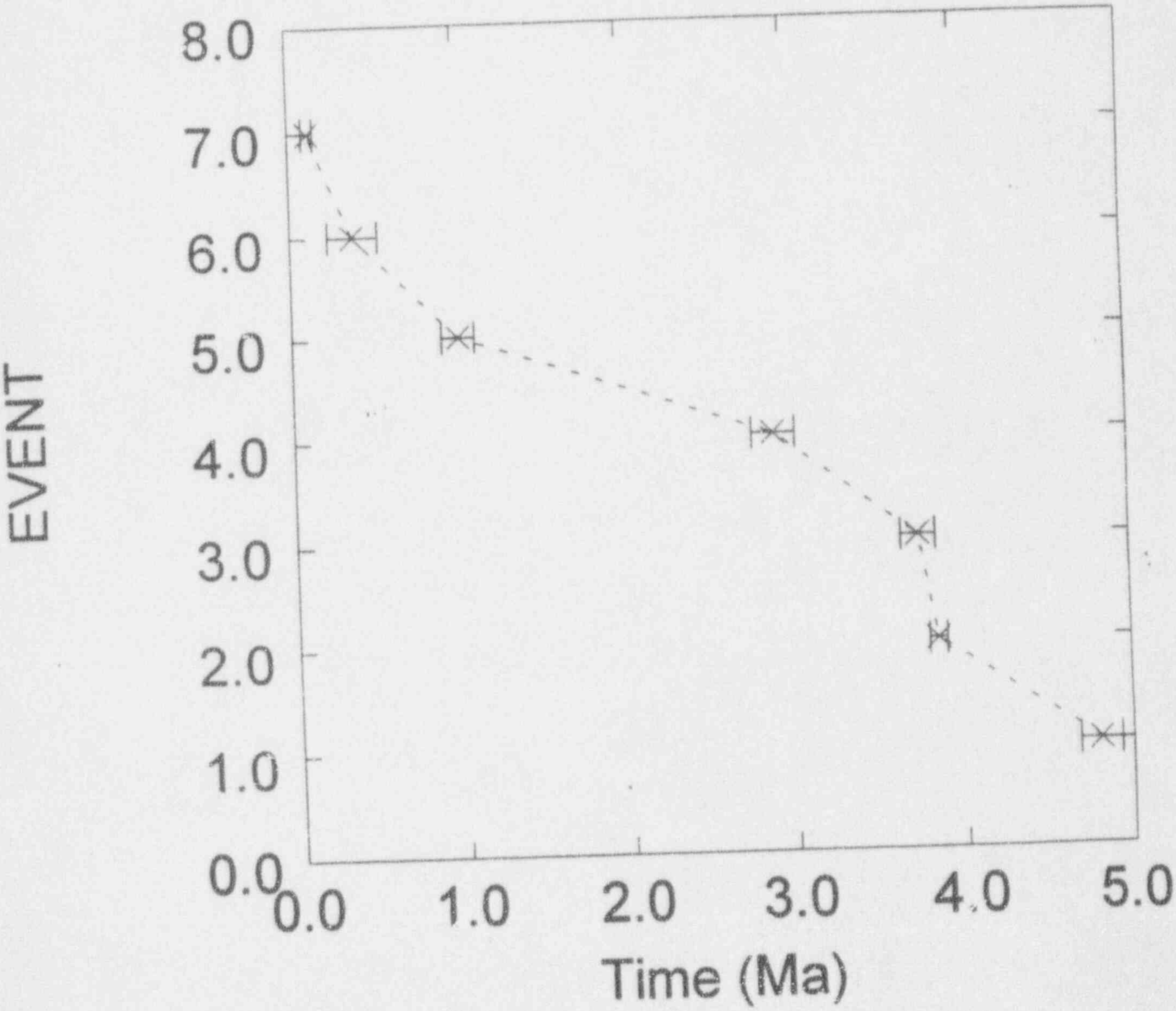
   Centers, Clusters

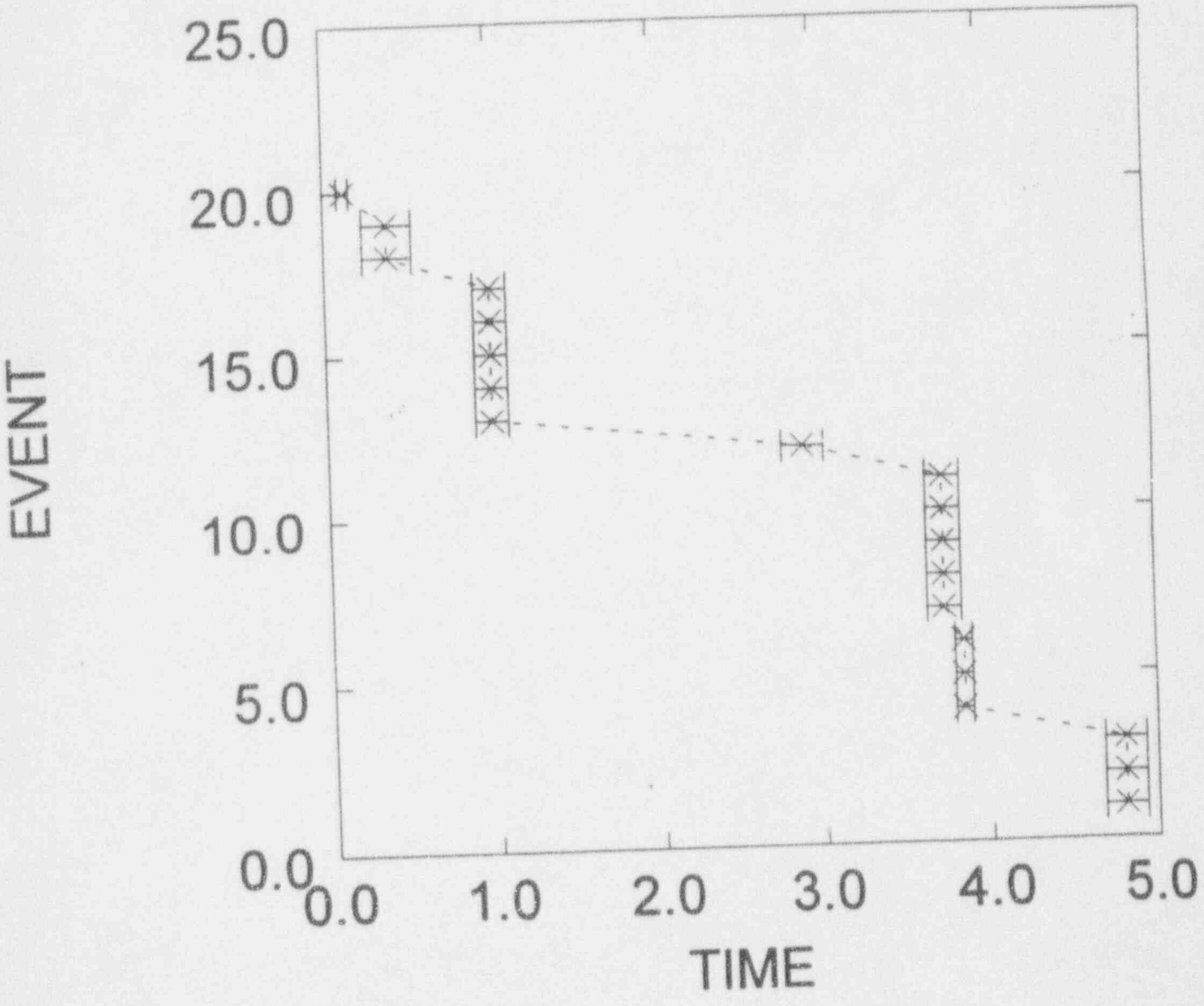
3. Time-Volume Models

   Magma Output Rate
   mostly non-significant regression calculations



(Las Vegas, Nevada: Home of the World's Most Predictable Volcano)


EVENT
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
Time (Ma)


25.0
20.0
15.0
10.0
5.0
0.0
EVENT
0.0
1.0
2.0
3.0
4.0
5.0
TIME

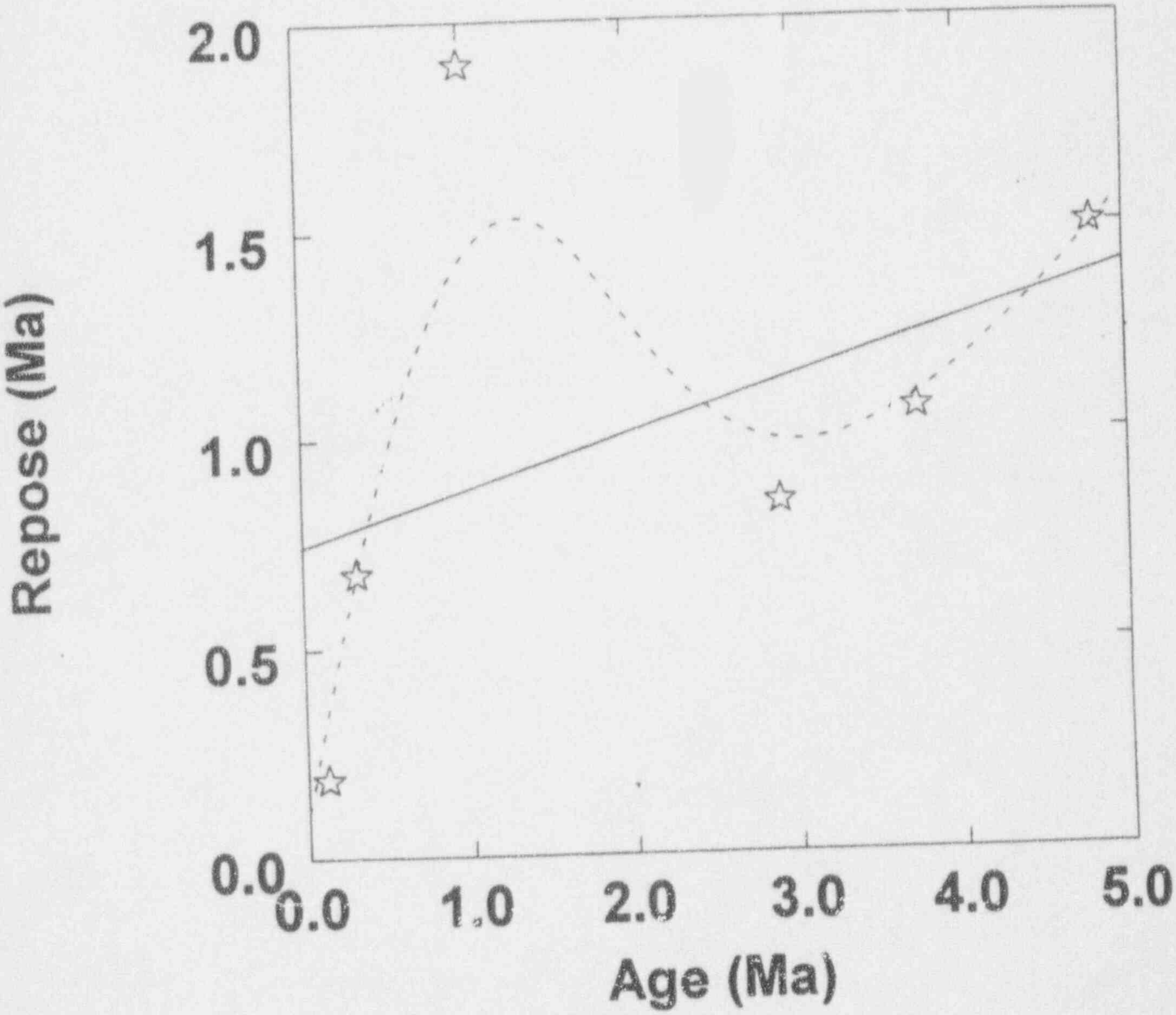

Repose (Ma)
2.0
1.5
1.0
0.5
0.0
0.0
1.0
2.0
3.0
4.0
5.0
Age (Ma)

Table 7.5. Table of Homogeneous Poisson Models for Volcanic Events (E1) in the YMR.

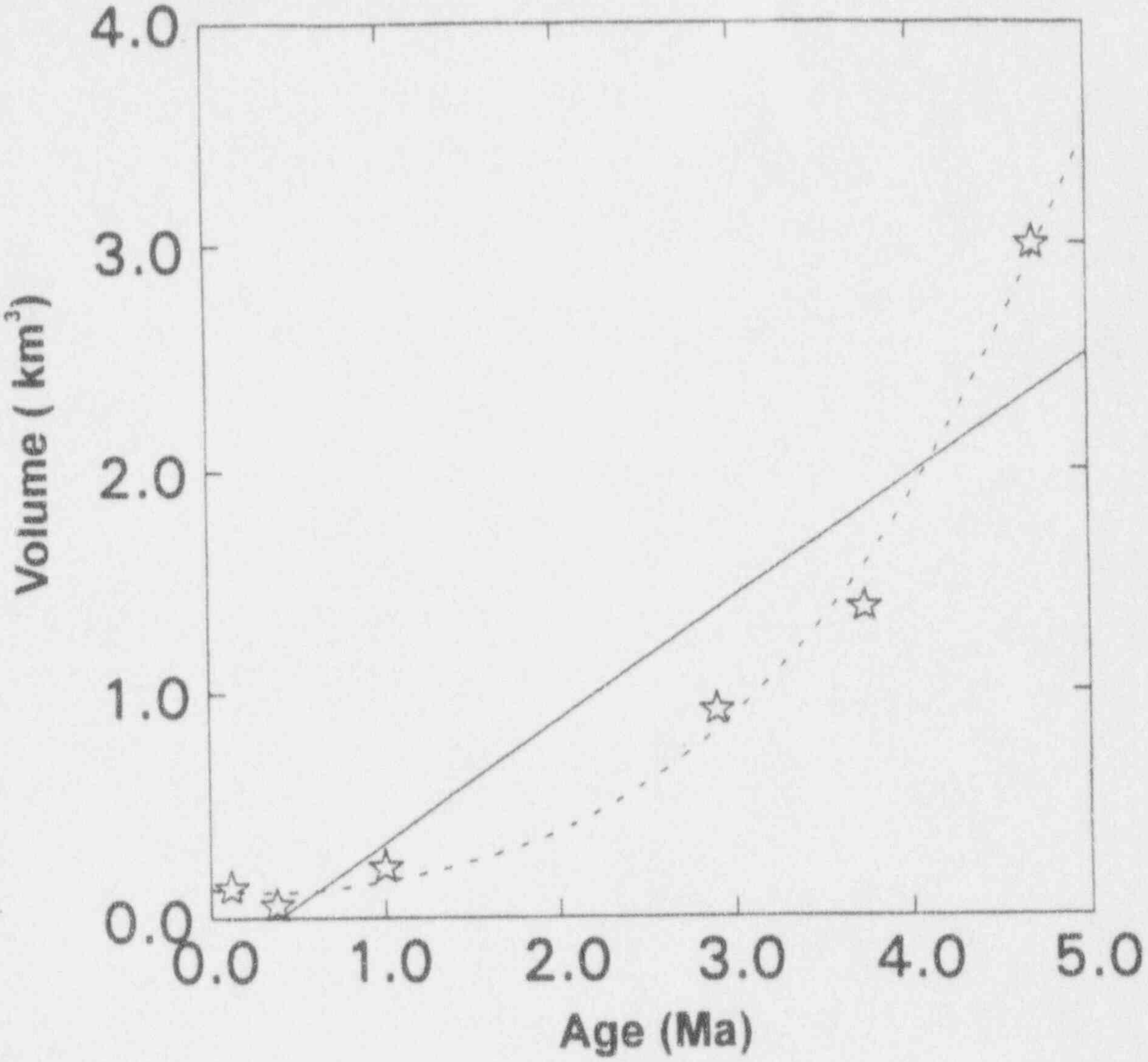
Interval	Model	Interval (yrs)	Minimum events yr^{-1}	Maximum events yr^{-1}	Most Likely events yr-1
Quaternary		2.00E+06			
	Poisson Events		3	8	6
	Poisson Rates		1.5E-06	4.0E-06	3.0E-06
	Stress-Dike		3	8	5
	Stress-Dike Rates		1.5E-06	4.0E-06	2.5E-06
Volcanic Cycle*		4.80E+06			
	Poisson Events		8	19	12
	Poisson Rates		1.7E-06	4.0E-06	2.5E-06
	Stress-Dike		8	10	10
	Stress-Dike Rates		1.7E-06	2.1E-06	2.1E-06
Quaternary		1.60E+06			
	Poisson Events		3	8	6
	Poisson Rates		1.9E-06	5.0E-06	3.7E-06
	Stress-Dike		3	6	5
	Stress-Dike Rates		1.9E-06	3.7E-06	3.1E-06
Quaternary Accelerated*		1.00E+06			
	Poisson Events		3	8	7
	Poisson Rates		3.0E-06	8.0E-06	6.0E-06
	Stress-Dike		3	6	5
	Stress-Dike Rate		3.0E-06	6.0E-06	5.0E-06
Summary Statistics (all Models)		***Mean***	***2.0E-06***	***4.6E-06***	***3.5E-06***
		Median	***1.8E-06***	***4.0E-06***	***3.1E-06***
		Geomean	***1.9E-06***	***4.3E-06***	***3.3E-06***
		Std Deviation	***0.6E-06***	***1.7E-06***	***1.3E-06***
Summary Statistics (Preferred Models)*		***Mean***	***2.3E-06***	***5.0E-06***	***3.9E-06***
		Median	***2.3E-06***	***5.0E-06***	***3.8E-06***
		Geomean	***2.3E-06***	***4.5E-06***	***3.6E-06***
		Std Deviation	***0.75E-06***	***2.53E-06***	***1.8E-06***

* Preferred models are models where the event counts span an interval that corresponds to cycles of volcanic activity (4.8 Ma to present; and 1.0 Ma to present.

Table 7.6 Nonhomogeneous Recurrence Models (E1) for the YMR

Interval	Model	Interval (yrs)	Minimum events yr^{-1}	Maximum events yr^{-1}	Most Likely events yr^{-1}
Quaternary		2.00E+06			
	Events		3	8	6
	Beta		3.10	2.10	2.30
	Weibull Rate		4.6E-06	8.4E-06	6.9E-06
	Stress Dike		3	8	5
	Beta		3.1	2.10	2.10
	Weibull Rate		4.6E-06	8.4E-06	5.2E-06
Volcanic Cycle*		4.80E+06			
	Events		8	19	12
	Beta		0.84	0.72	1.00
	Weibull Rate		1.4E-06	2.9E-06	2.5E-06
	Stress Dike		8	10	10
	Beta		0.84	0.9	0.9
	Weibull Rate		1.4E-06	1.9E-06	1.9E-06
Quaternary Rate		1.60E+06			
	Events		3	8	6
	Beta		1.7	1.4	1.7
	Weibull Rate		3.2E-06	7.0E-06	6.4E-06
	Stress Dike		3	6	5
	Beta		1.7	1.7	1.8
	Weibull Rate		3.2E-06	6.4E-06	5.6E-06
Quaternary Accelerated*		1.00E+06			
	Events		3	8	6
	Beta		0.94	0.60	0.70
	Weibull Rate		2.8E-06	4.8E-06	4.2E-06
	Stress Dike		3	6	5
	Beta		0.94	0.70	0.60
	Weibull Rate		2.8E-06	4.2E-06	3.0E-06
Summary Statistics (all models)		***Mean***	***3.0E-06***	***5.5E-06***	***4.6E-06***
		Median	***3.0E-06***	***5.6E-06***	***4.7E-06***
		Geomean	***2.8E-06***	***4.9E-06***	***4.0E-06***
		Std Deviation	***1.2E-06***	***2.4E-06***	***1.9E-06***
Summary Statistics (Preferred Modesls)*		***Mean***	***2.1E-06***	***3.4E-06***	***2.9E-06***
		Median	***2.1E-06***	***3.5E-06***	***2.7E-06***
		Geomean	***2.0E-06***	***3.2E-06***	***2.8E-06***
		Std Deviation	***8.08E-07***	***1.30E-06***	***9.76E-07***

* Preferred models are models with event counts spanning intervals that correspond to cycles of volcanic activity (4.8 Ma to present; 1.0 Ma to present)


4.0
3.0
2.0
1.0
0.0
Volume (km^3)
0.0
1.0
2.0
3.0
4.0
5.0
Age (Ma)

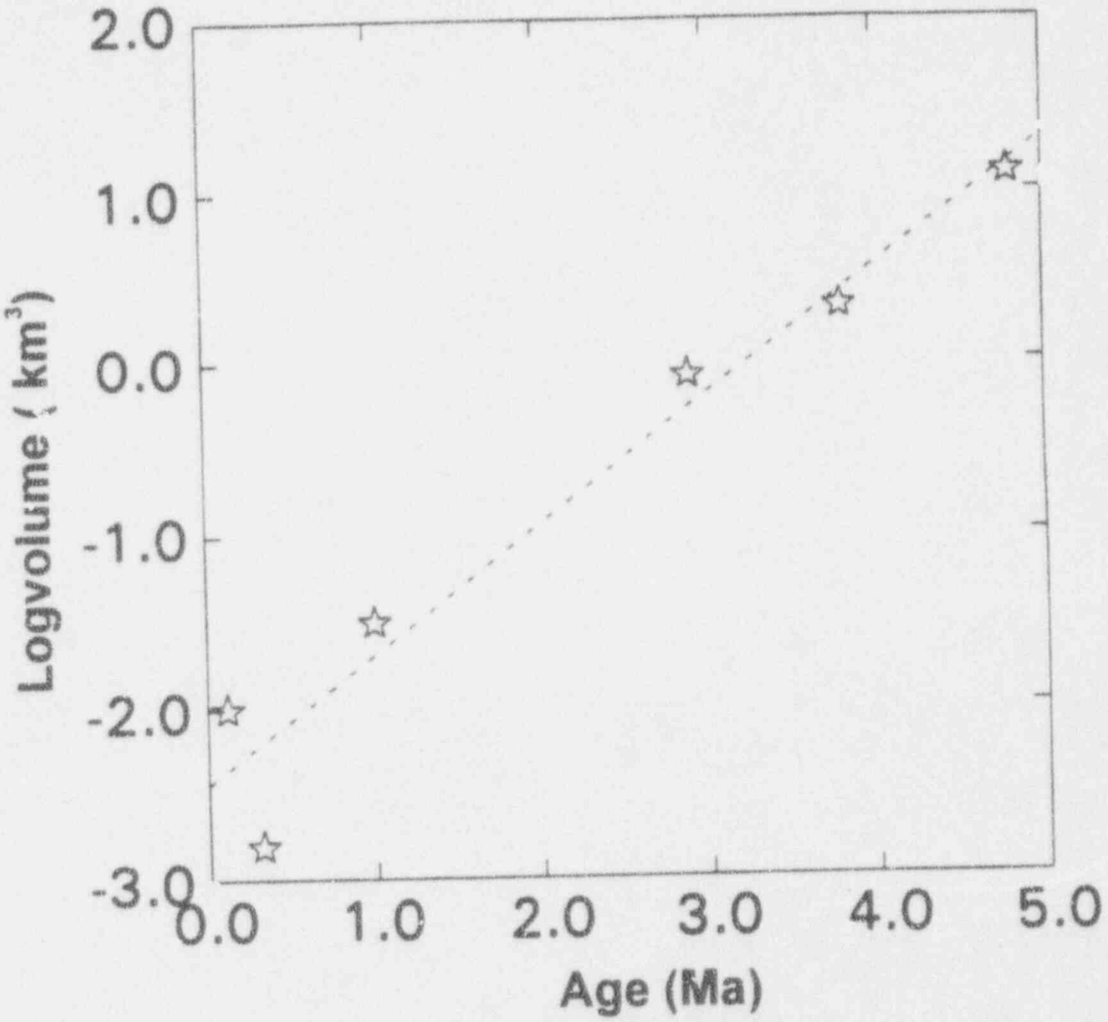

2.0
1.0
0.0
-1.0
-2.0
-3.0
0.0
1.0
2.0
3.0
4.0
5.0
Logvolume (km³)
Age (Ma)

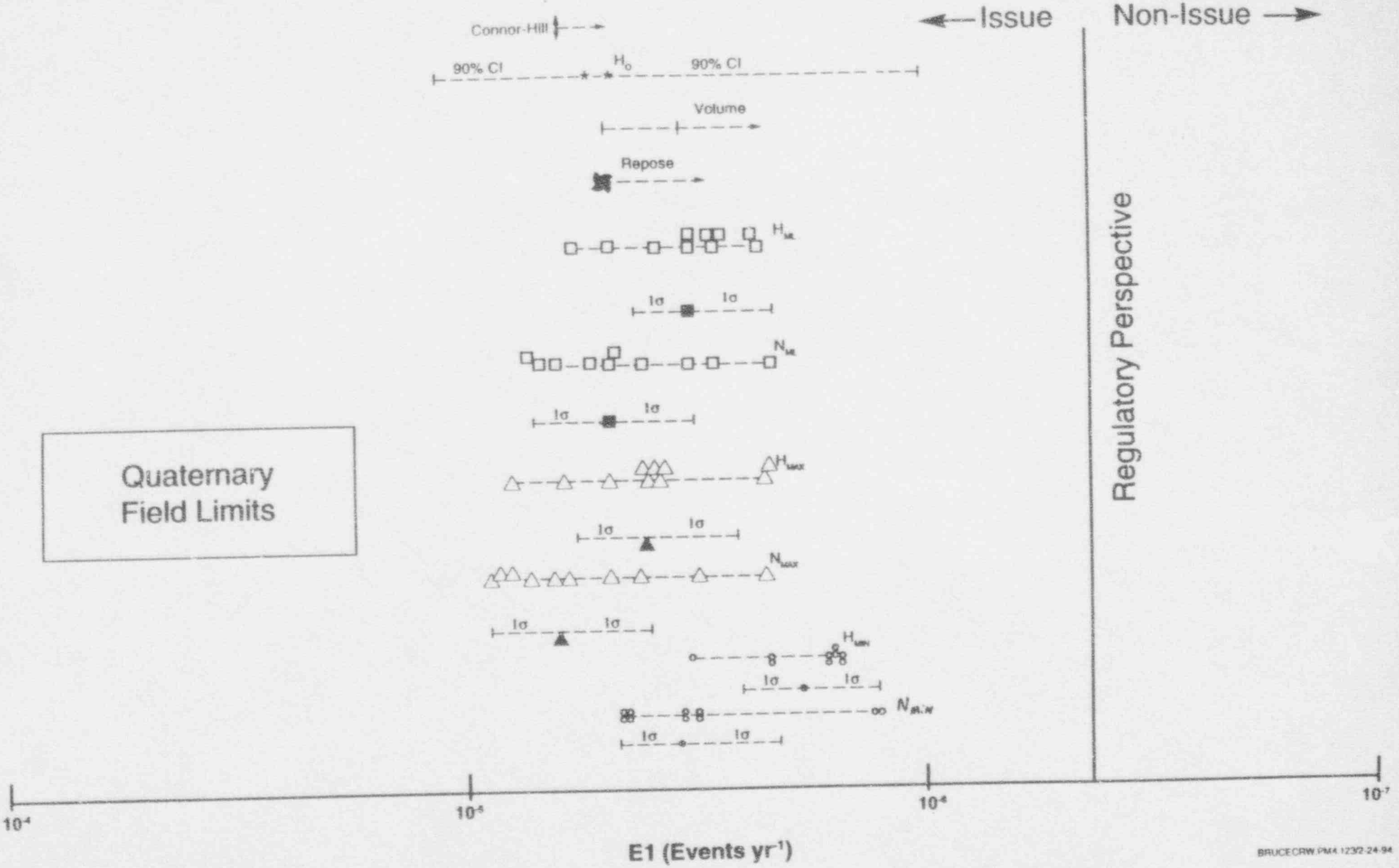
Table 7.9 Age, Cumulation Volume, Magma Ouput Rates, Generation Rates, and Event Rates for Pliocene and Quaternary Volcanic Centers of the YMR.

EVENT MODELS	AGE (Ma)	VOLUME	CUMVOL	MOR* ($m^3 yr^{-1}$)			
Event: Case I					GR** (mean)	GR (geomean)	GR (median)
Thirsty Mesa	4.8	3.0E+09	3.0E+09	305	2.5E+06	1.2E+06	9.7E+05
Amargosa Valley	3.8	3.0E+08	3.3E+09	268	2.8E+06	1.4E+06	1.1E+06
CF3.7	3.7	6.8E+08	4.0E+09		ER*** (mean)	ER (geomean)	GR (median)
Buckboard	2.9	9.2E+08	4.9E+09		4.0E-07	8.2E-07	1.0E-06
CF1.0	1.0	2.3E+08	5.1E+09		3.5E-07	7.2E-07	9.0E-07
Sleeping Butte	.32	5.9E+07	5.2E+09				
Lathrop Wells	.12	1.4E+08	5.3E+09				
Mean	*7.6E+08*	*Median*	*3.0E+08*				
Geomean	*3.8E+08*	*Std Deviation*	*1.0E+09*				
Event: Case II					**GR (mean)**	**GR (geomean)**	**GR (median)**
CF1.0	**1.0**	**2.3E+08**	**2.3E+08**	**305**	**4.6E+05**	**4.0E+05**	**4.5E+05**
Sleeping Butte	**.32**	**5.9E+07**	**2.9E+08**	**268**	**5.2E+05**	**4.5E+05**	**5.1E+05**
Lathrop Wells	**.12**	**1.4E+08**	**4.3E+08**		**ER (mean)**	**ER (geomean)**	**ER (median)**
Mean	*1.4E+08*	*Median*	*1.4E+08*		**2.2E-06**	**2.5E-06**	**2.2E-06**
Geomean	*1.2E+08*	*Std Deviation*	*8.5E+07*		**1.9E-06**	**2.2E-06**	**1.9E-06**
Event: Case III					**GR (mean)**	**GR (geomean)**	**GR (median)**
CF-North	**1.0**	**1.7E+08**	**1.7E+08**	**305**	**2.7E+05**	**2.1E+05**	**1.9E+05**
CF-South	**1.0**	**6.0E+07**	**2.3E+08**	**268**	**3.1E+05**	**2.3E+05**	**2.1E+05**
Hidden	**.32**	**3.5E+07**	**2.6E+08**		**ER (mean)**	**ER (geomean)**	**ER (median)**
Black Peak	**.32**	**2.4E+07**	**2.9E+08**		**3.7E-06**	**4.9E-06**	**5.3E-06**
Lathrop	**.12**	**1.4E+08**	**4.3E+08**		**3.2E-06**	**4.2E-06**	**4.6E-06**
Mean	*8.6E+07*	*Median*	*6.0E+07*				
Geomean	*6.5E+07*	*Std Deviation*	*6.5E+07*				
					Preferred Models	*Generation Rate*	*Event Rate*
					Preferred mean	*2.9E+05*	*3.4E-06*
					Preferred median	*2.0E+05*	*5.0E-06*
					Preferred geomean	*2.2E+05*	*4.5E-06*

*MOR : Magma Output Rate

**GR= Generation Rate

***ER = Event Rate



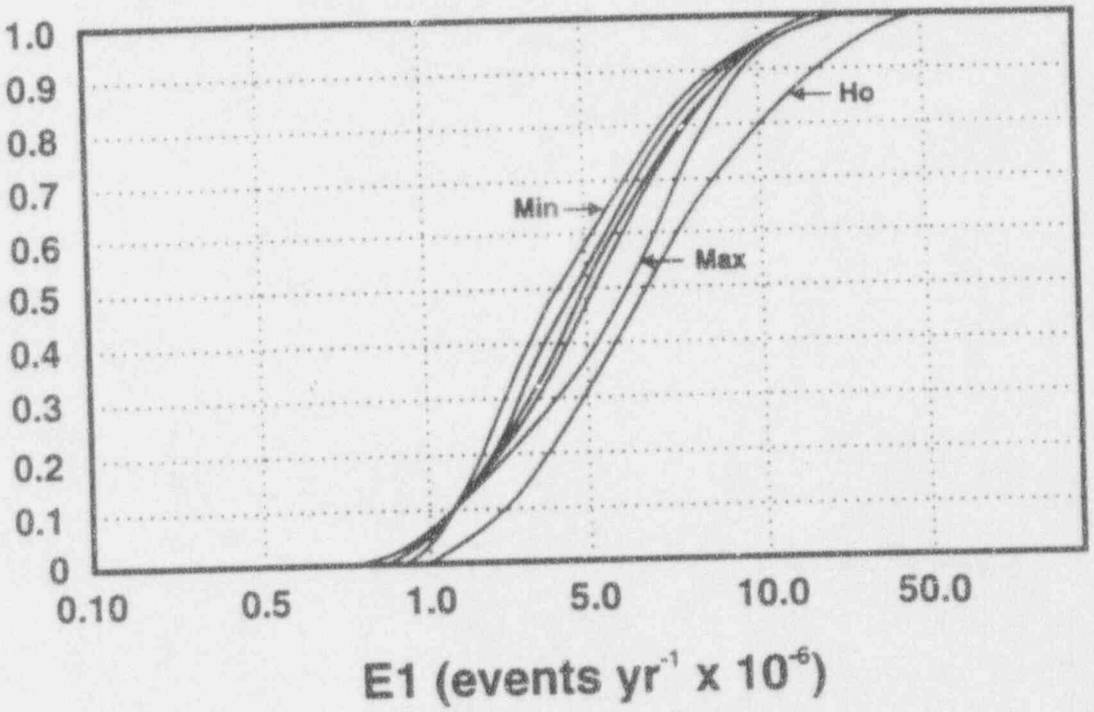
BRUCECRW PM4 123/2-24-94

Table 7.10 Simulation Matrix , expected values and matrix statistics for E1, the recurrence rate.

Model	**Min**	**Most Likely**	**Max**	**Min(all)**	**Max(all)**				
Homogeneous: All	2.1E-06	3.6E+00	4.6E-06	1.5E-06	8.0E-06				
Homogeneous: Pref	2.3E-06	4.1E-06	5.0E-06	1.7E-06	8.0E-06				
Nonhomogeneous: All	3.0E-06	4.4E-06	5.5E-06	1.4E-06	8.4E-06				
Nonhomogeneous: Pref	2.1E-06	2.9E-06	3.4E-06	1.4E-06	4.8E-06				
Repose			5.3E-06						
Volume-Predict	1.0E-06	3.2E-06	5.3E-06						
Distribution Boundaries	**quartiles**	**10%/1% limits**	**10%/5% limits**	**10%/10% limits**	**Normal (1 σ)**				
Risk Simulations	**Sim1**	**Sim2**	**Sim3**	**Sim4**	**Sim5**	*Mean*	*Median*	*Geomean*	*Std Dev*
Homogeneous: All	4.8E-06	4.4E-06	4.9E-06	5.4E-06	3.6E-06	*4.6E-06*	*4.8E-06*	*4.6E-06*	*6.8E-07*
Homogeneous: Pref	4.8E-06	4.1E-06	5.0E-06	5.5E-06	4.1E-06	*4.8E-06*	*4.8E-06*	*4.8E-06*	*5.2E-07*
Nonhomogeneous: All	4.8E-06	4.6E-06	5.1E-06	5.6E-06	4.5E-06	*4.9E-06*	*4.8E-06*	*4.9E-06*	*4.4E-07*
Nonhomogeneous: Pref	4.8E-06	4.3E-06	4.8E-06	5.4E-06	2.9E-06	*4.4E-06*	*4.8E-06*	*4.3E-06*	*9.3E-07*
Repose		4.7E-06	5.2E-06	5.7E-06		*5.2E-06*	*5.2E-06*	*5.2E-06*	*4.7E-07*
Volume	2.8E-06	4.4E-06	4.9E-06	5.4E-06	3.4E-06	*4.5E-06*	*4.6E-06*	*4.5E-06*	*1.1E-06*
Minimum		4.0E-06	4.6E-06	5.2E-06	2.2E-06	*4.0E-06*	*4.3E-06*	*3.8E-06*	*1.3E-06*
Maximum		5.3E-06	5.7E-06	6.1E-06	4.5E-06	*5.4E-06*	*5.5E-06*	*5.5E-06*	*6.7E-07*
Ho (1992)	7.0E-06								
Mean	*4.4E-06*	*4.5E-06*	*5.0E-06*	*5.5E-06*	*3.6E-06*				
Median	*4.8E-06*	*4.5E-06*	*5.0E-06*	*5.5E-06*	*3.6E-06*				
Geomean	*4.3E-06*	*4.5E-06*	*5.0E-06*	*5.5E-06*	*3.5E-06*				
Std Deviation	*8.8E-07*	*3.8E-07*	*3.1E-07*	*2.5E-07*	*8.4E-07*				

Simulations 1 - 4: Trigen distribution. Simulation 1: min- max from Tables 7.5 and 7.6. Simulations 2-4: min-max from Fig. 7.11
Simulations 5: Normal distribution. Median and standard deviation from Tables 7.5 and 7.6.

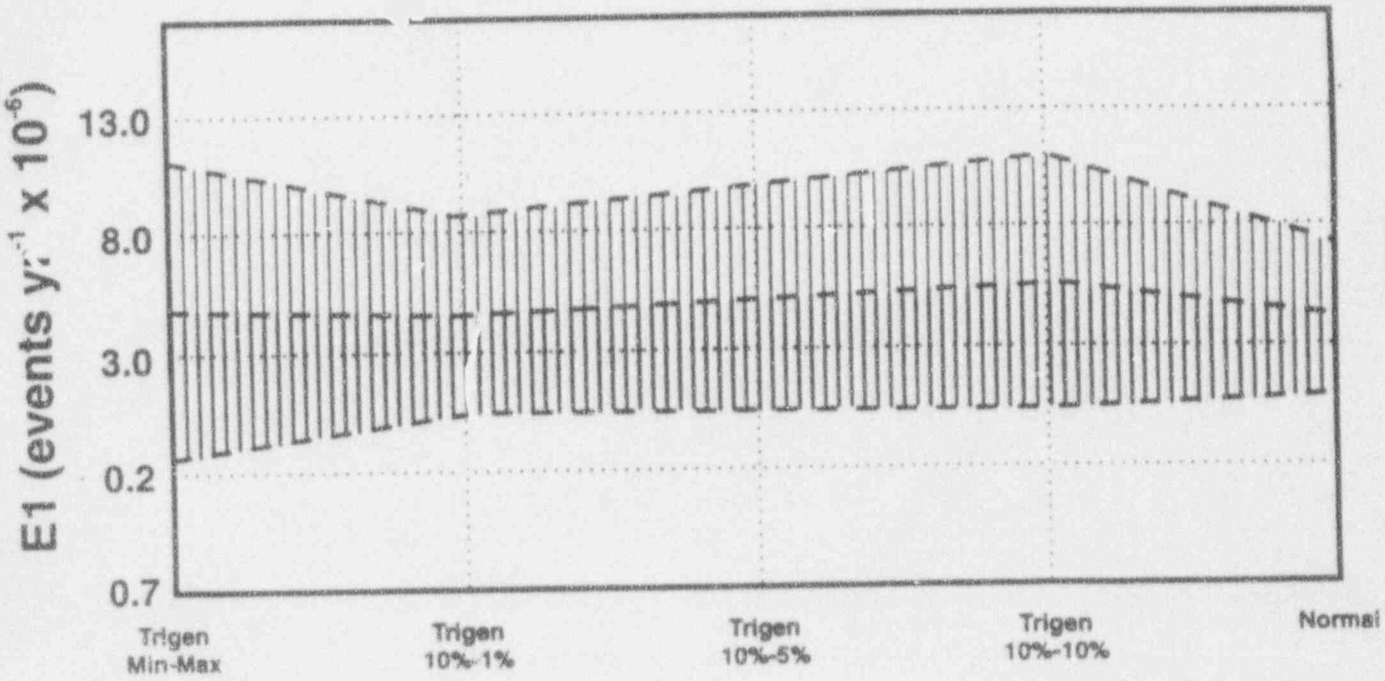
Simulated Results: E1



Expected Values:

Homogeneous $5.0E^{-6}$
Nonhomogeneous $4.8E^{-6}$
Repose $5.2E^{-6}$
Volume $4.9E^{-6}$
Minimum $4.6E^{-6}$
Maximum $5.7E^{-6}$
Ho(1992) $7.0E^{-6}$

Risk Simulation: Homogeneous Poisson

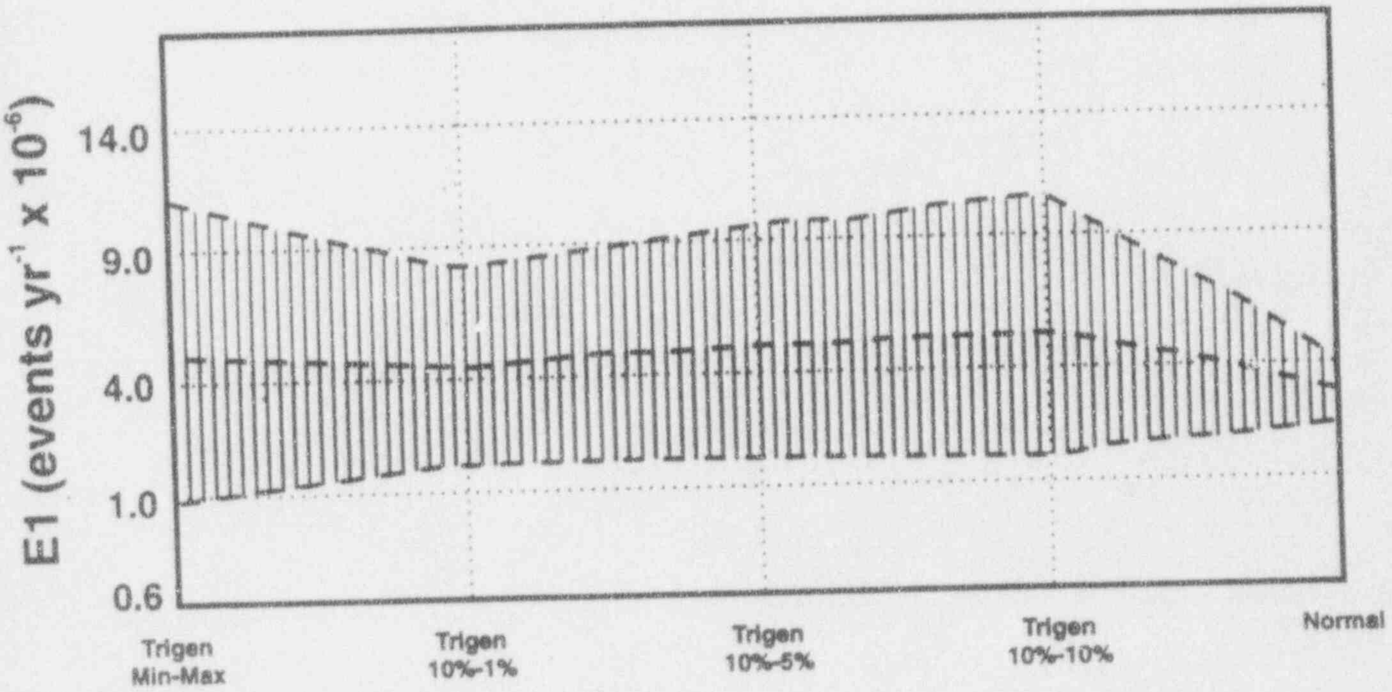


Top - - - - 90 per %

Center - - - - 50 Per %

Bottom - - - - 10 per %

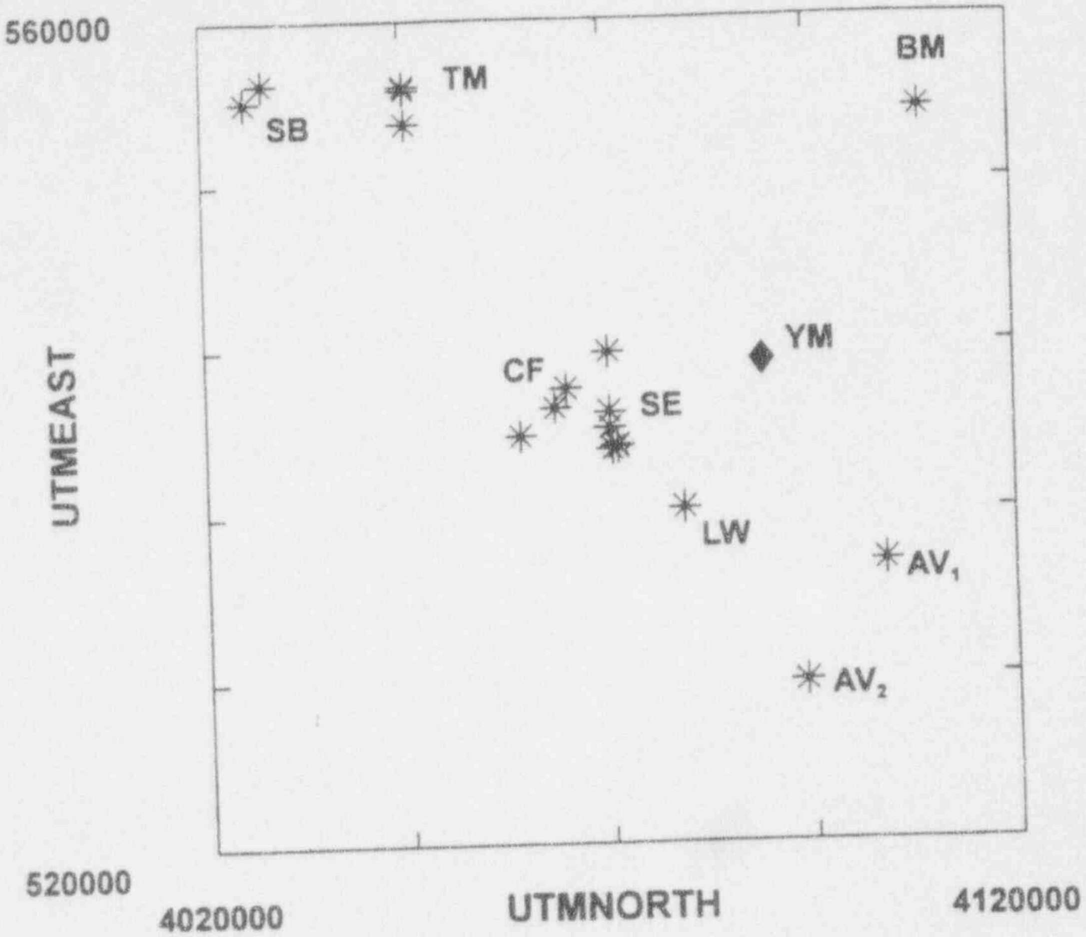
Risk Simulation: Nonhomogeneous Poisson



Top ---- 90 per %

Center ---- Mean

Bottom ---- 10 per %


560000
UTMEAST
520000
4020000
UTMNORTH
4120000
SB
TM
BM
YM
CF
SE
LW
AV₁
AV₂

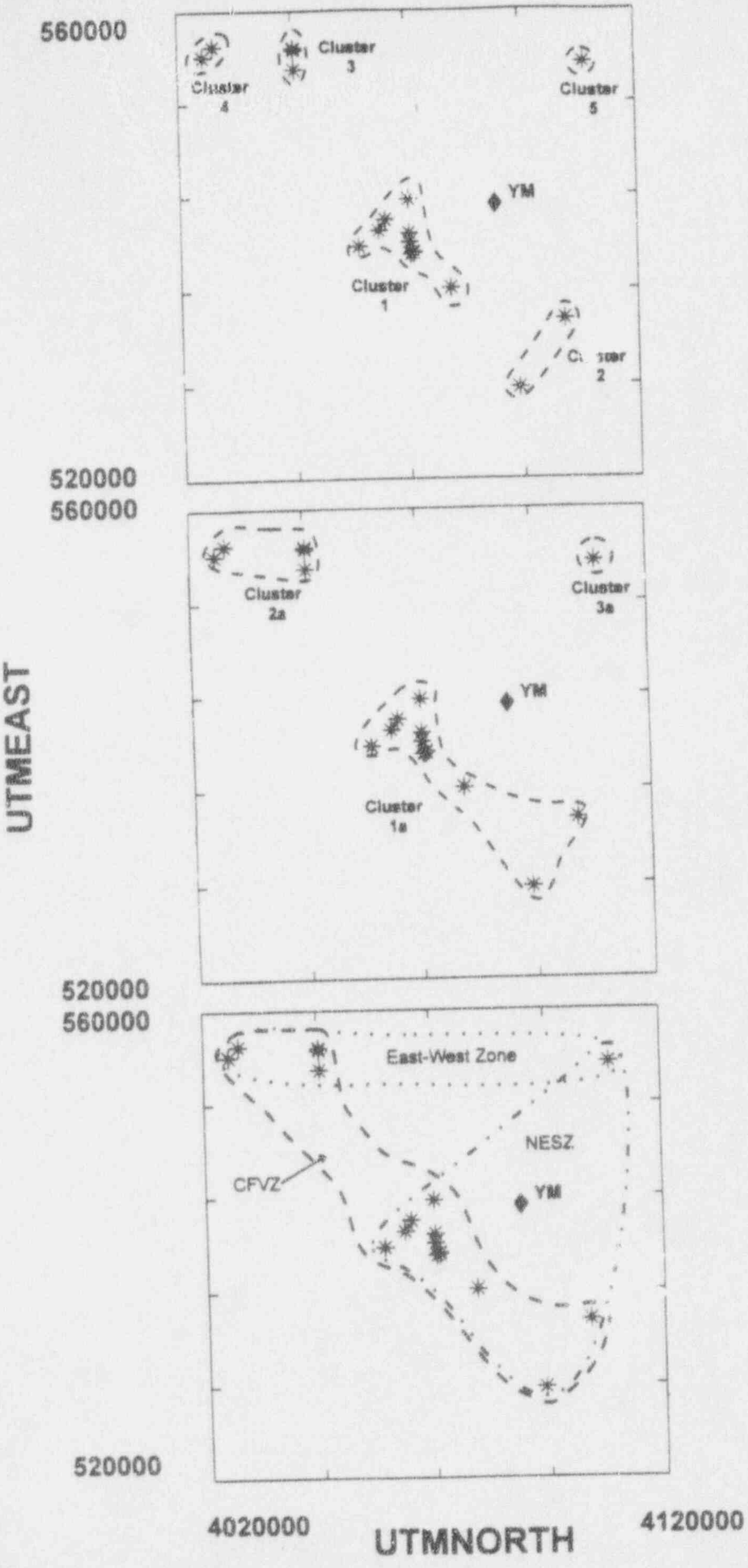
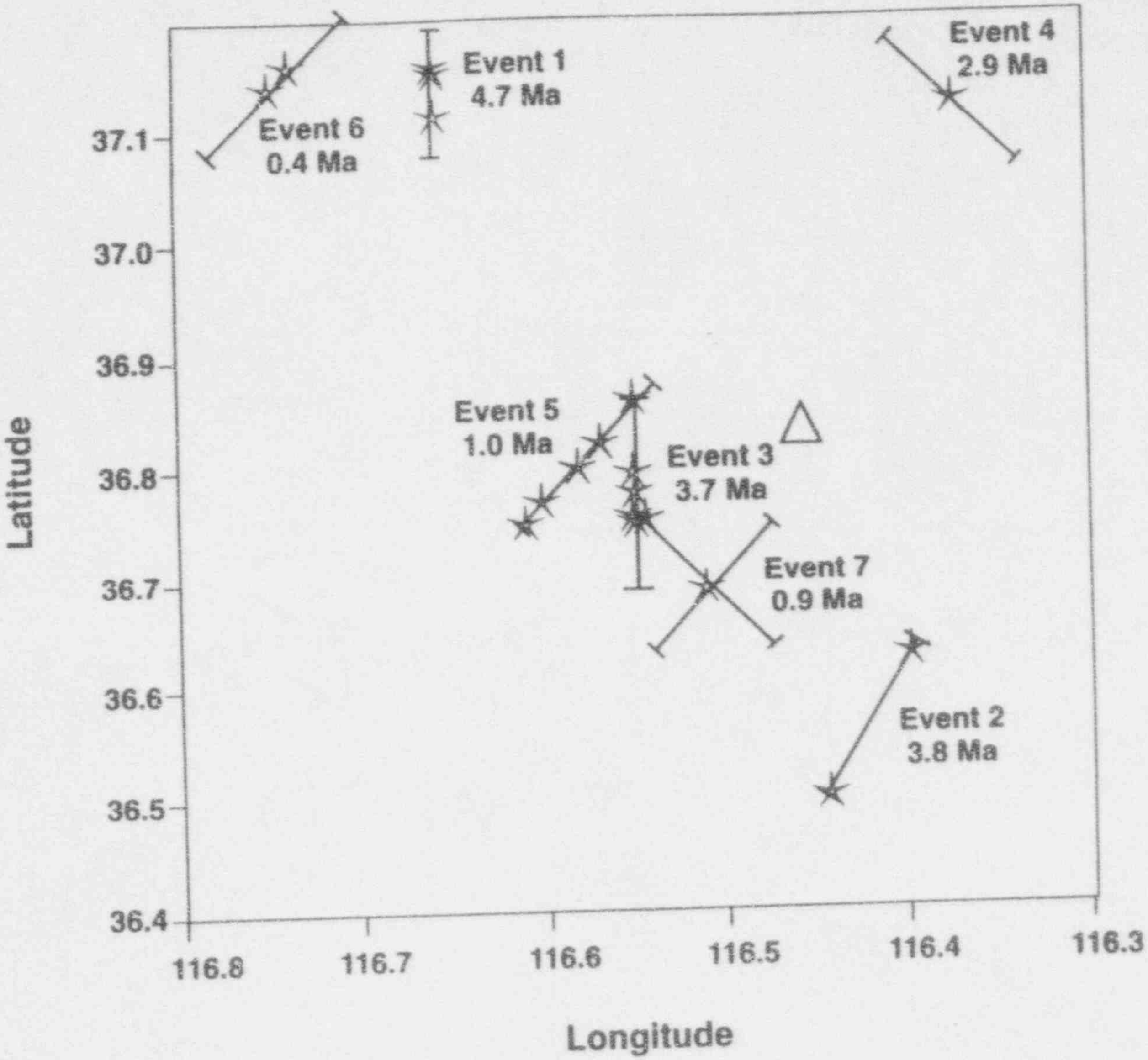

560000
Cluster 4
Cluster 3
Cluster 5
YM
Cluster 1
Cluster 2
520000
560000
Cluster 2a
Cluster 3a
YM
Cluster 1a
520000
560000
East-West Zone
NESZ
CFVZ
YM
520000
UTMEAST
4020000
4120000
UTMNORTH

Table 7.13. Spatial Distribution Models for E2. Model 1 = Random, Model 2 = Range Interior, Model 3 = Range Interior + Range Front

Spatial Model	Time (Ma)	Area (km2)	Model 1	Model 2	Model 3	Comments
Quat Centers (circle)	1.00	2400	2.5E-03	3.7E-04	6.2E-04	Crowe et al. 1982
Quat Centers (ellipse)	1.00	4400	1.4E-03	2.0E-04	3.4E-04	Crowe et al. 1982
Quat + BB (circle)	3.75	2500	2.4E-03	3.6E-04	6.0E-04	Crowe et al. 1982
Quat + BB (ellipse)	3.75	2000	3.0E-03	4.5E-04	7.5E-04	Crowe et al. 1982
Cluster 1*	3.75	400	1.5E-02	2.2E-03	3.7E-03	Crater Flat Volcanic Field*
Cluster 2	3.85					Intersection not possible
Cluster 3	4.80					Intersection not possible
Cluster 4	4.80					Intersection not possible
Cluster 5	2.90					Intersection not possible
Cluster 1a*	3.75	750	8.0E-03	1.2E-03	2.0E-03	Crater Flat + Amargosa*
Cluster 2a	4.80					Intersection not possible
Cluster 3a	2.90					Intersection not possible
CFVZ	4.80	1450	4.1E-03	6.2E-04	1.0E-03	Crater Flat Volcanic zone
NESZ	3.85	1200	5.0E-03	7.5E-04	1.2E-03	Northeast Structural Zone
East-west zone	4.80					Intersection not possible
Cluster 1	1.00					Intersection not possible
Cluster 2	1.00	110				Lathrop Wells cluster
Cluster 3	1.00					Intersection not possible
Cluster 1a*	1.00	400	1.E-02	2.2E-03	3.7E-03	Quaternary CF + Lathrop*
Cluster 2a	1.00					Intersection not possible
CFVZ	1.00	1310	4.6E-03	6.9E-04	1.1E-03	Crater Flat Volcanic Zone
NHPP Cluster	3.75		2.0E-03	3.0E-04	5.0E-04	Connor and Hill
NHPP Cluster	3.75		2.4E-03	3.6E-04	6.0E-04	Connor and Hill
NHPP Cluster	1.00		2.7E-03	4.0E-04	6.7E-04	Connor and Hill
NHPP Cluster	1.00		3.1E-03	4.6E-04	7.7E-04	Connor and Hill
	Summary Statistics	***Mean***	***5.1E-03***	***7.6E-04***	***7.6E-04***	
		Median	***3.1E-03***	***4.6E-04***	***7.6E-04***	
		Std Dev	***4.5E-03***	***6.8E-03***	***1.1E-03***	
		Skew	***1.8***	***1.8***	***1.8***	
	(unlikely cases excluded)	***Mean***	***3.0E-03***	***4.5E-04***	***7.5E-04***	
		Median	***2.6E-03***	***3.9E-04***	***6.5E-04***	
		Std Dev	***1.2E-03***	***1.8E-04***	***2.9E-04***	
		Skew	***0.6***	***0.6***	***0.6***	

*** Spatial models noted by the asterisk are included in the first group of summary statistics but repository intersection is judged to be unlikely from geometrical constraints on the propagation of dikes from the cluster areas, and the long 1/2 length of projected dike dimensions required to achieve intersection.**



VLCEV8.123.CDR/9-17-93

Table 17.14. Alternative Structural Models for the Distribution of Pliocene and Quaternary Volcanic Centers in the YMR.

Structural Model	Evidence for Model	Evidence Against Model	Subsets or Alternative Models
Model 1: Crater Flat Volcanic Zone (Quaternary). This structural model is based on the definition of the Crater Flat volcanic zone of Crowe and Perry (1989). The dimensions of the zone are defined from the distribution of Quaternary volcanic centers.	*Supportive Evidence: northwest-trending linear distribution of volcanic vents, coincidence of the zone and vent alignment with the orientation of the surface of maximum eruption volumes, predominance of northwest structural trends in the Walker Lane structural zone, possible evidence of strike-slip offset of structural features in Paleozoic rocks, strike-slip pull-apart origin of Crater Flat.*	**Negative Evidence:** small number of volcanic centers, distance of gap between Crater Flat and Sleeping Butte centers, secondary northeast alignment of vent clusters.	***Alternative Submodels:*** *The Crater Flat centers and the Sleeping Butte centers may be located in separate structural zones.*
Model 2: Crater Flat Volcanic Zone (YPB). Same as model 1 but the dimensions of the zone are defined by the distribution of the Pliocene and Quaternary volcanic centers of the Younger Post-caldera basalt.	*Supportive Evidence: Same as Model 1.*	**Negative Evidence:** Same as model 1, basalt of Buckboard Mesa is not included in the structural zone.	***Alternative Submodels:*** *Same as Model 1, the aeromagnetic anomalies of the Amargosa Valley may also be in separate structural zones.*
Model 3: Yucca Mountain Region. This is a non-structurally based zone defined by the distribution of Pliocene and Quaternary basalt centers of the YMR. It is similar to but slightly larger than the Area of Most Recent Volcanism of Smith et al. (1990).	*Supportive Evidence: Model is based on the distribution of Pliocene and Quaternary volcanic centers in the YMR.*	**Negative Evidence:** No structural basis for model.	

Table 7.14 (cont)

Model 4: Crater Flat Volcanic field: This zone assumes that the major control of the occurrence of basalt centers is the local Crater Flat volcanic field, which is the primary site of Pliocene and Quaternary basaltic volcanism.	*Supportive Evidence: most of the Pliocene and Quaternary volcanic events have occurred in the Crater Flat basin, Crater Flat is the centroid of the distribution of units of the YPB, the Crater Flat basin may be a remaining area of active tectonism and maximum extension, Crater Flat basin was a site of Miocene basaltic volcanism.*	**Negative Evidence**: Other basalt centers occur outside the Crater Flat basin, the linear north-northwest alignment of basalt centers is oblique to the north-south elongation of the Crater Flat basin.	***Alternative Submodels***. *Each group of volcanic rocks may record a separate volcanic field. These include the Crater Flat, Amargosa, Black Mountain and Buckboard fields.*
Model 5: Strike-Slip Structural Control: Model A. This structural model is based on the inference that the alignment of basalt centers parallels a concealed northwest-trending right-slip fault of the Walker Lane structural system. The model has been described by Schweickert (1989).	***Supportive Evidence:*** *linear northwest alignment of basaltic volcanic centers, proposed offset of structural features of Paleozoic rocks, Walker Lane structural setting, clockwise rotation of field magnetization directions of the Tiva Canyon Member, coincidence of the basalt centers with zone of maximum rotation of the magnetization directions, similar structural bounds may be defined for Miocene basaltic volcanism (Older basalt of Crater Flat, aeromagnetic anomaly of VH-2).*	**Negative Evidence**: Strike-slip fault is not expressed at the surface, there is not always a strong correlation between strike-slips faults and sites of Quaternary volcanism in the basin-range.	***Alternative Submodels***: *The Thirsty Mesa/Sleeping Butte centers and the aeromagnetic anomalies of the Amargosa Valley may be located on separate strike-slip faults and be unrelated to the Crater Flat basalt units.*

Table 7.14 (cont)

Model 6: Strike Slip Structural Control: Model B. This structural model is based on the inference that the south-southeast edge of the Crater Flat basin is bounded by a north-northwest trending, right slip fault. The Pliocene and Quaternary basalt centers are inferred to have ascended along this fault zone and diverted to the northeast (maximum compressive stress direction).	***Supportive Evidence***: *steep gravity gradient paralleling proposed strike-slip fault, presence of north-northwest trending right-slip fault in the arcuate ridge at the south end of Crater Flat, clockwise rotation of field magnetization directions of the Tiva Canyon member, structural models of Crater Flat basin.*	**Negative Evidence**: Bare Mountain fault shows predominately dip-slip offset, basalt centers do not occur on the Bare Mountain fault, no correlation between volume of basalt centers and proximity to proposed bounding strike-slip fault.	***Alternative Submodels***: *Same as model 5.*
Model 7: Stress-field Dike: Quaternary centers. This structural model assumes basalt magma ascended along a concealed structure defined by the northwest orientation of vents of the CFVZ. The feeder dike or dikes following this structure and diverted at shallow depths to follow the maximum compressive stress direction. The direction of dike propagation is **either** to the north-northeast or south-southwest.	***Supportive Evidence:*** *coincidence of the zone of maximum erupted volume of magma with the CFVZ, symmetrical distribution of vents about northwest-trending vent locations, cluster length of the Quaternary basalt of Crater Flat exceeds maximum likely dike length.*	**Negative Evidence**: multiple dikes are required only for the Quaternary basalt of Crater Flat, no recognized correlation between center chemistry and proposed dike systems, does not explain the distribution of all basalt centers.	***Alternative Submodels***: *This model is a subset of the strike-slip models.*

Table 7.14 (cont)

Model 8: Stress-field Dike: Pliocene and Quaternary centers. This model is identical to model 7. The dimensions of the structural zone are defined by the distribution of Pliocene and Quaternary volcanic centers.	***Supportive Evidence***: *Same as model 8, aeromagnetic anomalies of Amargosa Valley may be analogous to the Quaternary basalt centers of Crater Flat, and formed basalt centers only at the ends of the dikes.*	**Negative Evidence**: Does not explain the occurrence of the basalt of Buckboard Mesa.	***Alternative Submodels***: *May form three separate structural systems including the aeromagnetic anomalies of Amargosa Valley, the Crater Flat volcanic field, and the Thirsty Mesa/Sleeping Butte centers.*
Model 9: Chain model. Basalt centers follow northeast-trending chains and the chains form zones of higher risk for future volcanic events (Smith et al. 1990).	***Supportive Evidence***: *northeast-trends of clusters of contemporaneous volcanic centers, parallelism of northeast trends of clusters to bedrock faults of Yucca Mountain, analog comparison to other basaltic volcanic fields.*	Negative Evidence: risk zones are unsuccessful as predicators of future events, basalt of the YPB do not follow existing faults, dimensions of chains from analog volcanic fields exceed maximum cluster lengths of centers in the YMR, structural trends different for alignments of the Thirsty Mesa and basalt of southeast Crater Flat (north trending), longer chains occur only in alluvial basins, Lathrop Wells and Buckboard Mesa centers do not form chains, northeast trends are secondary to northwest trends.	

Table 7.14 (cont)

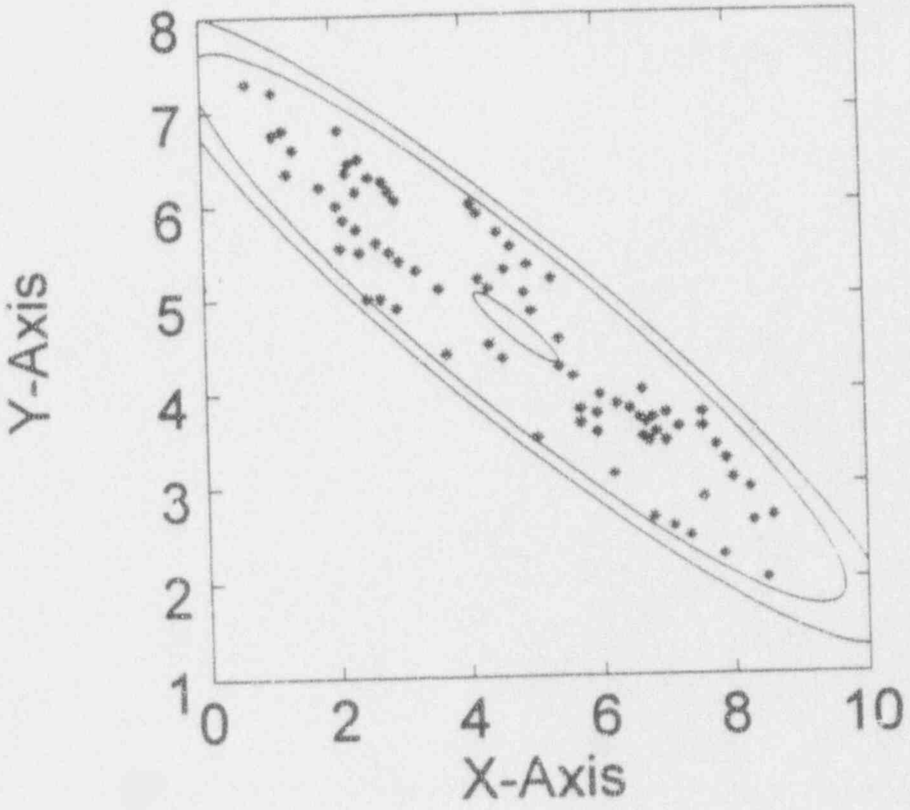
Model 10: Pull-Apart Basin: The Crater Flat basin is a pull-apart basin located at the termination of northwest-trending, strike-slip faults of the Walker Lane structural system. The basin is a tectonic basin and the basalt centers occur along extensional structures of the basin (Fridrich and Price 1992).	***Supportive Evidence:*** *discontinuous northwest-trending faults of the Crater Flat area, multiple basalt cycles of the Crater Flat basin (10.5 Ma and Pliocene and Quaternary), gravity data showing steep, northwest-trending gradients, clockwise rotation of field magnetization directions of the Tiva Canyon Member, Walker Lane structural setting.*	**Negative Evidence**: the occurrence of basalt centers is not confined to the pull-apart basins, limited continuity of northwest-trending fault systems.	
Model 11: Caldera Model. The Crater Flat basin is a structural depression formed by multiple, coalesced caldera collapses associated with eruption of the Crater Flat tuff. Basalt centers are inferred to follow the ring-fracture system of the caldera complex (Carr, 1990).	***Supportive Evidence:*** *Crater Flat basin is located on the south part of the southwest Nevada volcanic field, basalt centers are located commonly along ring-fracture zones of caldera complexes, basalt of Buckboard mesa is located on the ring-fracture of the Timber Mountain caldera, dike of Solatario Canyon and extensions may follow ring-fracture zone.*	**Negative Evidence:** caldera origin of the basin is controversial, basalt centers occur beyond the confines of the Crater Flat basin, basalt centers occur across the caldera floor and resurgent dome and are not confined to the ring-fracture zone.	

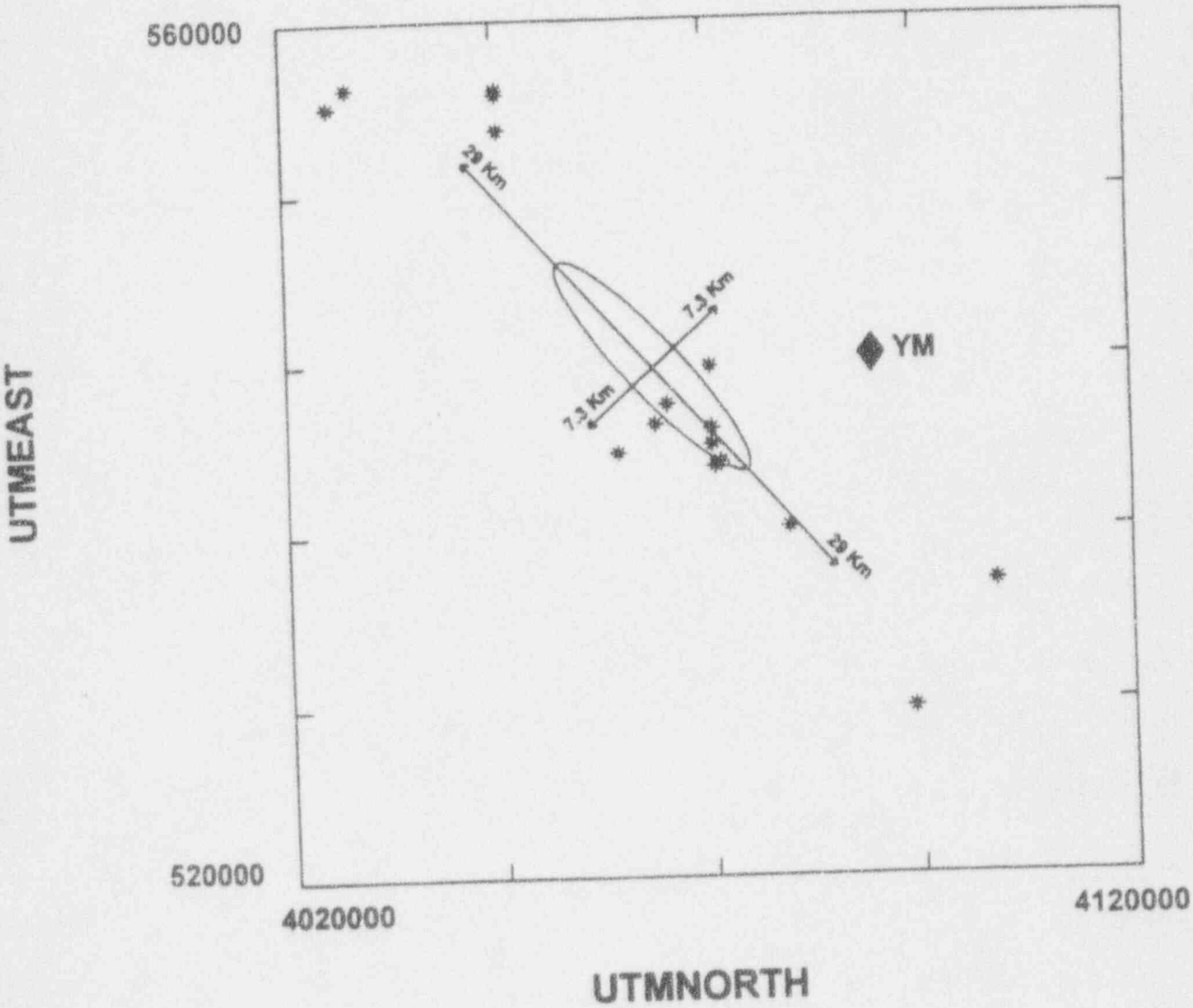
Table 7.14 (cont)

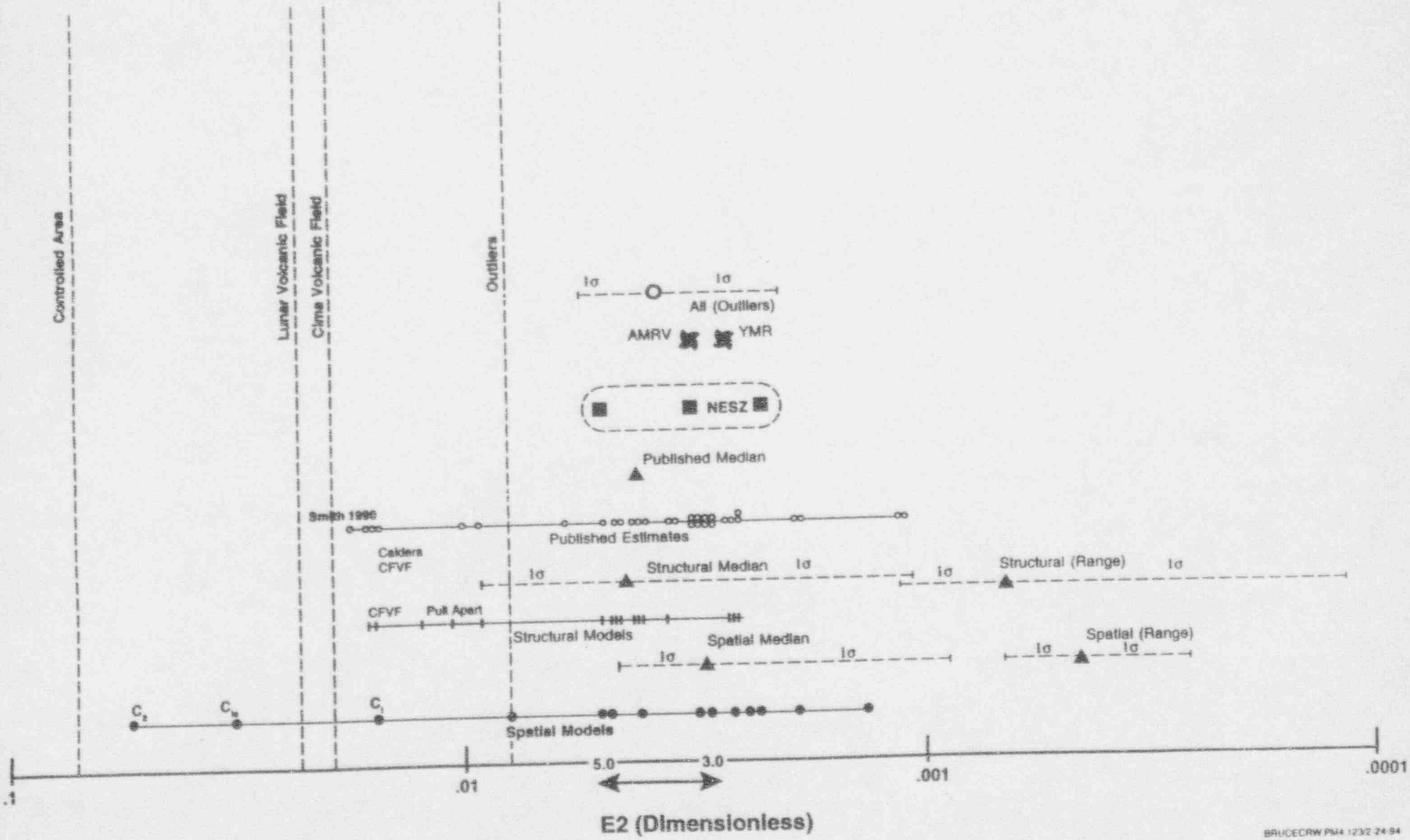
Model 12: Northeast Structural Zone: The YMR is located in a diffuse northeast trending, tectonic-volcanic rift zone. Sites of basaltic volcanism are more common in the zone than outside the zone; composite model proposed by Carr (1984; 1990; Kawich-Greenwater Rift zone, and Wright 1989; Amargosa Desert Rift zone).	***Supportive Evidence**: northeast-trending zone of closely spaced, normal faulting, orientation of caldera centers in the southwest Nevada volcanic field. northeast trending structural trough that is delineated partly by gravity data, concentration of basaltic volcanic centers in the northeast-trending structural zone.*	**Negative Evidence:** structural zones may be a composite of multiple different structures, basalt centers are present both in and outside the structural zone, northwest linear alignment of basalt centers occur within the northeast-trending zone.	
Model 13: Crater Flat and Buckboard Mesa volcanic zone: The basalt centers of Crater Flat and the basalt of Buckboard Mesa form a northeast trending zone that extends through the potential Yucca Mountain site (proposed by Smith et al. 1990 and Naumann et al. 1992).	***Supportive Evidence**: local northeast trends of basalt vents in Crater Flat, existence of the basalt centers of Crater Flat, and Buckboard Mesa.*	**Negative Evidence:** Distance of separation between the Crater Flat basalt centers and the basalt of Buckboard Mesa, interruption of the northeast-trends by oblique structures of the Timber Mountain-Oasis Valley caldera complex, northwest-trending vent alignments of the basalt of Buckboard Mesa, no basalt centers between Crater Flat and Buckboard Mesa.	

Table 7.15. Estimations of E2 for Structural Models of the Yucca Mountain Region.

Model Number	Name	Time Interval	Intersection repository	Area (km^2)	Forced Intersection	Likelihood Intersection	E2 Intersection	E2 Interior	E2 Front
Model 1	CFVZ	1.00	no	1100	1310	Low	4.6E-03	6.9E-04	1.2E-03
Model 2	CFVZ	3.85	no	1350	1450	Low	4.1E-03	6.2E-04	1.0E-03
Model 3	YMR/AMRV	4.80	yes	2180	2180	High	2.7E-03	4.1E-04	6.9E-04
Model 4	CFVF	3.75	no	220	400	Unlikely	1.5E-02	2.2E-03	3.7E-03
Model 4a	CFVF with AV	3.85	no	750	750	Unlikely	8.0E-03	1.2E-03	2.0E-03
Model 5	Strike Slip	1.00	no	1100	1310	Low	4.6E-03	6.9E-04	1.1E-03
Model 6	Strike Slip	4.80	no	1350	1450	Low	4.1E-03	6.2E-04	1.0E-03
Model 7	Stress-Dike	1.00	no	1100	1310	Low	4.6E-03	6.9E-04	1.1E-03
Model 8	Stress-Dike	4.80	no	1350	1450	Low	4.1E-03	6.2E-04	1.0E-03
Model 9	Chain Model	3.75	no	390	450	Low	2.7E-03	4.0E-04	6.7E-04
Model 9a	Chain Model	3.85	no	500	690	Low	7.8E-04	1.2E-04	2.0E-04
Model 10	Pull-Apart	3.75	no	390	450	Unlikely	1.3E-02	2.0E-03	3.3E-03
Model 10a	Pull-Apart	3.85	no	500	690	Unlikely	8.7E-03	1.3E-03	2.2E-03
Model 11	Caldera	3.75	no	220	400	Moderate	1.5E-02	2.2E-03	3.7E-03
Model 12	Kawich Rift	3.75	yes	1700	1700	High	3.5E-03	5.3E-04	8.8E-04
Model 12a	12 with AV	3.85	yes	2250	2250	High	2.7E-03	4.0E-04	6.7E-04
Model 13	NESZ	3.75	yes	1200	1200	High	5.0E-03	7.5E-04	1.2E-03
				Statistics	***(all models)***	***Mean***	***6.1E-03***	***9.1E-04***	***1.5E-03***
						Median	***4.6E-03***	***6.9E-04***	***1.1E-03***
						Geomean	***4.8E-03***	***7.2E-04***	***1.2E-03***
						StdDev	***4.4E-03***	***6.6E-04***	***1.1E-03***
				Statistics	***(intersection models)***	***Mean***	***3.5E-03***	***5.2E-04***	***8.7E-04***
						Median	***3.1E-03***	***4.7E-04***	***7.8E-04***
						Geomean	***3.4E-03***	***5.0E-04***	***8.4E-04***
						Std Dev	***1.1E-03***	***1.6E-04***	***2.7E-04***

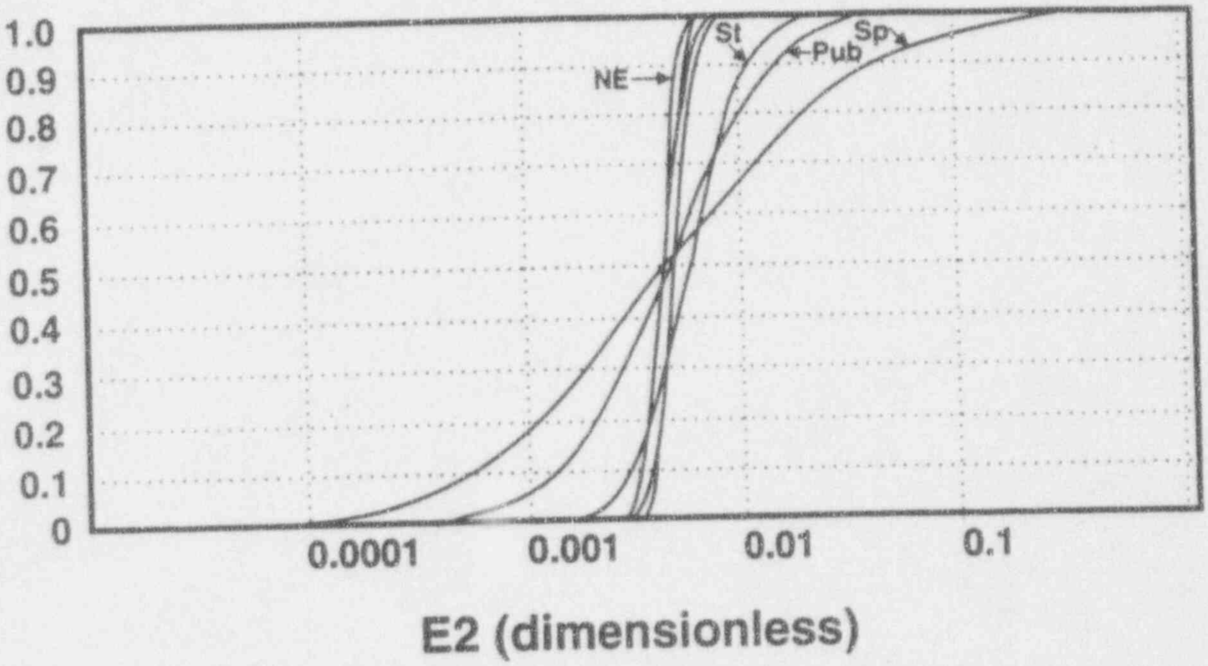

Y-Axis
X-Axis
1
2
3
4
5
6
7
8
0
2
4
6
8
10


560000
520000
4020000
4120000
UTMEAST
UTMNORTH
YM
29 Km
29 Km
7.5 Km
7.5 Km



BRUCECRW PM4 123/2 24 94

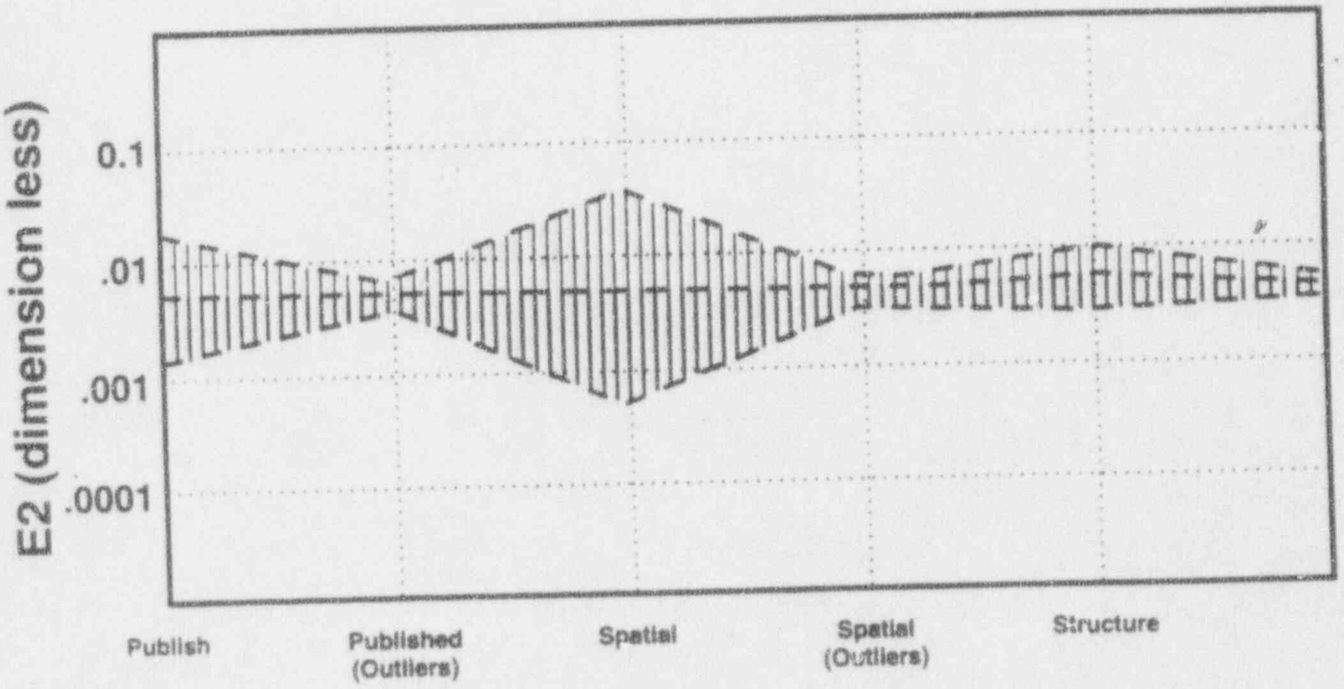
Simulation Results: E2



Expected Value

All Published $4.1E^{-3}$
Published (outliers) $3.8E^{-3}$
All Spatial $3.1E^{-4}$
Spatial (outliers) $2.8E^{-3}$
Structural $4.6E^{-3}$
NE Trend $3.1E^{-3}$

Risk Summary: E2intersect

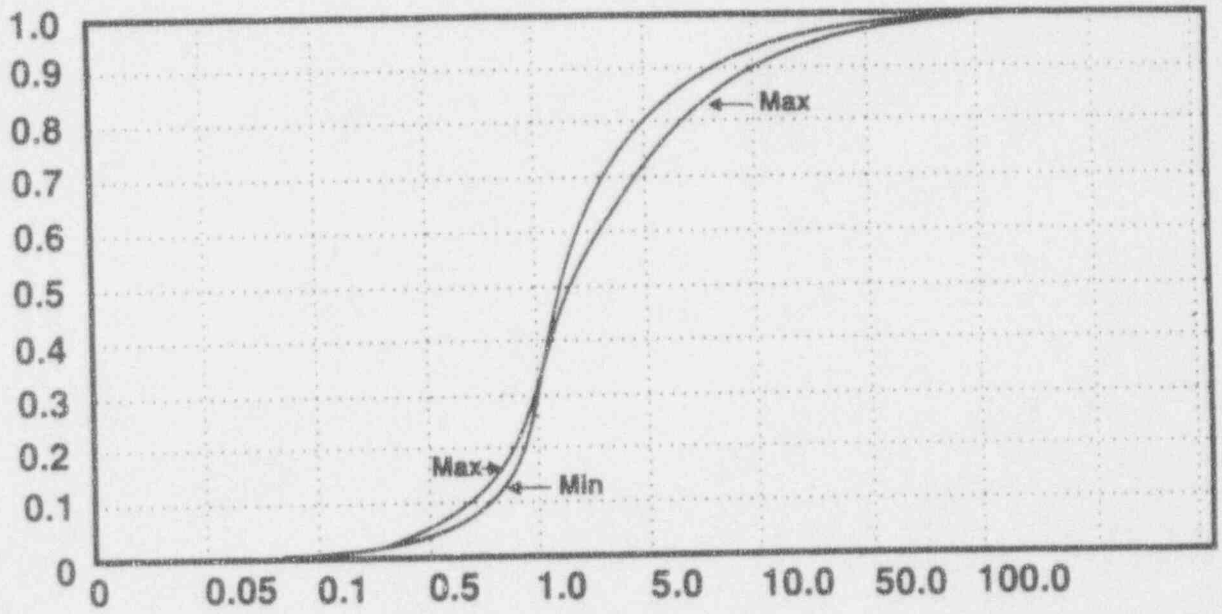


Top - - - - **90 per %**

Center - - - - **Mean**

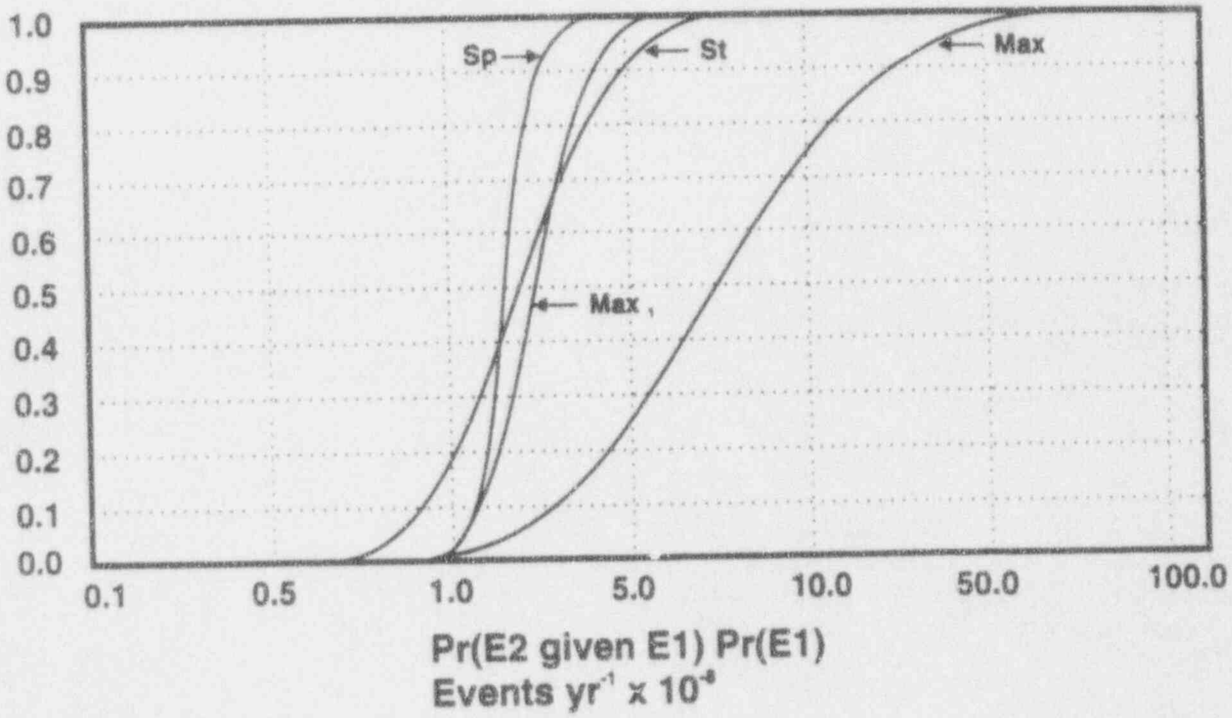
Bottom - - - - **10 per %**

Simulation Results: E2 Fixed



Pr(E_2 given E1)Pr(E1)
Events $yr^{-1} \times 10^{-6}$

Simulation Results: Intersection Models



Expected Value

Structural 2.25 x 10^{-8}
Spatial 1.5 x 10^{-8}
Maximum 7.3 x 10^{-8}
Maximum 2.4 x 10^{-8}
(outliers)

Table 7.23. Probability of magmatic disruption of the repository where the recurrence rate (E1) is adjusted for individual spatial and structural models of E2.

Spatial Models	E2	E1 Adjusted	Pr(E2 given E1)Pr(E1) Intersection	Z Score	Range
Cluster 1 (3.7)	*1.5E-02*	*2.6E-06*	*4.01E-08*	1.4	*6.0E-09*
Cluster 1a (3.85)	8.0E-03	2.3E-06	1.9E-08	0.0	2.8E-09
CFVZ (4.8)	4.1E-03	3.7E-06	1.5E-08	-0.1	2.3E-09
NESZ (3.85)	5.0E-03	3.6E-06	1.8E-08	0.0	2.7E-09
Cluster 1a (1.0)	*1.5E-02*	*5.0E-06*	*7.5E-08*	3.6	*1.1E-08*
CFVZ (1.0)	4.6E-03	6.0E-06	2.7E-08	0.6	4.1E-09
Structural Models					
CFVZ (1.0)	4.6E-03	6.0E-06	2.7E-08	0.6	4.1E-09
CFVZ (4.8)	4.1E-03	2.5E-06	1.0E-08	-0.5	1.5E-09
YMR (4.8)	2.7E-03	2.5E-06	6.9E-09	-0.7	1.0E-09
CFV Field (3.75)	1.5E-02	1.6E-06	2.4E-08	0.4	3.6E-09
CFV Field + AV	8.0E-03	2.3E-06	1.9E-08	0.0	2.8E-09
Strike Slip (1.0)	4.6E-03	6.0E-06	2.7E-08	0.6	4.1E-09
Strike Slip (4.8)	4.1E-03	2.3E-06	9.5E-09	-0.5	1.4E-09
Stress-Dike (1.0)	4.6E-03	2.7E-06	1.2E-08	-0.4	1.8E-09
Chain Model (3.7)	2.7E-03	1.6E-06	4.3E-09	-0.9	6.4E-10
Chain Model (3.85)	7.8E-04	2.1E-06	1.6E-09	-1.0	2.4E-10
Pull-Apart (3.7)	1.3E-02	1.6E-06	2.1E-08	0.2	3.2E-09
Pull-Apart (3.85)	8.7E-03	2.1E-06	1.8E-08	0.0	2.7E-09
Caldera (3.75)	1.5E-02	1.6E-06	2.4E-08	0.4	3.6E-09
Kawich Rift (3.7)	3.5E-03	1.6E-06	5.6E-09	-0.8	8.5E-10
Kawich Rift (3.85)	2.7E-03	2.1E-06	5.5E-09	-0.8	8.3E-10
NESZ (3.7)	5.0E-03	1.9E-06	9.4E-09	-0.6	1.4E-09
	Summary Statistics	*Mean*	*1.9E-08*		*2.9E-09*
		Median	*1.8E-08*		*2.7E-09*
		Geomean	*1.5E-08*		*2.2E-09*
		StDev	*1.6E-08*		*2.1E-09*
		Skewness	*2.2*		*2.2*
		Minimum	*1.6E-09*		*2.4E-10*
		Maximum	*7.5E-08*		*1.1E-08*

What Have We Learned
Probability Estimates

1. Recurrence Models: well constrained

    insensitive to mid-point estimates
    boundary assumptions far more important

How much could they Change?
    undetected intrusions
    undetected centers

    Factor of 2 or 3 to be significant

14 to 21 *undetected* centers or intrusions

2. Structural Models

    small number of structural/spatial models are significant
        dike lengths
        structural models
        Geophysics/field studies may be useful
        Pliocene or Quaternary dikes in exploration block
    Northeast-trending models are not sensitive

Judgment required: suitability of high probability disruption ratios

3. Effects Studies are Needed

    Controlled Area
    Yucca Mountain Region
    Repository (dependent on range interior models)

Judgment required: suitability of models
criterion on probability distribution curve

Future Directions
Probability/Volcanism Studies

1. Examination of Polycyclic Models/Probability Estimates

    High E1, very low E2, probable very very low E3

    "Standoff" distance being assessed for subsurface effects

2. Geophysical Studies

    Magma bodies
    Test structural models
    Subsurface geometry: small volume basalt centers
    Undetected features (but is this significant?)

3. Evolutionary Patterns of Volcanic Fields

    Test assumptions of probability models

4. Yearly Updates: Probability Estimates

    Sensitivity to site characterization
    Simulation Framework Established: Revisions relative easy

5. Importance of Expert Judgment

USE OF EXPERT JUDGMENT IN YUCCA MOUNTAIN PROBABILISTIC VOLCANIC HAZARD ASSESSMENT

Kevin Coppersmith
Roseanne Perman
Geomatrix Consultants

Bruce Crowe
Los Alamos National Laboratory

Jeanne Nesbit
DOE YMSCPO

Jean Younker
Martha Pendleton
TRW/M&O

Nuclear Waste Technical Review Board
Structural Geology and Geoengineering Panel

March 8-9, 1994
San Francisco, CA

OVERVIEW OF PVHA PROJECT

Status

The project is just beginning. The first task will be the development of a program plan and a peer review plan.

Purpose

1. To quantify the probability of occurrence of volcanic activity in the Yucca Mountain vicinity and the probability of disruption of the repository due to volcanic processes
2. To quantify the uncertainties associated with these assessments, including the diversity of interpretations among multiple experts

Procedure

To be determined. Role of the technical facilitator/integrator will be defined. Process will include selecting experts, facilitating expert interaction, eliciting expert judgment, and aggregating expert judgments. Documentation procedures will be defined.

PERTINENT PRECEDENTS IN EXPERT JUDGMENT METHODOLOGIES

- EPRI Yucca Mountain Earthquakes and Tectonics Project
- EPRI Yucca Mountain Performance Assessment Project
- CNWRA Assessment of Future Climate
- DOE, NRC, EPRI Seismic Hazard 'Resolution' Project
- LLNL/NRC Eastern U.S. Seismic Hazard Assessment
- EPRI Eastern U.S. Seismic Hazard Assessment
- SNL studies for WIPP

COMMONLY ASKED QUESTIONS ABOUT EXPERT JUDGMENT AND THE YUCCA MOUNTAIN PVHA PROJECT

What is expert judgment?

The analysis of pertinent data by knowledgeable individuals to arrive at interpretations of the likelihood of future events.

Why use expert judgment?

Earth sciences data do not provide a unique determination of what will occur in the future. There is always a need for some analysis of the data; this analysis is termed 'expert judgment'.

When should expert judgment be used?

In a strict sense, expert judgment is required any time analysis of data is needed. The explicit documentation of the judgments of multiple experts can be an effective way of dealing with important earth sciences issues that are associated with considerable uncertainty.

Is expert judgment being used to avoid data collection?

Expert judgment is *not* a substitute for data collection--they are two separate processes. Data must be gathered to define the location, nature, extent, and frequency of volcanic processes. To arrive at an interpretation of the likelihood of future volcanic processes, these data must be interpreted by one or more experts.

Why use multiple experts?

Interpretations of the same set of geologic data by different knowledgeable individuals can be different. These differences can be due to different methodologies and/or different levels of reliance on the available data. In most cases, the presence of larger amounts of high-quality data leads to greater agreement in the interpretations by multiple experts.

Why use expert judgment when the YM project scientists have worked on the volcanic hazard problem for over ten years?

The YM project scientists are themselves experts; hence, the analysis of data by Bruce Crowe et al. is itself 'expert judgment'. It is probable that there are other knowledgeable experts outside of the YM project who can provide their interpretations of the available data as well.

Is there a precedent for using expert judgment in PVHA?

Perhaps not specifically for PVHA, but for other natural hazards. For example, considerable experience has been gained in the use of multiple experts for assessing earthquake hazards. These studies, which have a regulatory context, have direct applicability to the development of an appropriate methodology for the volcanic hazard analysis at Yucca Mountain.

What is the best way to incorporate the judgments of multiple experts?

There is no unique methodology for eliciting and incorporating the judgments of multiple experts. Approaches have ranged from the independent elicitation of multiple experts, to the development of 'consensus' assessments with a group of experts, to the peer review of assessments developed by a single group. The pros and cons of these approaches will be evaluated in the course of developing a methodology for the Yucca Mountain PVHA project.

BASIC COMPONENTS OF THE METHODOLOGY

- Selection of the experts
- Identification and review of technical issues:

  Workshops, field trips, interactions

- Training in elicitation methods
- Elicitation of experts:

  Individual interviews, feedbacks

- Compilation of results, sensitivity analysis
- Documentation of entire process

Nuclear WasteTechnical Review Board

Meeting of March 8-9, 1994

Probabilistic Natural Hazard Estimation for Use in Design of Engineered Facilities

C. Allin Cornell

A Bias: I am an ardent supporter of probabilistic methods for this purpose. At each step below ask yourself: does a deterministic method do this as well, as completely, or at all?

1. Products to Engineers/Decision Makers
   - **Estimate of the Probability** (mean frequency) **that in the next n years a specified "effect" variable** (or variables) **will exceed a specified level** (or levels). Formats: hazard curves, scenarios, etc.
   - **Provide representative quantitative statements about the epistemic (knowledge-related) uncertainty** associated with these estimates. Formats: sensitivity studies, confidence bands, etc.

2. Objectives of the Process
   - **Communicate, coordinate, describe,** integrate, etc. **all the scientific information** (data, evidence, theories, interpretations, etc.) about the relevant elements, identify factors (critical to the conclusion) for further investigation.
   - **Combine this scientific information into** a representative **scrutable, defendable hazard estimate and uncertainty statement.**
   - **Communicate the hazard estimate and the confidence levels** among the various specialists and to the users (technical and other) in the most effective way.
   - **Avoid** implicitly or explicitly **making value judgements in isolation.** Priority setting, risk-cost-benefit analysis, implications of "beyond-design-basis" loads, "how safe is safe enough", etc. are the purview of others in the chain. "Enough is enough" is in this category.

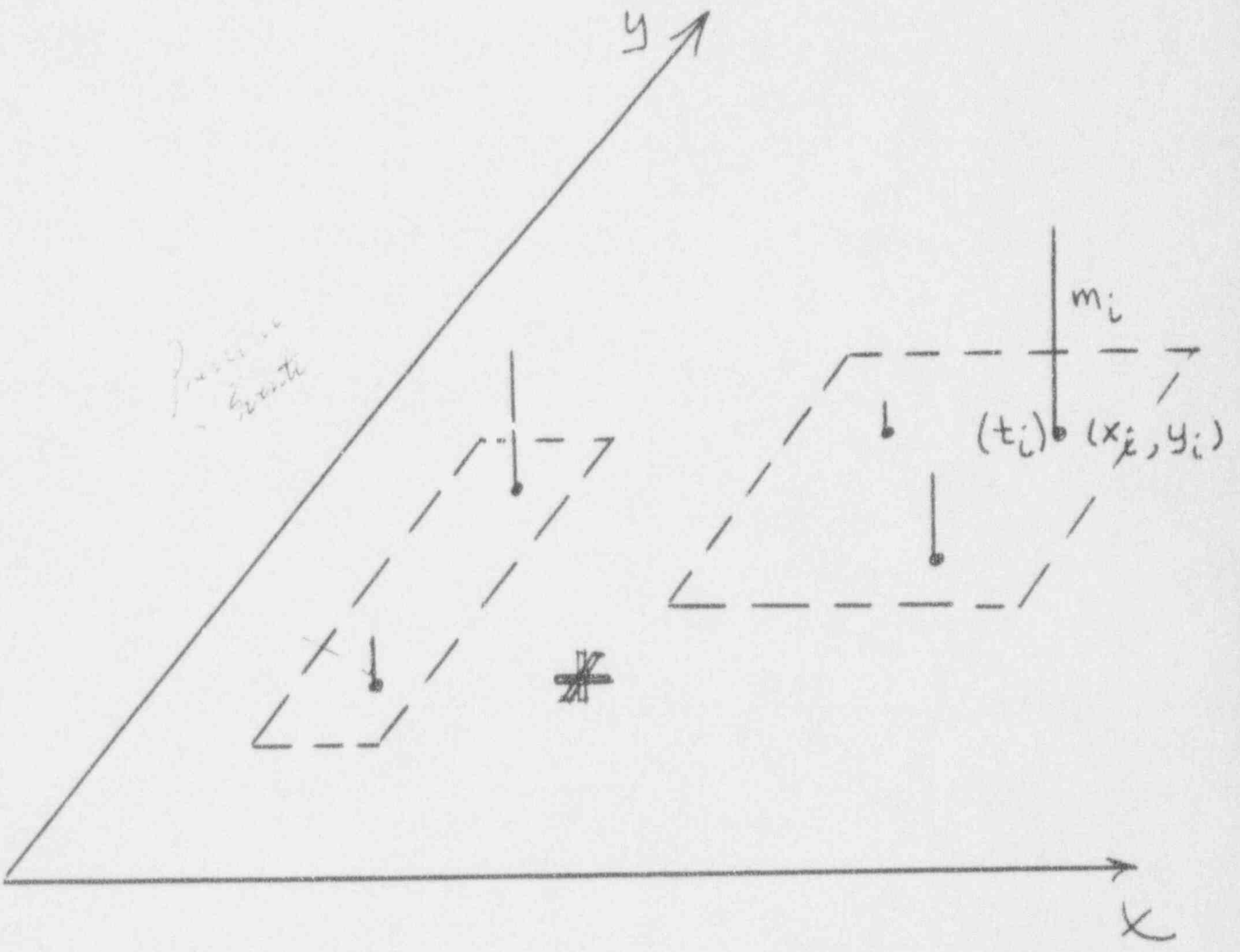
3. Background
   - **Probabilistic characterization of "design loads", etc., grew out of engineering need** to provide reasonable and uniform (across sites, across load types, etc.) design bases. Direct-empirical basis: floods and wind loads, since early this century. More structured models for seismic, hurricane winds, and waves, etc., in last 30 years or more.

- **Today design** in all countries in all fields **of virtually every engineered facility** for resistance to extreme natural hazards **is based on a probabilistic load definition**: offshore structures, buildings, etc.; wave loads, tornado loads, as well as seismic loads. Remaining exceptions include some critical facilities; e.g. large dams for floods and earthquakes. "Higher tech" fields are more likely today to use a probability basis in more fundamental ways, e.g., if objective is 10^{-3} or 10^{-4} performance goal, assess at 10^{-3} or 10^{-4} load level (as opposed to a 10^{-2} level times an "ad hoc" factor).
- **There is much greater variability, "randomness", and uncertainty in natural hazards than in the engineered system itself.**

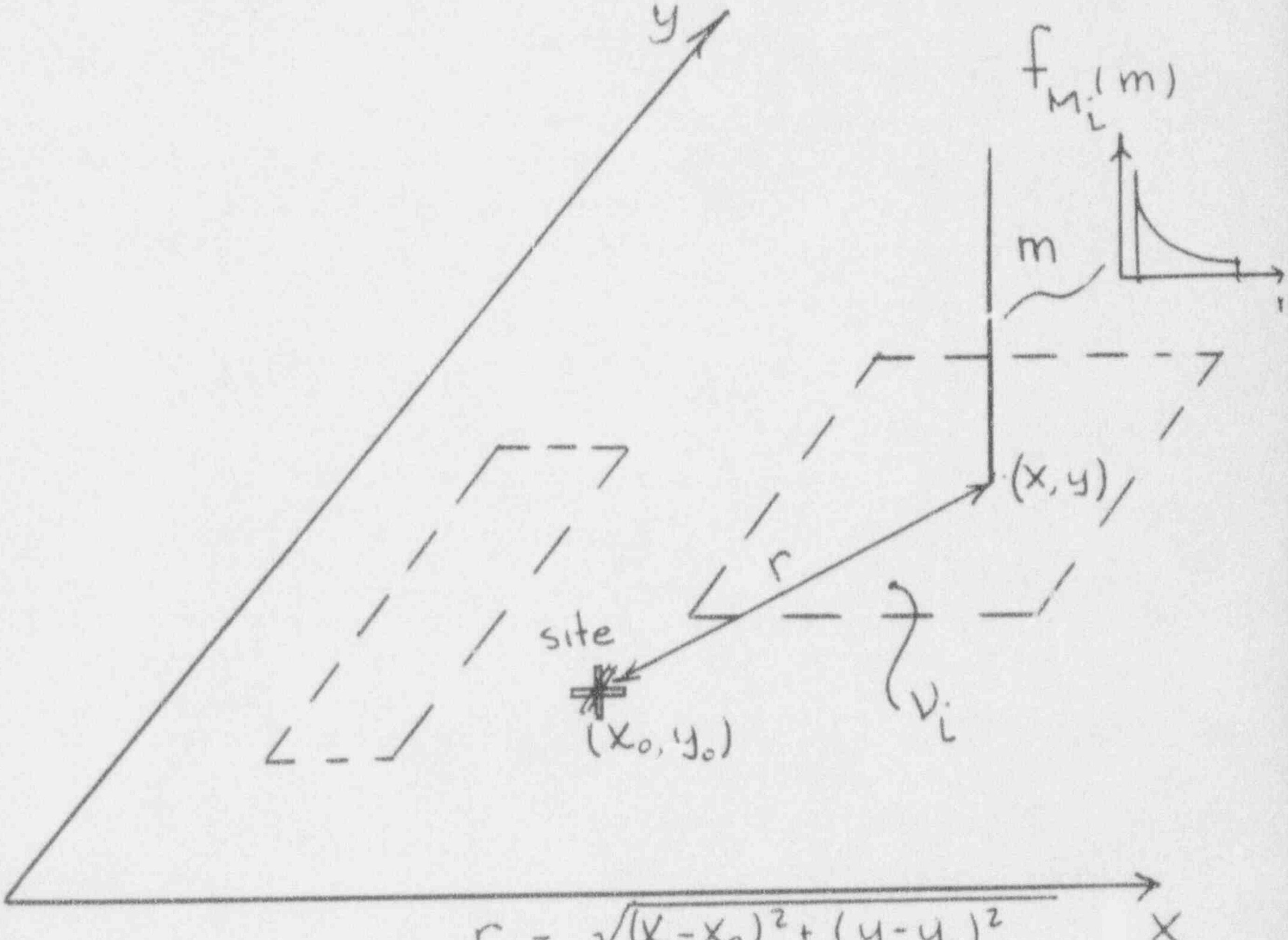
  Hence, it is critical that their characterization be probabilistic.
- **What is recent (1980's) and more narrowly applied is: The explicit quantitative treatment of epistemic uncertainty** (parameter value uncertainty, model uncertainty, formal staistical analysis, expert elicitation, aggregation of diverse judgements, etc.). The seismic, nuclear field has been a leader in applying these tools.

4. Basic Structure of Usual Models and Assessment

- **The probabilistic/stochastic model:** a temporal, spatial recurrence model (usually a marked point process) coupled with a random effects model. Examples: Tornado occurs in effect at a point in time and space with random "source" characteristics: maximum wind speed, travel speed, path width, length, and orientation; and with a random field effect; e.g., the mean wind-speed field falls of roughly geometrically on either side of the path center line, but there is variability about the mean. Earthquakes and their effects (ground motion and faulting), and volcanoes and their effects are analogous.
- **Each element of the model requires probabilistic characterization;** e.g., the mean annual occurrence rate of events is non-uniform in space; it may or may not be homogeneous in time; the recurrence process may or may not be Poissonian (e.g., a more general, renewal model permits either clustering or more "cyclic" behavior). The stochastic model should be as complicated as the scientific information requires. Alternative models are commonly retained.
- **A vector of parameter values is identified and values estimated**; the mean annual rate now and in the future. Some parameters may also vary spatially. Critical parameters <u>may</u> be limits; e.g., upper bound magnitudes, maximum displacements. Here deterministic and probabilistic approaches to setting a design basis <u>may</u> share a common focus.



Time Space
Occurrence Model - for Low frequency Events



$$r = \sqrt{(x-x_0)^2 + (y-y_0)^2}$$

$$p = f(m, r)$$

$$= 1 - \Phi\left(\frac{\ln a - \ln(q(m,r))}{\sigma_{\ln a}}\right)$$

Effecti

- **Numerical analysis**: For these models, complex as they may be, this step should not be a barrier. Nor need this step be one that causes a lack of transparency. That comes next.

- **Uncertainty Assessment, Elicitation, Aggregation**

  The "simple" objective is a point estimate of each parameter value and a probability distribution describing the (epistemic) uncertainty about that value. The reality is that:

  (1) The model is complex (in order to capture what is known) involving many parameters which may vary over time and space; **uncertainty analysis adds another dimension on top**; therefore, the description, characterization, communication, formal estimation, elicitation of uncertainty in individual's interpretation, etc., are difficult to do, to comprehend, to make transparent, etc.

  (2) The concept of "parameter" estimate and uncertainty has to be extended in extreme cases to include alternate models (theories) and "relative weights".

  (3) Important cases should reflect diversity of experts' interpretations.

  (4) The process of eliciting uncertainty in expert technical interpretations has not been without its difficulties. Scientists are not necessarily trained or gifted in uncertainty analysis, expression, communication, etc. Experts in these topics cannot be expected to have deep knowledge in the relevant fields of science. Yet they must interact effectively.

  No major project should underestimate the difficulty of this part of the process. Insufficient care can distort the "answers". Yet it is necessary to the communication to forward in the design /decision process.

5. Examples

- As mentioned, virtually all structures today are designed based on loads with specified mean return period. Traditionally, the design basis was linear elastic behavior under "not unexpected load levels", e.g., 100-year mean return periods. But more recently, more advanced practice has had a second-level design check at the level of near-failure (implying non-linear structural behavior) for loads with annual frequencies approximately equal to the target failure probability ("performance goal"). Examples include the Norwegian Petroleum Directorate wind-wave-current criteria for offshore structure design, and American Petroleum Institute guidelines for seismic design and re-evaluation. This practice culls out brittle, non-redundant systems, and it better characterizes site-to-site differences in hazard at the levels that really matter to safety, but it requires natural hazard estimates in the 10^{-3} to 10^{-4} range. (This practice would likely have avoided the catastrophic life loss potential that the failure of several long-span parking garage failures in the 1994 Northrdige represented.)

- The evaluation of probabilistic seismic hazard estimation for U. S. nuclear power over the last 20 years is on the whole a success story in my opinion, but one not without its difficulties. It has made it possible to make realistic probabilistic risk assessments that permit comparison with other initiators, and to develop new probability-based design bases. The robustness of the estimates has been a continuing issue. The current level of agreement between EPRI and LLNL Eastern U. S. hazard estimates (medians and, now, means) is hopefully a stable one.

6. Issues and Problems

- **Of necessity we are dealing with very rare events**, implying

  (a) the need to exploit all relevant information, be it measured data or expert interpretation;

  (b) it is necessary to combine sources of information: model building, space-for-time exchanges, analogues, etc., and this demand expert interpretation;

  (c) the preferred approach is one of building a physically-based model and deducing very small probabilities and combinations of not-so-small probabilities;

  (d) the final results are difficult to test by formal statistics and the judgements are difficult to calibrate.

- **Multiple disciplines are involved**; communication and cross-training are essential and time-consuming. Probability is common but not universally practiced language.

- **The results are often used in a highly visible arena**, with a perhaps contentious environment, with implications with respect to defensibility, concensus, etc.

- **Probabilistic analysis is non-trivial and not familiar to all involved.** The physical processes are spatial and temporal and vector-valued. The corresponding (less familiar) probabilistic models are, therefore, not trivial. The added dimension of uncertainty characterization is still more difficult and much less familiar, and, indeed, not fully mature as a (social) science. To be complete, therefore, it is difficult to maintain transparency to all concerned. Both developers (scientists) and users (engineers, managers, decision-makers) must make an effort. Perhaps, more effort is needed at the interface to improve the communication to insure trust.

I was aked to comment on:

- **Krinitzsky's Kriticisms:** I am familiar only with his "Hazard of Hazard Analysis" article in Civil Engineering magazine: yes, the use of probability is dangerous but so is the use of axes, power saws and brain surgeon's scalpels. Are the alternatives less so?

7. Yucca Mountain Specific Issues

- **The long-time frame** has implications with respect to:

  (a) sensitivity of certain assumptions, e.g., the **Poisson versus Non-Poisson** decision is less critical for those events whose mean recurrence time is less than the facility life;

  (b) the need for clear thinking about the **statement of the criteria**: how, if at all, is a 10^{-2} risk in 10^{-4} years different from a 10^{-6} risk per year if all processes are stationary? (Most engineering life safety criteria are expressed in annual terms and for good reasons.) If they are not different, is the question only whether or not the physical process is stationary (in a 10^{-4} year time frame)? And then only non-stationary to a degree (e.g., a factor of 10 or more in 10^{-4} years) greater than current uncertainty bounds in the current annual rate? Given the discounting in consequences (including lives lost) permitted in modern risk-cost analyses, future events are less important than current ones, implying less sensitivity of decisions to uncertainties about the distant future. (And, yes, discounting of future lives lost is consistent with inter-generational equity concerns; current capital resources buried 'unnecessarily' at Yucca Mountain will deprive future generations of some of the benefits of compounded technological growth that must be delayed for lack of capital.)

  ? 10^{4}

- The fact that **the facility involves radioactive waste** implies that this is very serious business and that the scientists must, therefore, do a state-of-the-art job analyzing and communicating the natural hazards and their uncertainties; this implies using the most complete tools available (i.e., probability and uncertainty analysis) even if the users, reviewers, decision makers, etc., have to make an increased effort to improve their understanding and comfort.

- Within the limits of my understanding (which are severe in the first case), **volcanism and earthquakes are equivalent problems** from the perspective of this general overview of probabilistic natural hazard assessment.

*Does either of **two deterministic methods of determining a design basis earthquake (the EUS or the California version) apply in the Yucca Mountain short-history, very low displacement rate context?**

U.S. DEPARTMENT OF ENERGY
OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT

NUCLEAR WASTE TECHNICAL REVIEW BOARD
STRUCTURAL GEOLOGY AND GEOENGINEERING PANEL MEETING

SUBJECT: **USE OF PROBABILISTIC VOLCANIC HAZARD ASSESSMENT IN THE YUCCA MOUNTAIN PROGRAM**

PRESENTER: **DR. JEANNE C. NESBIT**

PRESENTER'S TITLE AND ORGANIZATION:
GEOLOGIST
REGULATORY AND SITE EVALUATION DIVISION
LAS VEGAS, NEVADA

PRESENTER'S TELEPHONE NUMBER: (702) 794-7930

SAN FRANCISCO, CALIFORNIA
MARCH 8-9, 1994

Overview

- Objectives of probabilistic volcanic hazard assessment (PVHA)
- Use of PVHA in programmatic and statutory decisions
- Use of expert judgment
- Determination of when “enough is enough”
- Critical studies that need to be completed

Objectives of Probabilistic Volcanic Hazard Assessment

- Assess the probability of magmatic disruption of the potential repository and/or waste isolation system
- Constrain the effects of magmatic events at or near the potential repository

Primary focus to date: Is the probability of magmatic disruption of the potential repository large enough to disqualify the Yucca Mountain site?

Use of PVHA in Programmatic and Statutory Decisions

Regulatory Requirements

10 CFR 960

- Compliance with
  - 40 CFR 191 total system performance requirements
  - 10 CFR 60
    - Engineered barrier system containment and release rate requirements
    - Total system performance requirements
- Meet the postclosure tectonics qualifying condition

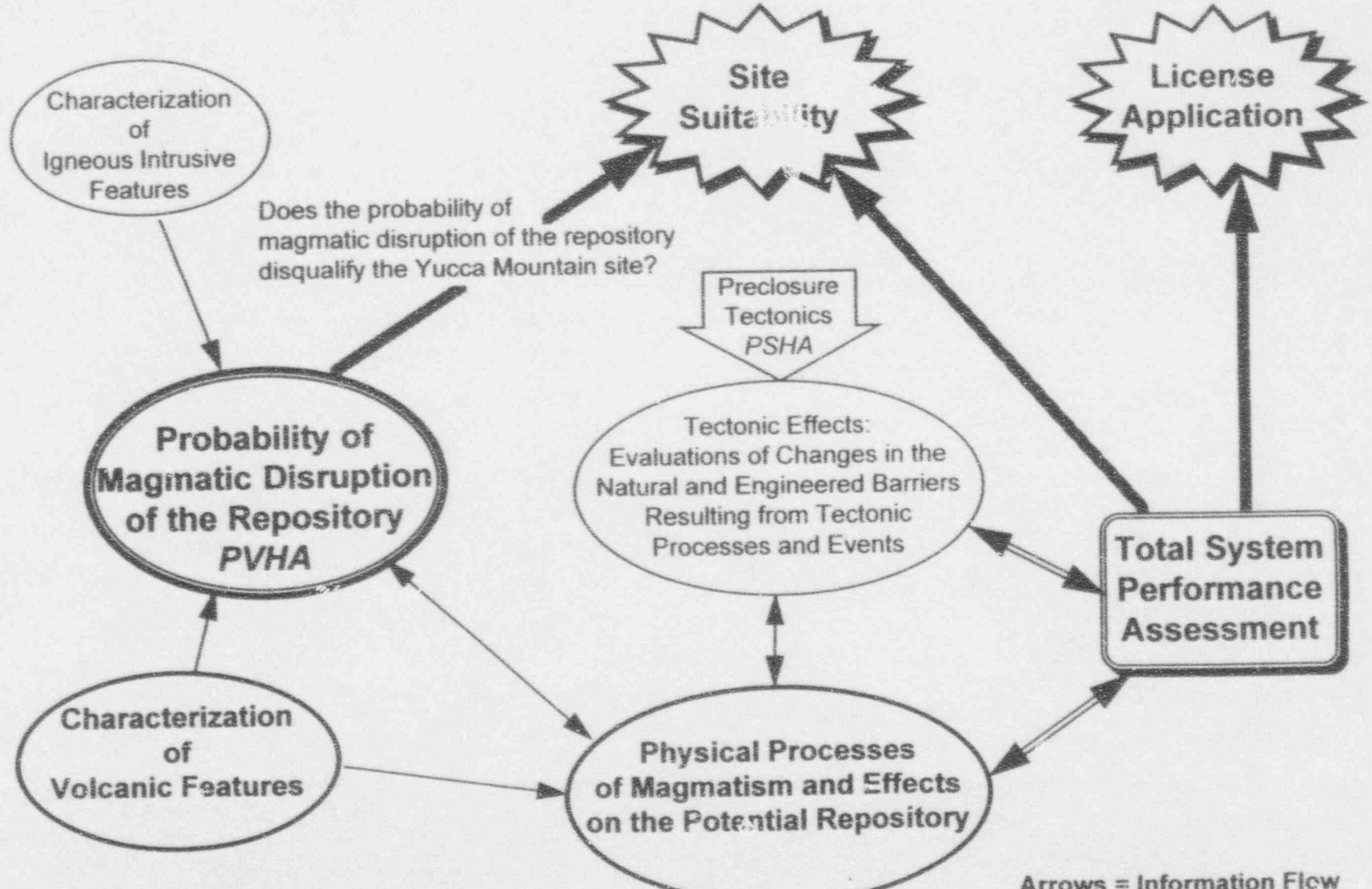
10 CFR 60

- Potentially adverse condition of volcanism does not significantly impact total system performance

Use of PVHA in Programmatic and Statutory Decisions

- Early Site Suitability Evaluation (1992)
  - Tectonics qualifying condition is likely to be met (low level finding)
  - Recommendation: continue volcanism studies as planned
- Total System Performance Assessment
  - TSPA I (1991)
    - » Eruptive effects of dike intrusion into the proposed repository
    - » Consequences do not exceed regulatory release limits (*based on limited "effects" data*)
    - » Recommendations:
      - Estimate probability of occurrence of subsurface events
      - Determine quantity of debris that could be ejected from repository depths during a volcanic eruption
  - TSPA II (1993)
    - » No new volcanism information considered

Use of PVHA in Programmatic and Statutory Decisions



Site Suitability

License Application

Characterization of Igneous Intrusive Features

Does the probability of magmatic disruption of the repository disqualify the Yucca Mountain site?

Preclosure Tectonics *PSHA*

Probability of Magmatic Disruption of the Repository *PVHA*

Tectonic Effects: Evaluations of Changes in the Natural and Engineered Barriers Resulting from Tectonic Processes and Events

Total System Performance Assessment

Characterization of Volcanic Features

Physical Processes of Magmatism and Effects on the Potential Repository

◯ **Volcanism Program Studies**

Arrows = Information Flow for Postclosure Tectonics

Determination of When "Enough is Enough"

Different perspectives = different questions

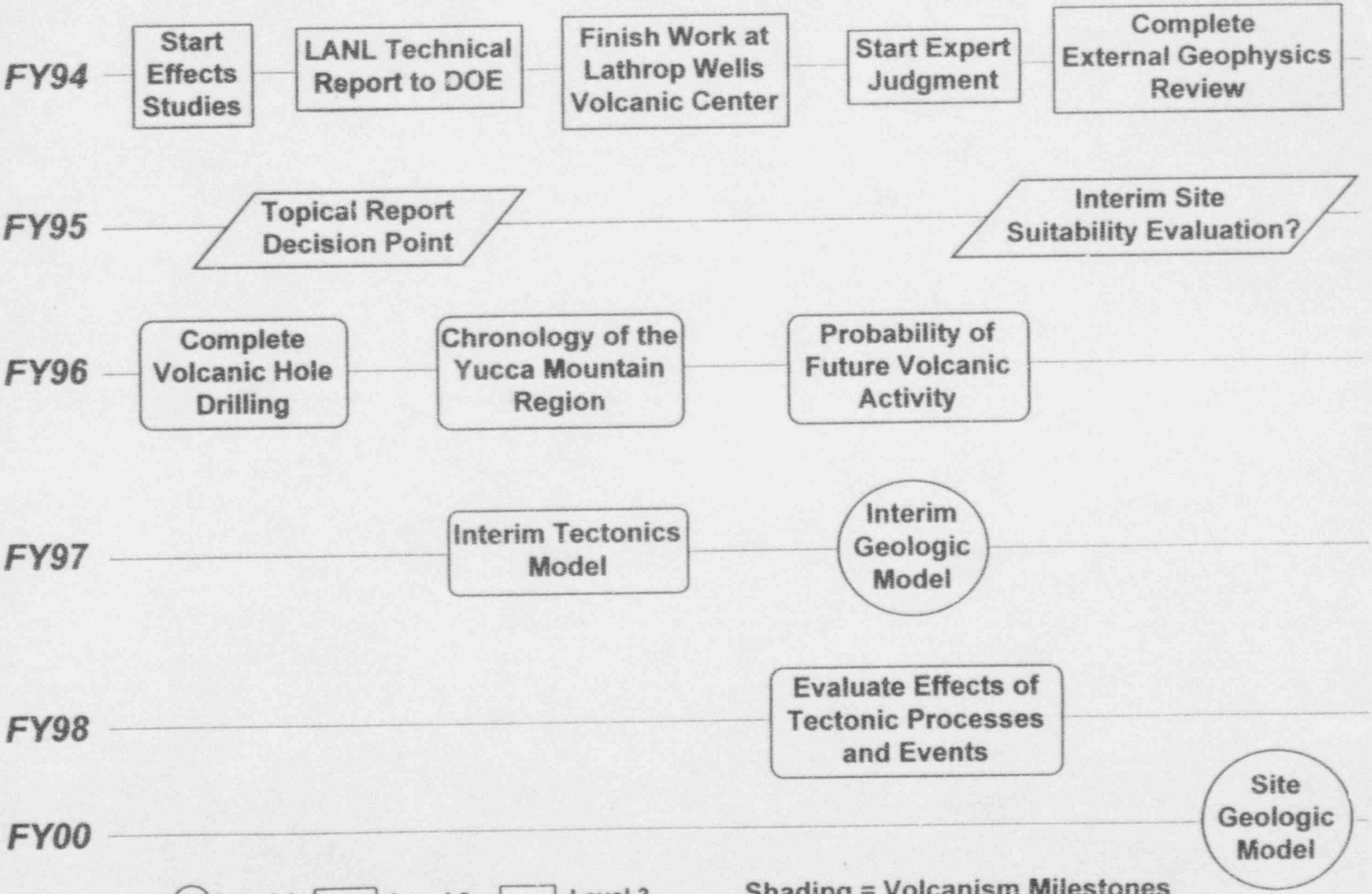
- Principal Investigators
  - Study plans complete?
  - Adequate confidence in results?
- DOE
  - Value of obtaining additional site data vs. cost?
  - Cost/benefit of additional performance assessment?
  - How strong is the case for compliance?

Determination of When “Enough is Enough”

Tools

- Interim site suitability evaluations
- Issue resolution
- Total system performance assessment
- Formal peer review/expert judgment
- Feedback from oversight groups and regulator

Milestones



FY94
- Start Effects Studies
- LANL Technical Report to DOE
- Finish Work at Lathrop Wells Volcanic Center
- Start Expert Judgment
- Complete External Geophysics Review

FY95
- Topical Report Decision Point
- Interim Site Suitability Evaluation?

FY96
- Complete Volcanic Hole Drilling
- Chronology of the Yucca Mountain Region
- Probability of Future Volcanic Activity

FY97
- Interim Tectonics Model
- Interim Geologic Model

FY98
- Evaluate Effects of Tectonic Processes and Events

FY00
- Site Geologic Model

Milestones: ○ Level 1 ▭ Level 2 ▢ Level 3

Shading = Volcanism Milestones

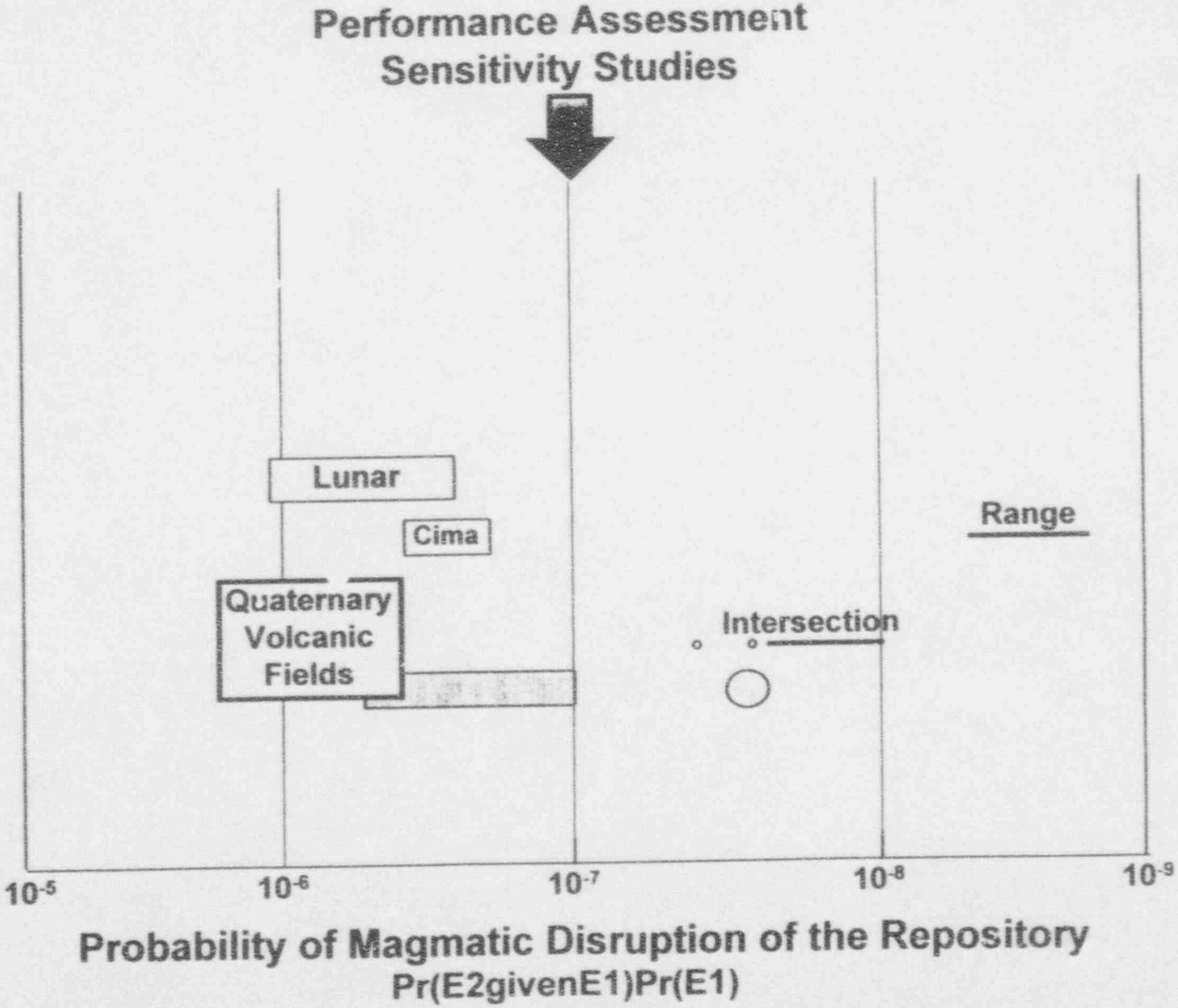
Use of Expert Judgment
Yucca Mountain Volcanism Program

- DOE experts are being used to determine adequacy of data set and analysis
- Independent technical review is accepted part of Yucca Mountain program
- Alternative mechanisms are being considered for ensuring diversity of interpretations and completeness (e.g. peer review, elicitations, etc.)
- Expert judgment will be used to refine volcanism probabilities

Critical Studies Still Needed

- Subsurface effects studies
- Sensitivity studies
- Compilation of a comprehensive eruptive effects data set from natural analogs
- Subsurface information
- Probability of polycyclic volcanism
- Magmatic evolution model for the Crater Flat volcanic zone

Summary
Yucca Mountain Probabilistic Volcanic Hazard Assessment



Priority Items for FY94 and FY95 “Effects” Studies

- Determination of the quantity of debris that could be erupted from repository depth
- Determination of the spatial scales of hydrothermal processes for a relevant range of intrusion geometries and host rock properties
- Eruption mechanisms and volatile content issue
  - Follow strategy in Study Plan
    - » Use analog studies to determine the range of quantities of repository material that could be erupted
    - » IF this range is such that risk simulations suggest E3 is close to unity, then
    - » Pursure detailed eruption models and dispersal mechanism to further constrain E3

PRESENTATION TO THE NUCLEAR WASTE TECHNICAL REVIEW BOARD

ANALYSES FOR IGNEOUS ACTIVITY

Keith McConnell and John Trapp

OUTLINE OF PRESENTATION

- IGNEOUS ACTIVITY:
  1) Basis for Criteria with Respect to Volcanism
  2) Acceptance Criteria for Data and Analysis (When 'enough is enough'")
  3) NRC's Review of DOE's Progress to Date - [illegible] Status Report 8/93 - report DOE
  4) Investigations that are Needed for Hazard Assessment

NWTRB 03/9/94

BASIS FOR NRC CRITERIA WITH RESPECT TO IGNEOUS ACTIVITY

- Criteria with respect to probabilistic analysis of igneous activity relate primarily to determining compliance with the overall system performance objective (60.112); however, the results of these analyses are not, by themselves, the sole criteria by which decisions will be made.

- Associated + Parallel criteria must also be addressed. For example, those related to the investigation of the site, including the requirements of 60.122 (i.e., Potentially Adverse Conditions) that require DOE to:

    A. provide information to determine whether, and to what degree igneous activity is present
    B. provide information to determine to what degree igneous activity is present, but undetected
    C. assure the lateral and vertical extent of data collection is sufficient to determine the presence of igneous activity
    D. evaluate information with assumptions and analysis methods that adequately describe igneous activity

ACCEPTANCE CRITERIA FOR IGNEOUS ACTIVITY

- The Staff considers the following to be minimum requirements for determining when "Enough is Enough."

1. Collection of data used in support of the probabilistic analysis is sufficient to support assumptions made in the analysis.
2. Expert judgement has not been used as a substitute for field or experimental data, or other more technically rigorous information that is reasonably available or obtainable.

NWTRB 03/09/94

NRC ACCEPTANCE CRITERIA FOR IGNEOUS ACTIVITY (Cont.)

3. Analyses are transparent, sensitivity analyses have been performed, alternative models (e.g., statistical and conceptual) have been identified and evaluated, and the results of analyses of individual alternative models are explicitly treated.
4. Analyses clearly reflect the uncertainty in the understanding of tectonic processes.

(Site-specific acceptance criteria are being identified during development of the License Application Review Plan)

- Ultimately, the final determination will be an assessment of repository performance and full consideration of uncertainty.

NRC'S REVIEW OF DOE'S PROGRESS TO DATE

DOE has made progress towards an acceptable PVHA, however,

- DOE's approach does not consider all significant processes and events in the analysis of igneous activity:
  EXAMPLE: The Tripartite probability addresses only a subset of significant processes and events that must be considered.

- Data presented to date to support probabilistic analyses are not sufficient to meet Part 60 requirements:
  EXAMPLE: Geophysical testing to date has not established the extent to which the condition may be present, but undetected or the potential for and extent of structural control.

- DOE's approach appears to emphasize tests and analyses to confirm a preferred model to the detriment of testing alternative models and approaches:
  EXAMPLE: Analyses by CNWRA indicate that homogeneous Poisson models are not suitable for use at YM and other statistical models may affect probability calculations.

NRC'S REVIEW OF DOE'S PROGRESS TO DATE

- Probabilistic models used to date are not transparent and do not address the uncertainty in the analysis.
  EXAMPLE: the CNWRA has demonstrated that uncertainty in ages for basaltic events causes variation in the results of probabilistic analyses. The staff expects the license application to contain this type of uncertainty analysis.

- Probabilistic models used to date are largely based on statistical models and do not adequately incorporate geologic processes and the uncertainty in understanding of those processes.
  EXAMPLE: The potential for structural control and the extent and significance of low velocity zones at depth have not been adequately factored into DOE's analysis.

CRITICAL INVESTIGATIONS AND ANALYSES

Although many critical investigations are ongoing, the following need to be done:

- An assessment of geophysical techniques to determine the level of detection for Quaternary igneous features.
- An appropriate range of tectonic models that address potential for structural contol at depth and near the surface.
- A more robust incorporation of geologic data into the statistical analysis forming the basis of probabilities.
- Site-specific subsurface information on the significance of low-velocity zones at depth at Yucca Mountain.
- Petrologic, mineralogic, and geochemical analyses that adequately test alternative hypotheses used in models.
- A transparent analysis that includes sensitivity analyses to determine the important sources of uncertainty.
- An analysis that includes both direct and indirect effects of igneous activity.

[illegible] [illegible] on [illegible] or [illegible]. [illegible] [illegible] [illegible] ([illegible] [illegible]) [illegible]
CC - status . [illegible] [illegible] [illegible]

Cornell - [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] [illegible]

STATUS OF CNWRA VOLCANOLOGICAL PROBABILITY STUDIES

FIN B-6644

Sheridan - Need to incorporate [illegible] [illegible]:
- Recurrence [illegible] [illegible] cluster - [illegible] [illegible] [illegible] [illegible] [illegible] cluster.

PRESENTED BY
CHARLES B. CONNOR

PRESENTED AT THE
NWTRB MEETING ON PROBABILITY MODELS
MARCH, 1994

Investigators:
Charles B. Connor, Brittain E. Hill, Chin Lin
Gerry L. Stirewalt, Stephen R. Young

CNWRA Project Manager: H. Lawrence McKague

CNWRA VOLCANO PROBABILITY MODELS

OUTLINE OF THE PRESENTATION

- Overview of CNWRA Volcano Probability Models under development
- Spatial and temporal patterns in vent distribution
- The Near-Neighbor Nonhomogeneous Poisson model
- A spatio-temporal homogeneous Markov model
- Limitations of the current CNWRA models

CNWRA VOLCANO PROBABILITY MODELS

Models Under Development at CNWRA

- Near-Neighbor Nonhomogeneous Poisson
- Markov
- Cox (Cluster) Process

How are these models different from other probability models?

These Models:

- Are based on spatial and temporal patterns in volcanism (statistically significant spatio-temporal clustering)
- Avoid the need to define discrete areas in order to estimate probability
- Map probability surfaces (provides a sense of spatial variability)
- Can be expanded to capture geologic detail (easy to integrate into Iterative Performance Assessment and to work toward a geologic hazard map)

CNWRA VOLCANO PROBABILITY MODELS

Volcanoes form spatial clusters in the YMR (Hopkins F-test; Clark-Evans test, K-function) with 99% confidence. Differences in ages of near-neighbor cinder cones are less than expected (99% confidence, paired Student t-test).

- Recurrence rate must vary within the YMR

- Homogeneous Poisson models do not adequately describe volcano distribution

Homogeneous Poisson models will overestimate the probability of volcanism in some parts of the YMR, far from Quaternary volcanoes, and underestimate the probability of volcanism close to late Quaternary Crater Flat volcanoes.

NONHOMOGENEOUS POISSON MODEL

Estimating Recurrence Rate in a Nonhomogeneous Model

One approach is to use near neighbors: $\lambda_r (x,y) = \dfrac{m}{\sum_{i=1}^{m} u_i t_i}$

where: λ_r is the recurrence rate at a point, x,y

t_i is the time since the formation of volcano, i

u_i is the area of a circle whose radius is the distance from i to x,y

and $u_i t_i$ is minimum for the nearest m neighbors

The number of the near neighbors can be constrained by integrating the recurrence rate over the entire region. To estimate the recurrence rate in the YMR, λ_t:

$$\lambda_t = \sum_{i=0}^{m} \sum_{j=0}^{n} \lambda_r (i,j) \Delta x \Delta y$$

NONHOMOGENEOUS POISSON MODEL

Using a spatially varying recurrence rate, it is possible to estimate the probability of a new volcano forming within or near the repository block:

$$P\,[N \geq 1] = 1 - \exp\left[-t\int_x\int_y \lambda_r(x,y)\;dy\,dx\right]$$

or

$$P[N \geq 1] = 1 - \exp\left[-t\sum_a \lambda_r\,\Delta x \Delta y\right]$$

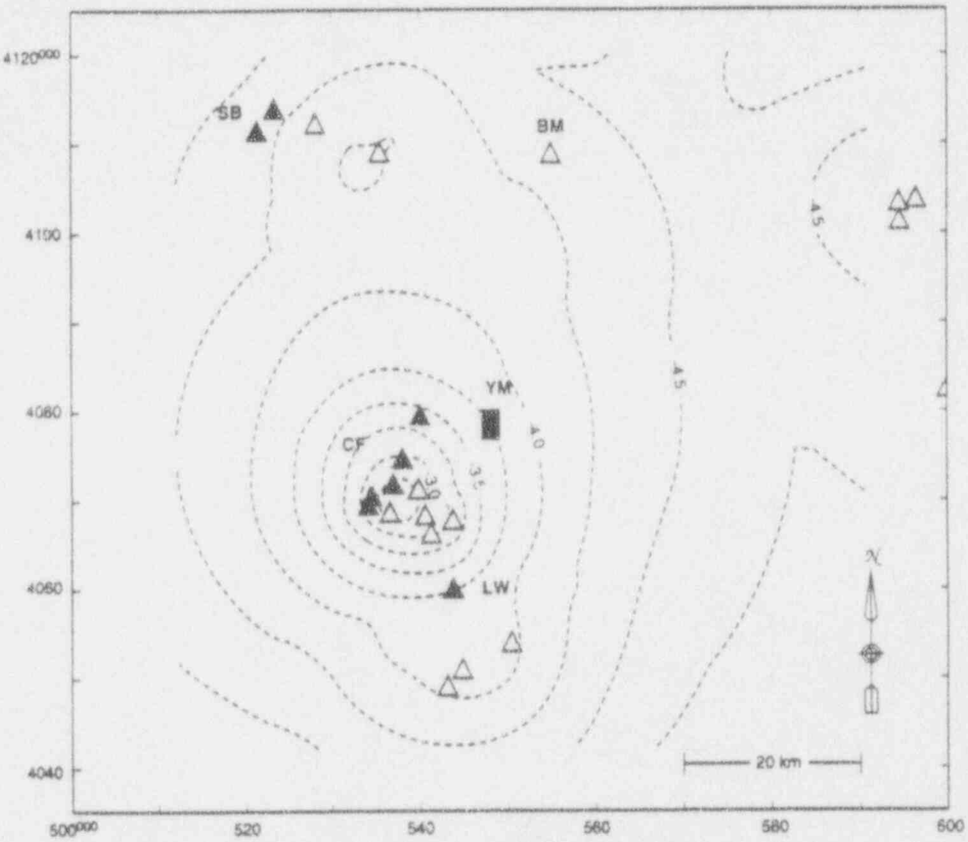
where

t = 10,000 years

λ_r is the expected recurrence rate at point x,y

a is the area of the repository

NEAR-NEIGHBOR NONHOMOGENEOUS POISSON MODEL



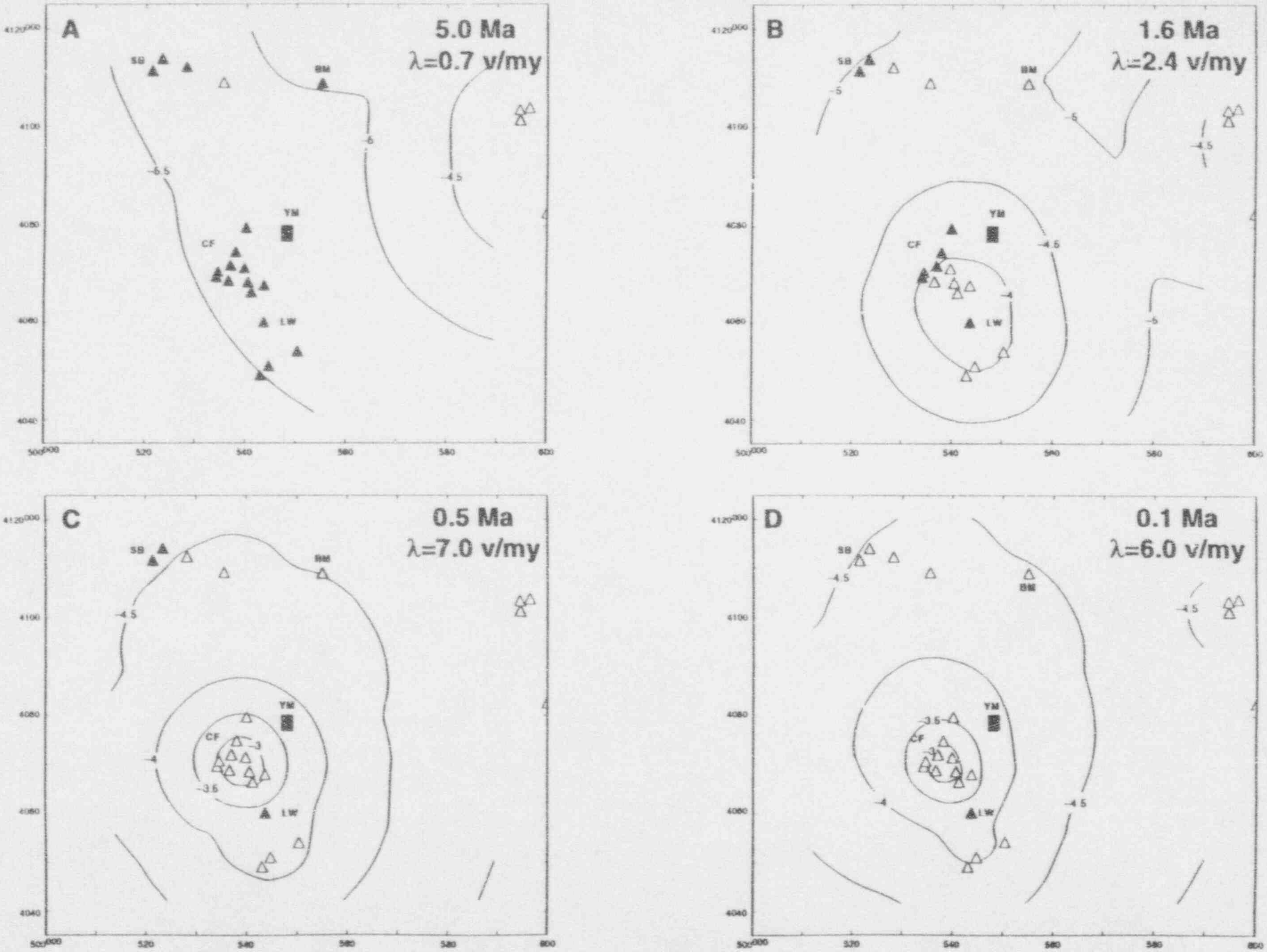
WHAT'S CONTOURED?

THE PROBABILITY OF A NEW VOLCANO FORMING WITHIN AN 8 KM^2 AREA WITHIN THE NEXT 10,000 YR IS CONTOURED. THE CONTOUR INTERVAL IS IN LOG PROBABILITY. FOR EXAMPLE, WITHIN THE -4 CONTOUR THE PROBABILITY OF A NEW VOLCANO FORMING IS GREATER THAN 1 IN 10,000 IN 10,000 YR, WITHIN THE -3 CONTOUR THE PROBABILITY OF A NEW VOLCANO FORMING WITHIN A GIVEN 8 KM^2 AREA IS GREATER THAN 1 IN 1,000 IN 10,000 YR.

ASSUMPTIONS IN THIS SOLUTION

- POSITION AND TIMING OF VOLCANISM ARE KNOWN
- PAST ACTIVITY IS A GOOD INDICATOR OF FUTURE ACTIVITY
- THE REGIONAL RECURRENCE RATE IS ABOUT 7 V/MY (SIX NEAR-NEIGHBORS)
- GEOLOGIC DETAILS (E.G., FAULT CONTROL) ARE NOT CONSIDERED

TESTING NONHOMOGENEOUS MODELS



MARKOV MODEL

Used to predict the most probable location of future eruptions assuming volcanoes have the properties of Markov variables

- Location of most recent eruption most influences position of future eruptions [homogeneous Markov model]
- The position of future eruptions tends toward a Homogeneous Poisson model, described by the diffusion equation, with time since last eruption
- Parameters used in the model are estimated from positions of past volcanic eruptions in the YMR

MARKOV MODEL

The conditional probability density function is given by the Fokker-Planck equation:

$$\frac{\partial P}{\partial t} + (\eta P) - \frac{1}{2} \frac{\partial^2}{\partial x^2} (\sigma^2 P) = 0$$

Where η and σ^2 are time derivatives of mean and variance of volcano position, respectively.

$$a(x_o,t,t_o) = E\{x(t) \mid x(t_o) = x_o\}$$

$$= \int_{-\infty}^{\infty} x(t)\ P(x,t;\ x_o,t_o)dx$$

$$b(x_o,t,t_o) = E\{[x(t) - a(x_o,t,t_o)]^2 \mid x\ (t_o) = x_o\}$$

$$= \int_{-\infty}^{\infty} (x - a)^2\ P(x,t;\ x_o,t_o)dx$$

MARKOV MODEL

$$\eta(x_o,t_o) = \left.\frac{\partial a(x_o,t,t_o)}{\partial t}\right|_{t = t_o}$$

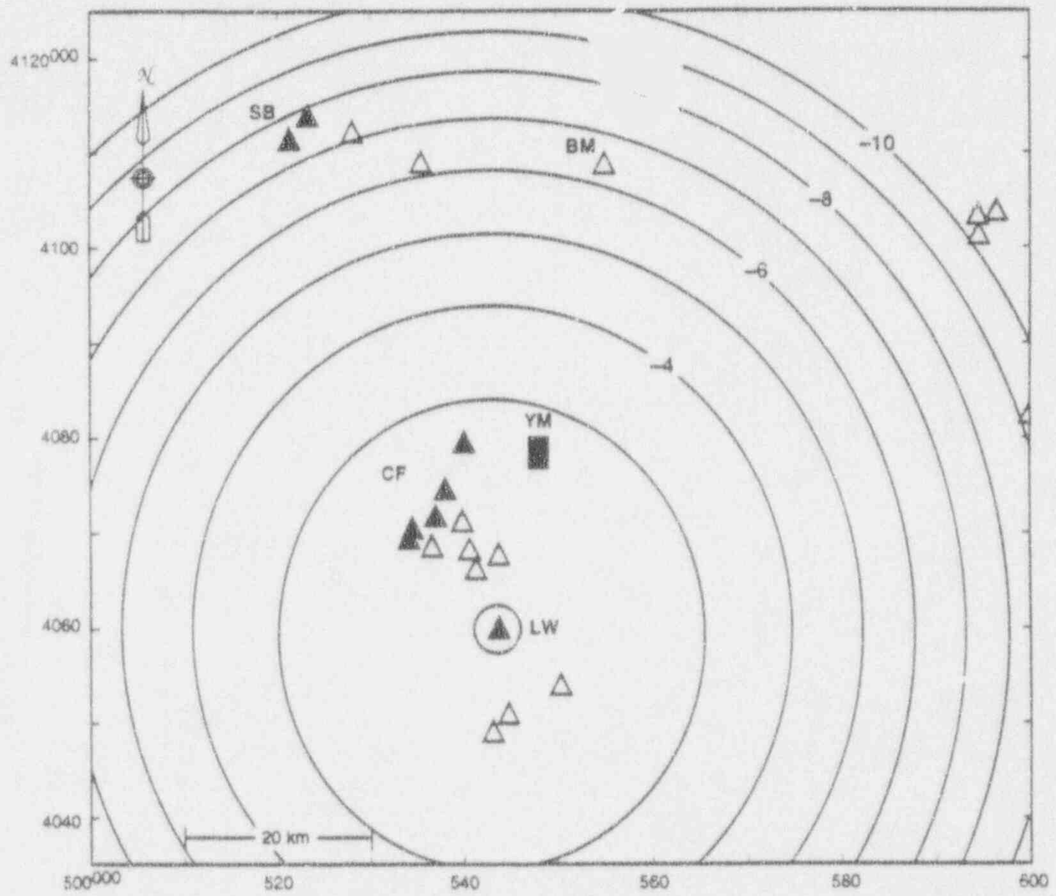
$$\sigma^2(x_o,t_o) = \left.\frac{\partial b(x_o,t,t_o)}{\partial t}\right|_{t = t_o}$$

In two dimensions the conditional probability density function becomes:

$$P = \frac{1}{2\pi(t - t_o)\sqrt{\sigma_x^2\ \sigma_y^2}} \exp\left\{ - \frac{[x(t) - x_o - \eta_x(t - t_o)]^2}{2\sigma_x^2(t - t_o)} - \frac{[y(t) - y_o - \eta_y(t - t_o)]^2}{2\sigma_y^2(t - t_o)} \right\}$$

with parameters estimated from the volcano distribution.

MARKOV MODEL



WHAT'S CONTOURED?

CONTOURED IS THE LOG PROBABILITY OF A NEW VOLCANO FORMING WITHIN AN 8 KM^2 AREA AT THE PRESENT TIME, IF A VOLCANO WERE TO FORM NOW. HENCE, INTEGRATING ACROSS THE ENTIRE REGION, THE PROBABILITY IS UNITY.

ASSUMPTIONS IN THIS SOLUTION

- POSITION AND TIMING OF VOLCANISM ARE KNOWN (LW = 0.13 Ma)
- PAST ACTIVITY IS A GOOD INDICATOR OF FUTURE ACTIVITY. MODEL PARAMETERS ARE ESTIMATED FROM PAST ACTIVITY
- CINDER CONES IN THE YMR BEHAVE AS HOMOGENEOUS MARKOV VARIABLES
- GEOLOGIC DETAILS (E.G., FAULT CONTROL) ARE NOT CONSIDERED

CNWRA VOLCANO PROBABILITY MODELS

Probability of disruption in 10,000 yr using near-neighbor nonhomogeneous Poisson Model

Quaternary YMR recurrence rate (7 ± 3 *v/my*):

8.0×10^{-5} to 3.5×10^{-4}

with most estimates between 1×10^{-4} and 3×10^{-4}

Based on the preliminary results of the homogeneous Markov model and a 0.05 to 0.15 Ma age for Lathrop Wells, the probability that a new volcano will form within the repository boundaries, should volcanism occur:

1.5×10^{-3} to 3×10^{-3}

CNWRA VOLCANO PROBABILITY MODELS

THESE NUMBERS ARE LIKELY TO CHANGE

Current CNWRA models treat volcanoes as points. Using areal terms, for example PDF'S for dikes or accounting for satellite vents, will increase the probability of disruption

No probability model currently incorporates geologic and geophysical information to a sufficient (convincing) degree

- Indirect effect of volcanism
  - Change in the hydrologic setting
  - Change in geochemical transport rates

- Role of fault control and/or tectonic control
  - Scale of structural control on magma ascent
  - Deformation rates and magmatism
  - Change in magma supply

CNWRA VOLCANO PROBABILITY MODELS

THESE NUMBERS ARE LIKELY TO CHANGE (Cont'd)

- Impact of uncertainty
  - Shallow intrusion to extrusion ratio
  - Geochronology

- Range of explosivity of small-volume basaltic eruptions
  - PDF for explosivity
  - Impact of the repository itself on magma ascent
  - Ash and waste dispersion models

CNWRA VOLCANO PROBABILITY MODELS

Current probability models for direct magmatic disruption of the candidate repository suggest that:

$$P\,[N \geq 1,\ 10{,}000\ YR] = 5 \times 10^{-5}\ \text{To}\ 6 \times 10^{-3}$$

Where N is the number of small-volume basaltic volcanoes. These are based on widely varying assumptions and solution strategies.

- All probability models indicate that volcanism is a PA concern
- A probability model that does not include geologic detail does not fully address the volcanism issue
- Range in current models strongly impacts PA

SUMMARY

RESULTS OF THE CNWRA ANALYSIS TO DATE:

- Vents cluster in time and space in the YMR
- Probability of eruptions has been highest near Crater Flat since at least the beginning of the Quaternary
- Probability of a new volcano forming within the candidate repository site, based on the nonhomogeneous model, is on the order of 1×10^{-4} to 3×10^{-4} in 10,000 years
- Markov models support the idea that volcanism is most likely to occur in the Crater Flat region in the future

CNWRA PROBABILITY MODELS WILL NOT BE COMPLETE UNTIL GEOLOGIC DATA ARE INCORPORATED TO A SUFFICIENT DEGREE, INCLUDING:

- Indirect effects
- Explosivity
- Structural and tectonic control

IT IS WORTH EXPLORING A FULL RANGE OF MODELS

- The effort that goes into model development is small compared to the effort that goes into data collection
- Test models using other volcanic fields will reveal strengths and limitations

Sheridan - deterministic ([illegible]) [illegible] argument. [illegible] sense for similar project possible [illegible] later.

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

Eugene I. Smith
Dept. Geoscience
University of Nevada
Las Vegas, Nevada 89154
(702) 895-3971
(702) 895-4064 FAX
eismith@nevada.edu (E-mail)

C.H. Ho
Dept. Mathematical Sciences
University of Nevada
Las Vegas, Nevada 89154
(702) 895-3494
(702) 895-4343
chho@nevada.edu (E-mail)

CVTS

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

Eugene I. Smith
Dept. Geoscience
University of Nevada
Las Vegas, Nevada 89154
(702) 895-3971
(702) 895-4064 FAX
eismith@nevada.edu (E-mail)

C.H. Ho
Dept. Mathematical Sciences
University of Nevada
Las Vegas, Nevada 89154
(702) 895-3494
(702) 895-4343
chho@nevada.edu (E-mail)

——— *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

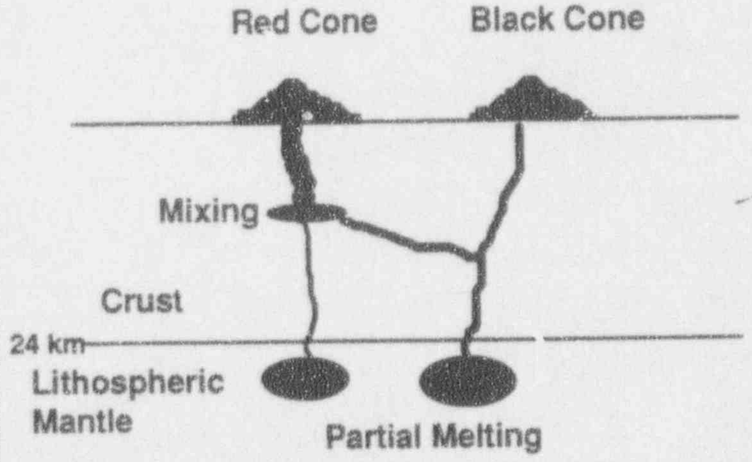
Three events:

Lathrop Wells, 1.1 Crater Flat, 3.7
Crater Flat

3??

CVTS

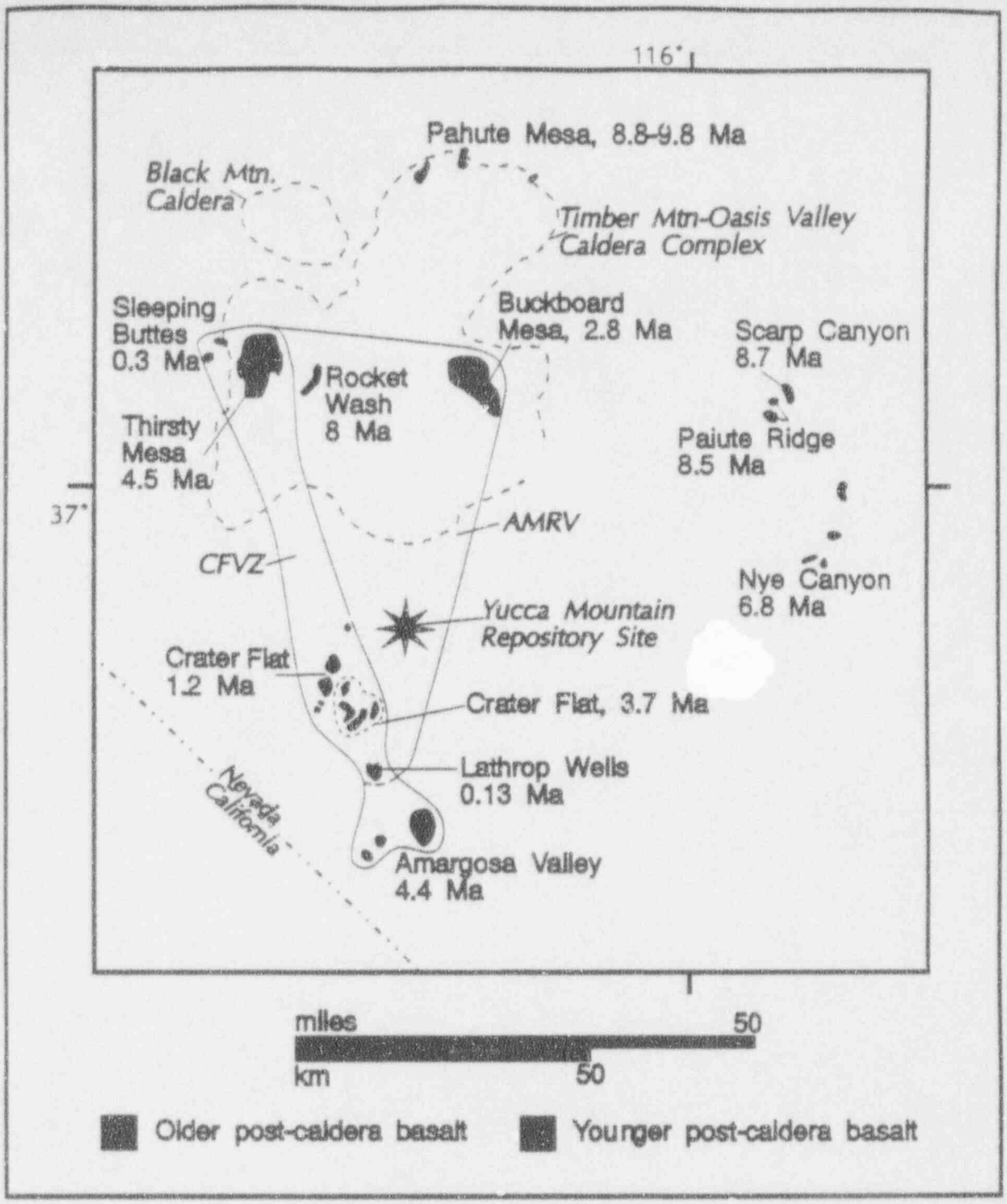
Crater Flat



but Mix of
Test should
a Play of Central.

FC

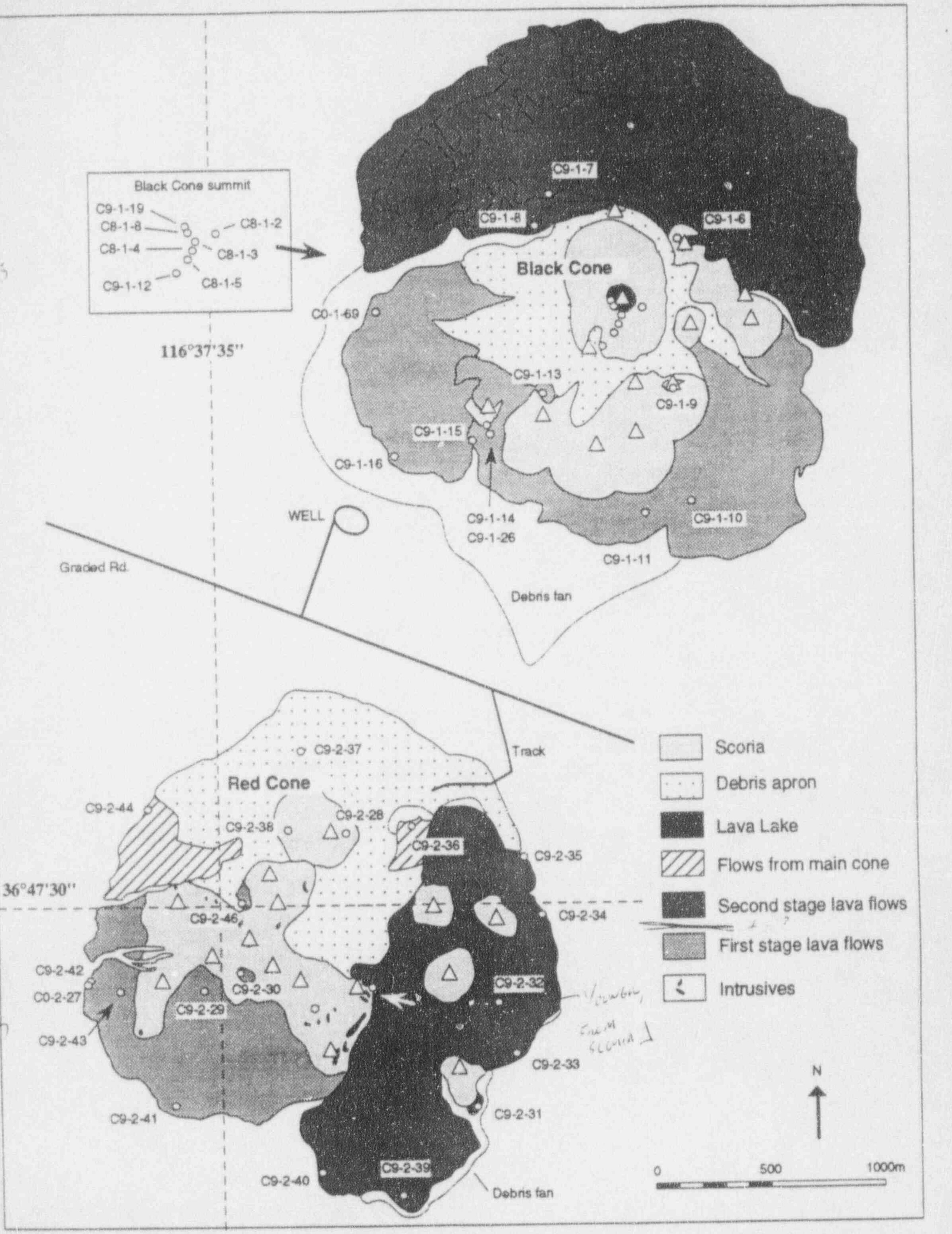
CVTS

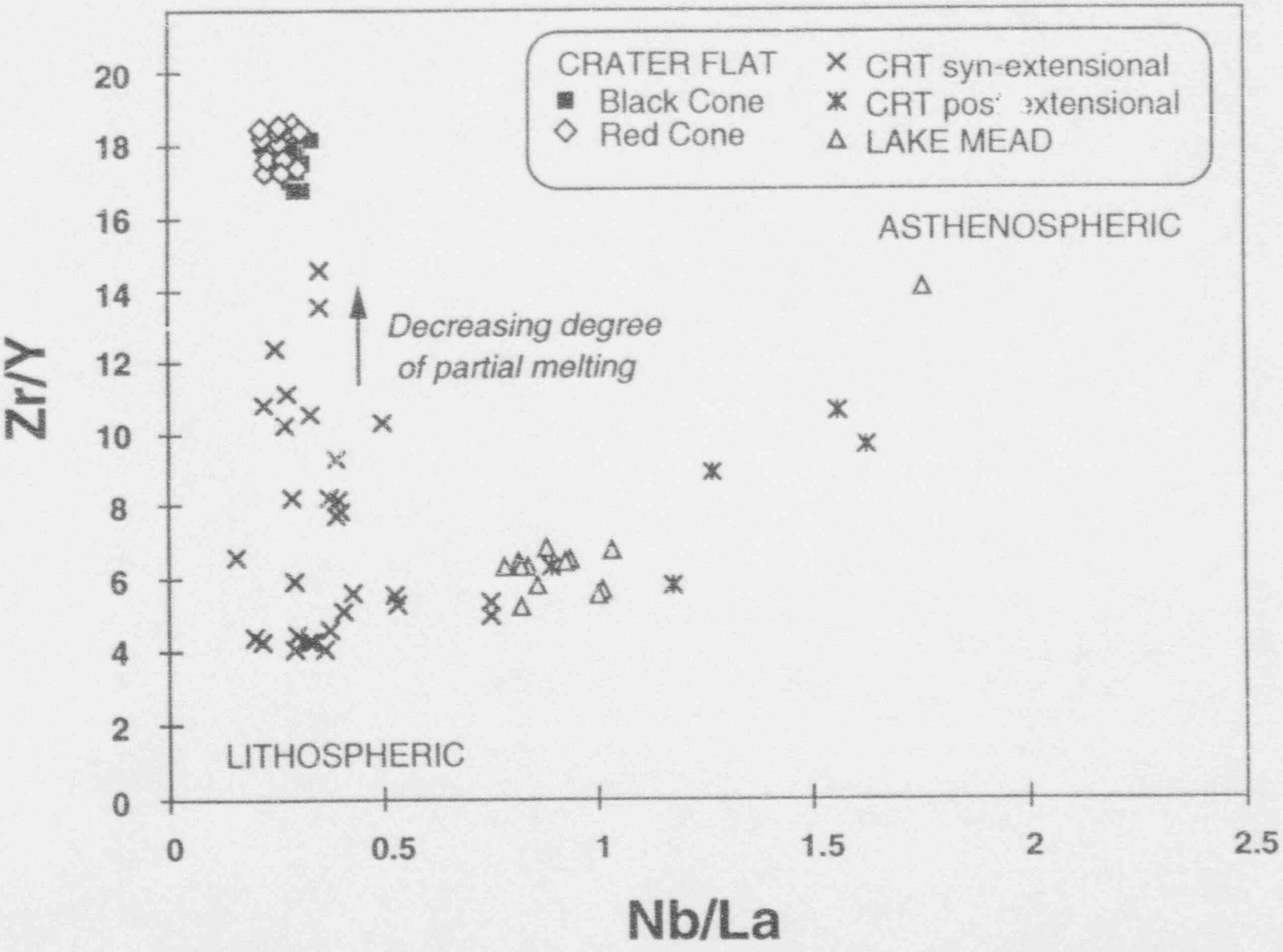


FROM:

Directly From:
Connor + Hill (1993)

CROWE (1990)
CROWE ET AL. (1982; 1983)
VANIMAN AND CROWE (1981)
CROWE AND PERRY (1991)
CROWE (1992, WRITTEN COMMUNICATION (NWTRB))


Black Cone summit
C9-1-19
C8-1-8
C8-1-4
C9-1-12
C8-1-2
C8-1-3
C8-1-5
Black Cone
C9-1-7
C9-1-8
C9-1-6
C0-1-69
116°37'35"
C9-1-13
C9-1-9
C9-1-15
C9-1-16
C9-1-14
C9-1-26
C9-1-10
C9-1-11
WELL
Graded Rd.
Debris fan
Track
Red Cone
C9-2-37
C9-2-44
C9-2-38
C9-2-28
C9-2-36
C9-2-35
36°47'30"
C9-2-46
C9-2-34
C9-2-42
C0-2-27
C9-2-43
C9-2-30
C9-2-29
C9-2-32
C9-2-33
C9-2-31
C9-2-41
C9-2-40
C9-2-39
Debris fan
Scoria
Debris apron
Lava Lake
Flows from main cone
Second stage lava flows
First stage lava flows
Intrusives
N
0
500
1000m


CRATER FLAT
■ Black Cone
◇ Red Cone
× CRT syn-extensional
✱ CRT post-extensional
△ LAKE MEAD
ASTHENOSPHERIC
Decreasing degree of partial melting
LITHOSPHERIC
Zr/Y
Nb/La
0
2
4
6
8
10
12
14
16
18
20
0
0.5
1
1.5
2
2.5

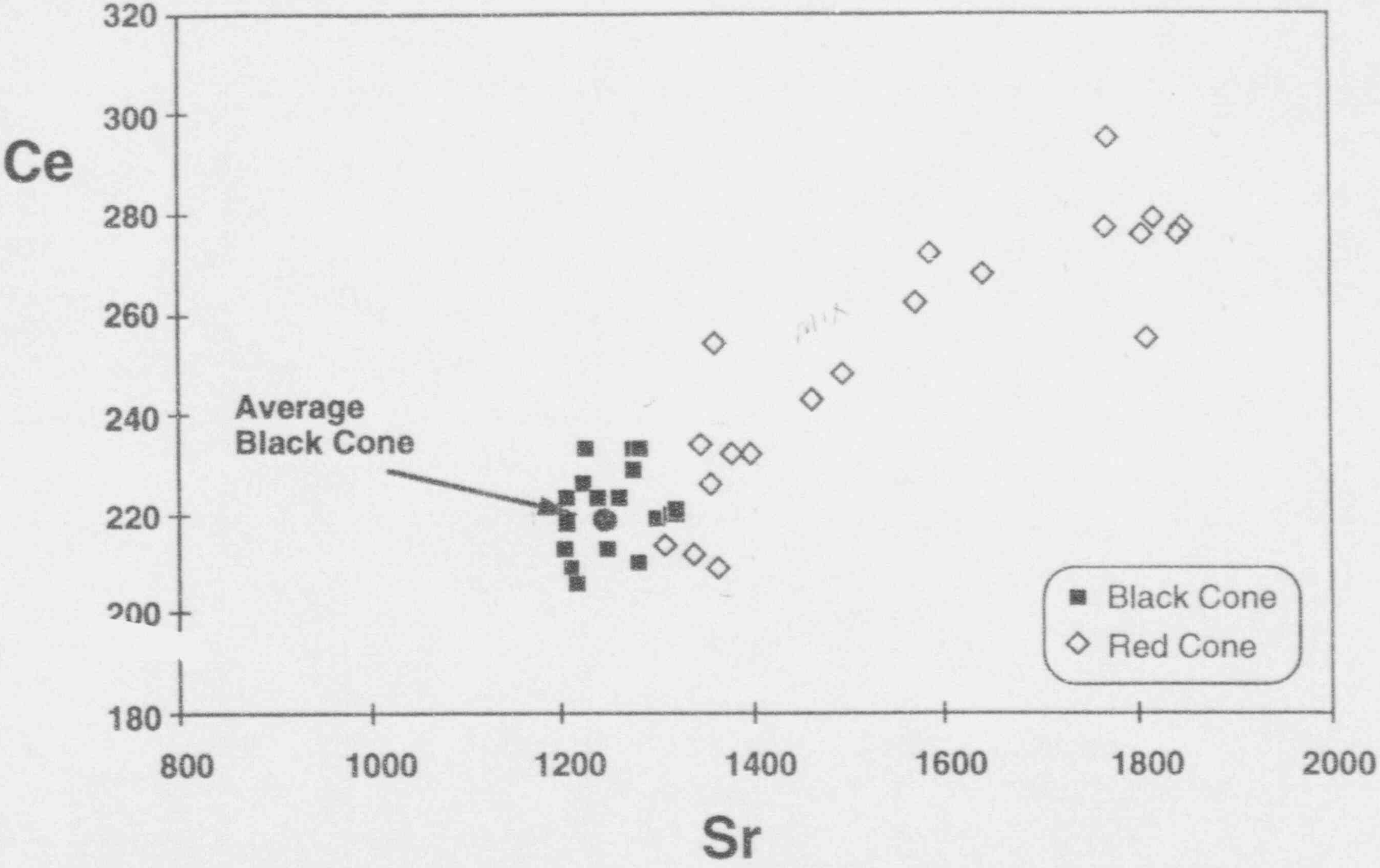
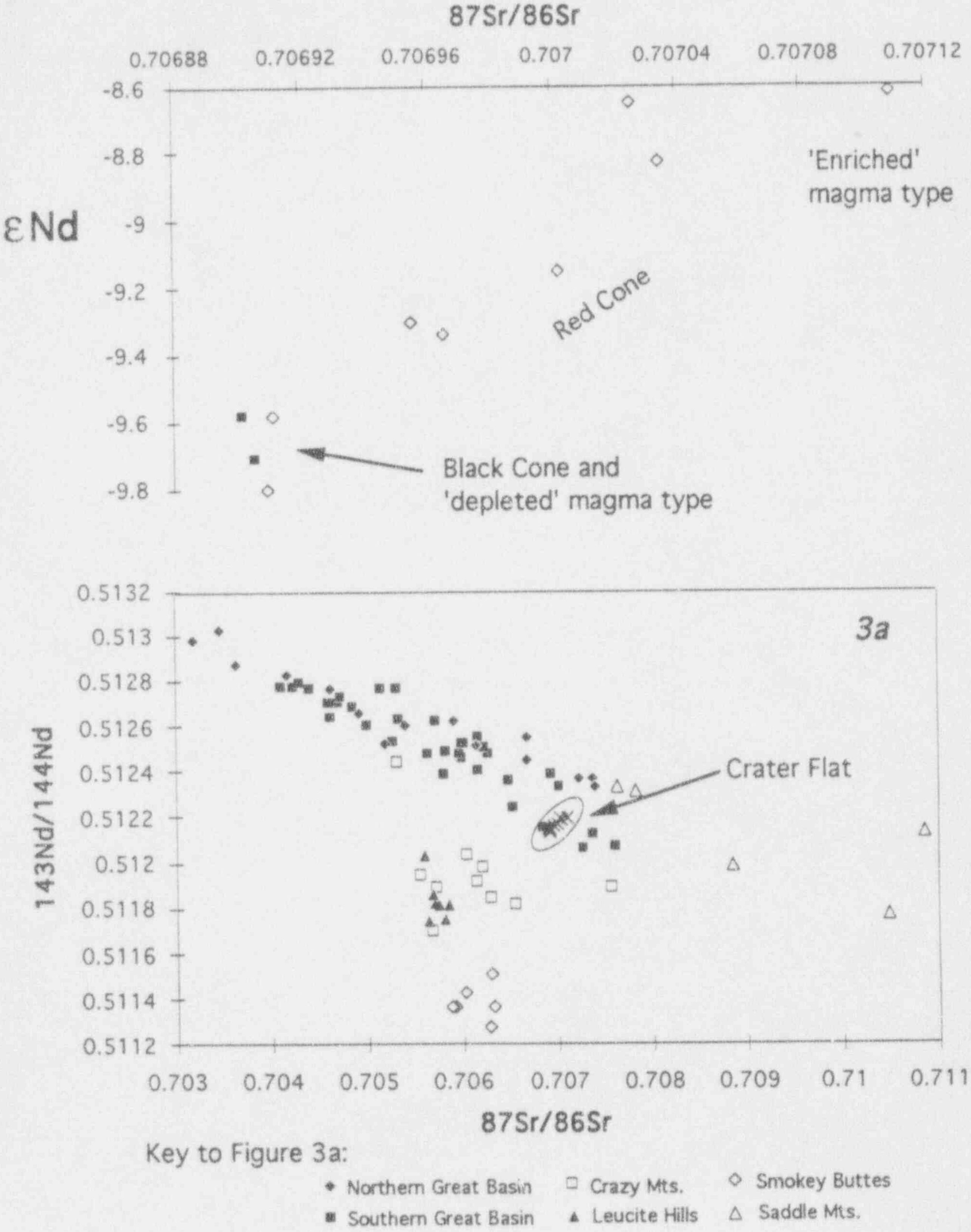
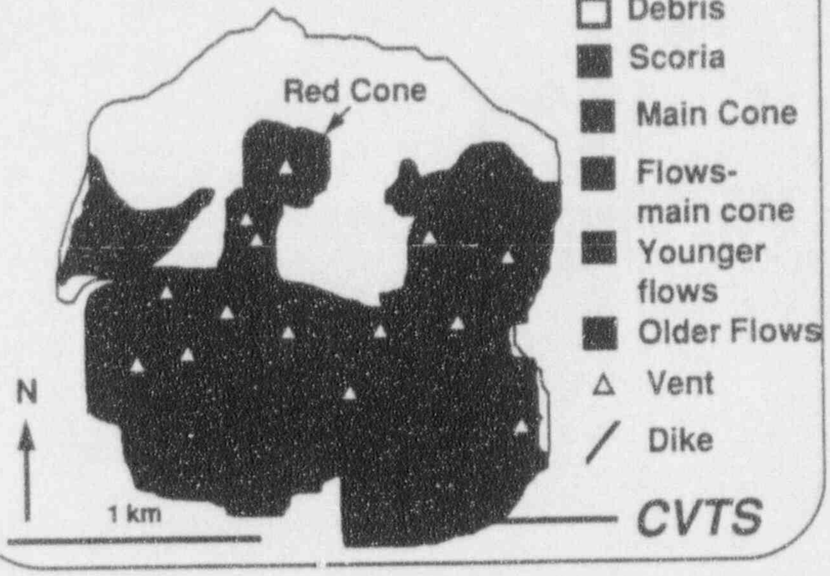

Ce
320
300
280
260
240
220
200
180
800
1000
1200
1400
1600
1800
2000
Sr
Average
Black Cone
■ Black Cone
◇ Red Cone

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

Why are there Venting vents
without Rotten Mound ??

Eruptions separated by a significant periods of time

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

Based on chem

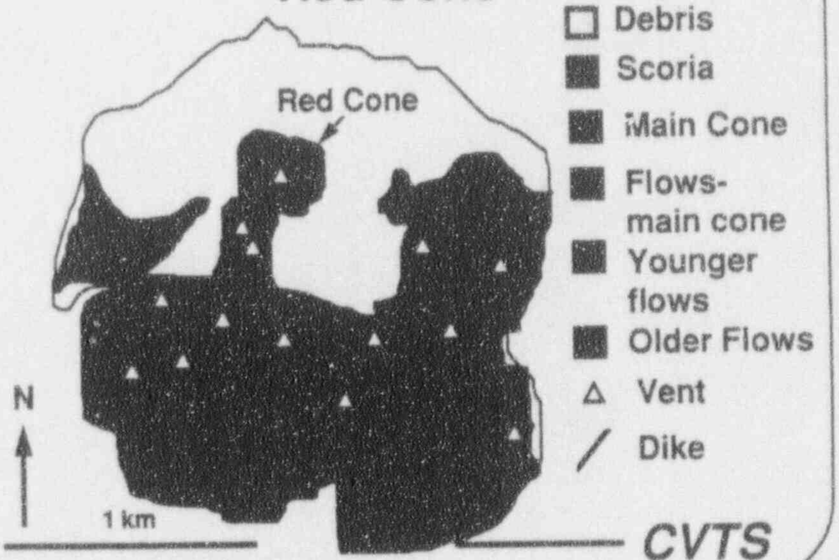
CVTS

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*

[illegible]

Future [illegible]

- Continuing small Bs

[illegible]

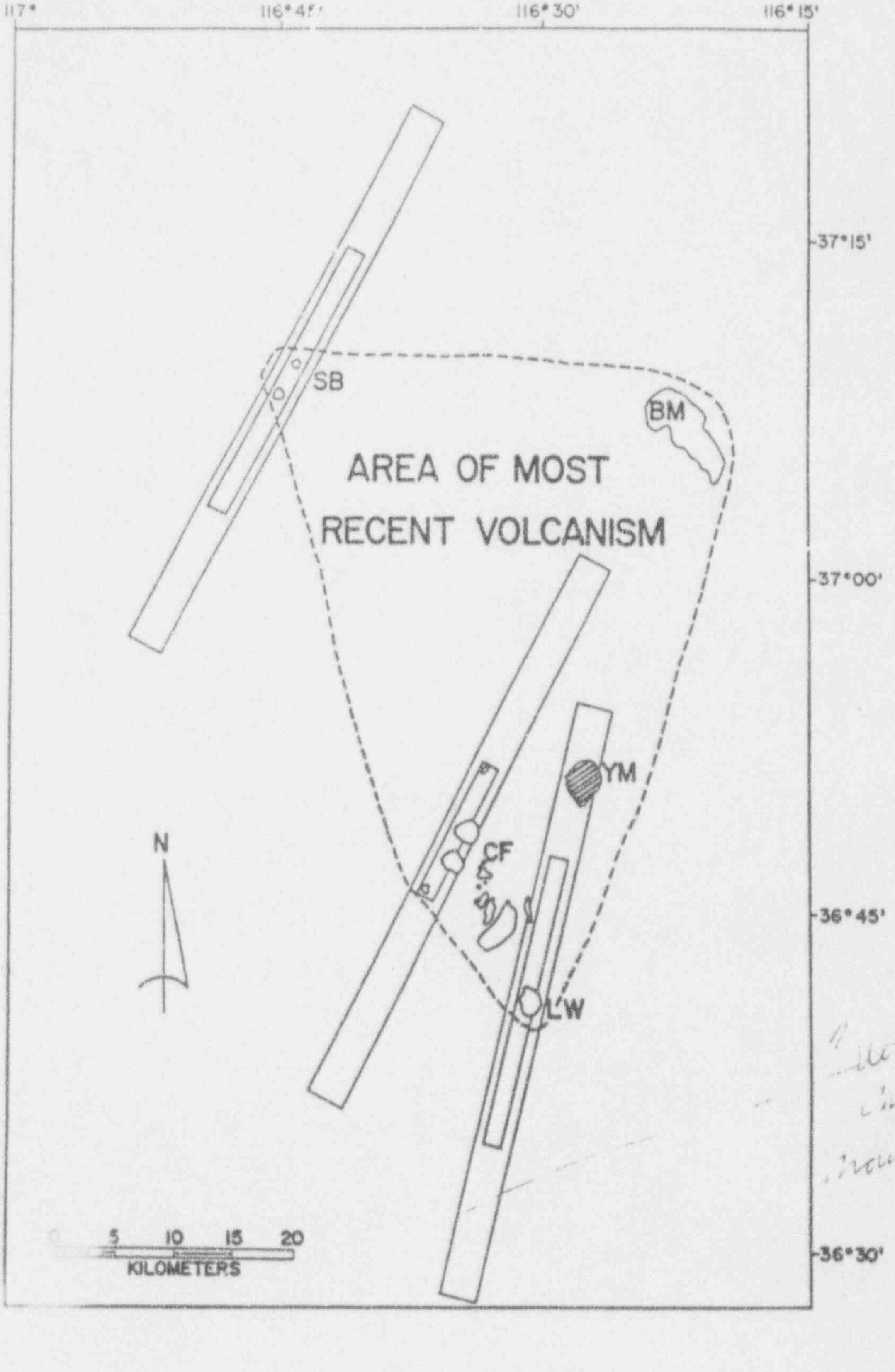
[illegible]

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*

[illegible] Rock', instead
[illegible] CFVZ



"Worst
line from
around YM.

Definition; Hazard Zone that accounts for;

~~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.

DOMINO EFFECT,

CVTS

Future

upper crust

Fault + [illegible]

Tractions effects

- Volcanic [illegible]

→ Nevada – 1/15% in Range, [illegible] @ Peaks (But Paleo Topo = ?)

Consequence of Eruption

Cinder cone eruptions can be explosive (Plinian or subplinian)

For example Tolbachik in Kamchatka

CVTS

2 Scopes

Tom Wagners +

[illegible]

a) Case II

b) Case I ? w/

[illegible] column + Cloud

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*

Sobolev – Chussikov (1993) = Craters ~2.1
Cinders ~0.5%
A-c ~2%
[illegible] ~2

ECS, v.74, p 682

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.

——— *CVTS*

B, Large –
+ [illegible] data
subduction in BR-Type
Plinian ✓✓

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

——— *CVTS*

[illegible]
C.H. Ho

– [illegible] – "[illegible]"
[illegible]

✓ – [illegible] " [illegible] " but rather " [illegible] "

To Quantify

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

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 rocess omo oisson	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

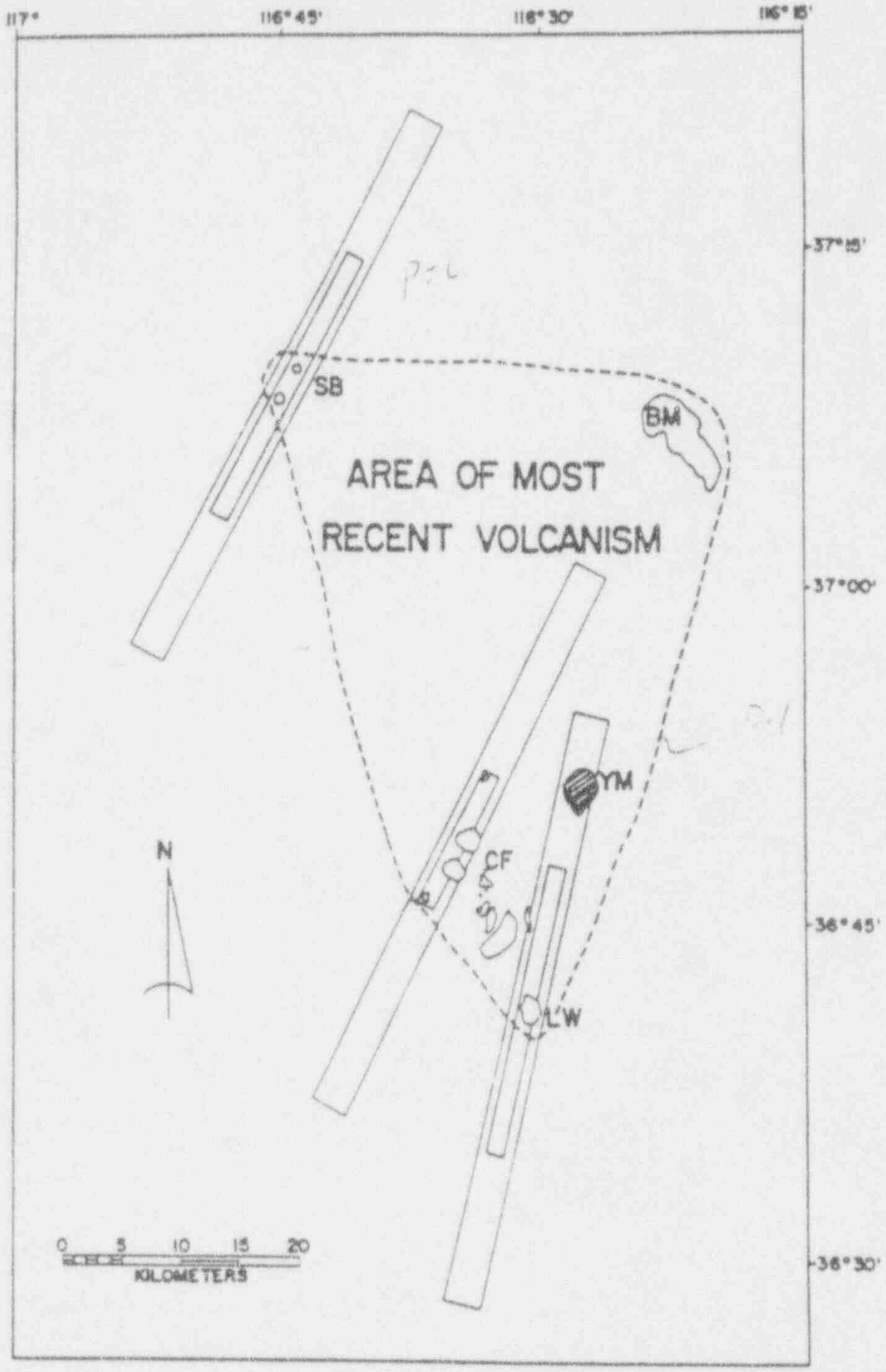
1.1×10^{-3} to 8×10^{-2} ??

Two approaches for *p*

Classical

- $p = 1.1 \times 10^{-3}$
- $p = 8 \times 10^{-2}$

Bayesian — $p \sim U(0,8/75)$



"Range of Pi
0 to 1"
[illegible]

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 , fig. 7)

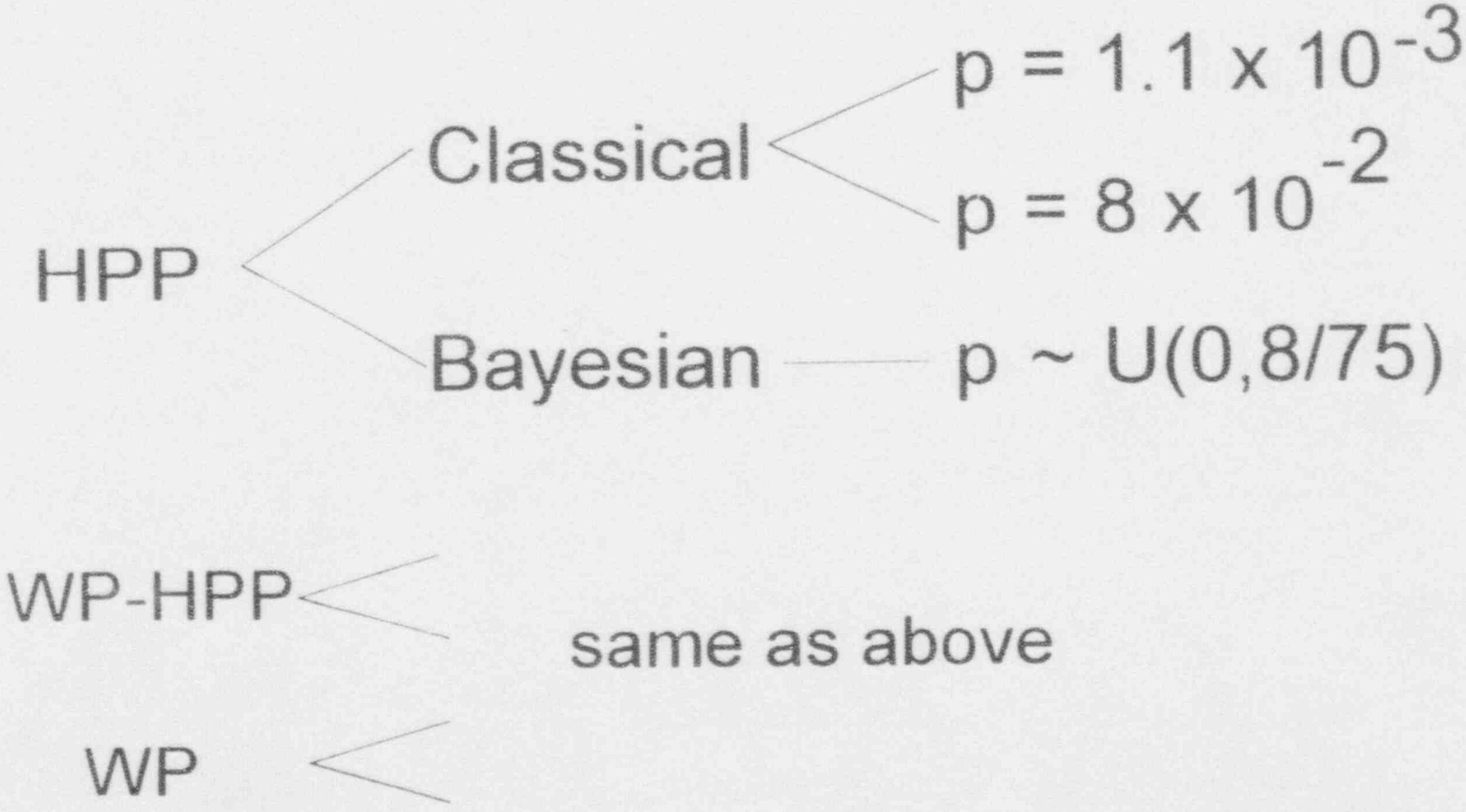
We have

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

2. $a = 8\ \mathrm{km}^2$ (area of the respository,
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

same as above

WP

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

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)	Risk		
		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	$(5.83 \times 10^{-6}, 8.23 \times 10^{-6})$	$(6.41 \times 10^{-5}, 9.06 \times 10^{-5})$	$(4.65 \times 10^{-3}, 6.57 \times 10^{-3})$	$(3.10 \times 10^{-3}, 4.38 \times 10^{-3})$

Skipped

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)	Risk		
		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	$(3.41 \times 10^{-6}, 5.67 \times 10^{-6})$	$(3.75 \times 10^{-5}, 6.24 \times 10^{-5})$	$(2.72 \times 10^{-3}, 4.53 \times 10^{-3})$	$(1.82 \times 10^{-3}, 3.02 \times 10^{-3})$

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.

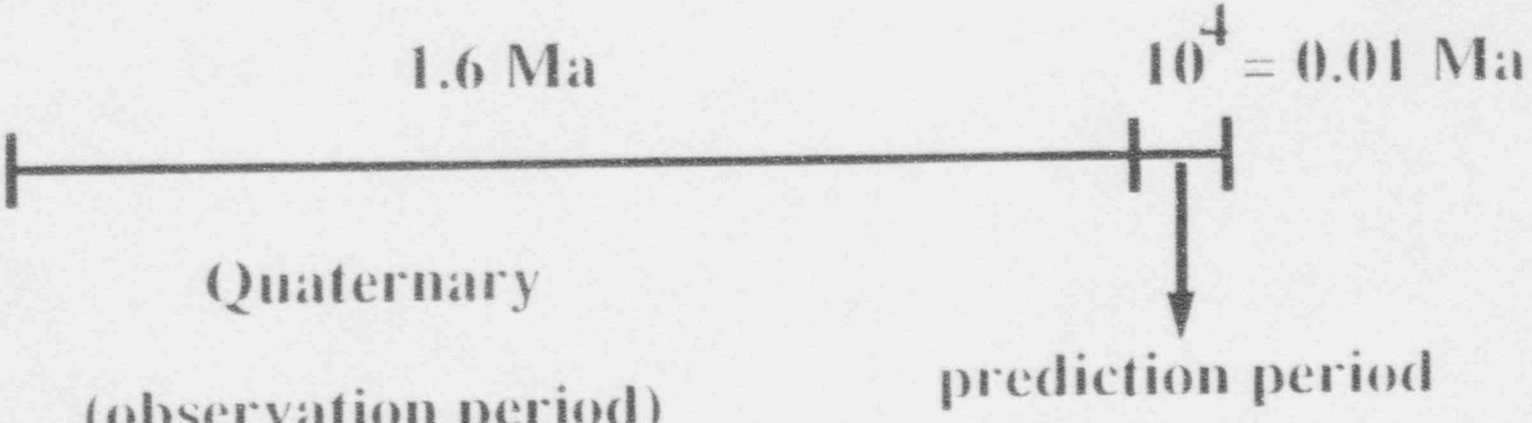
   - Reason: length of the Pliocene period outweighs the greater number of events.

HPP - 4-6 $\times 10^{-6}$
WP - 5-10 $\times 10^{-6}$; [illegible]

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.

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.

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

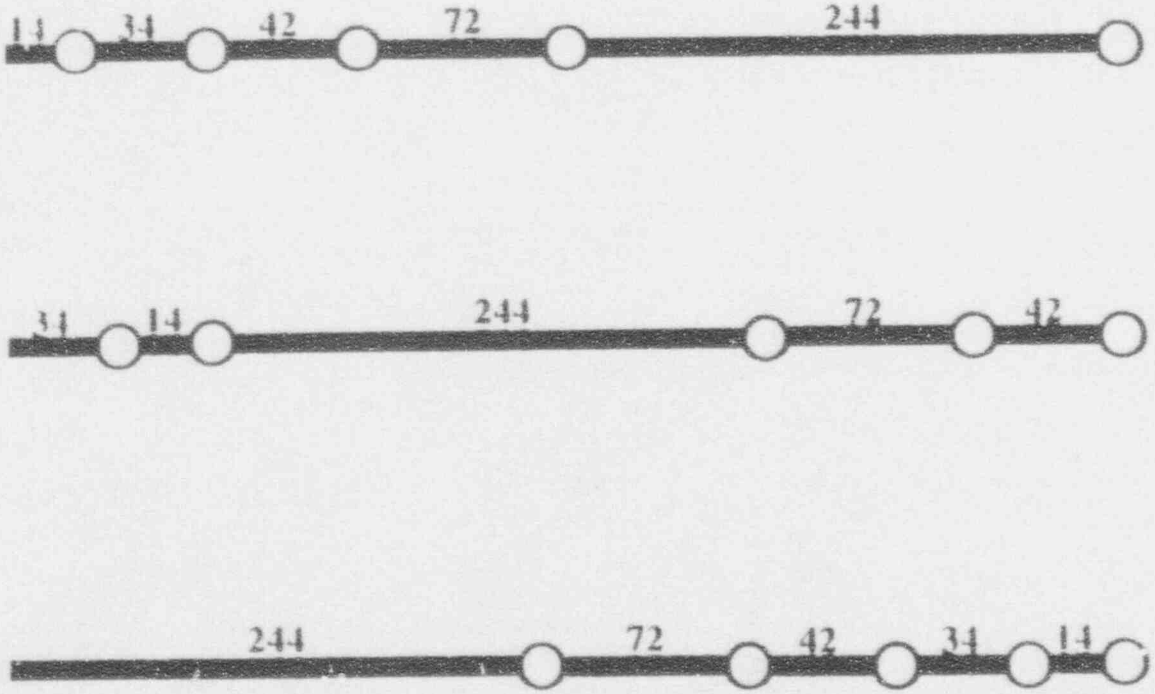
⇓

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.

CK



β

0.63

0.99 HPP

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** $(\hat{\beta} = 2.43)$.

4.5×10^{-3} ??

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% 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?

Peter – [illegible] [illegible] Yes, [illegible] problem! [illegible] effect [illegible] volcanism [illegible].

NWTRB
Structural Geology
and Geoengineering
Panel Meeting

Sensitivity Studies on Volcanic Hazard at Yucca Mountain

San Francisco, CA
March 9 1994

Peter C. Wallmann

Golder Associates

Volcanic Disruptive Events

- How frequently does an event occur?
  E1 - Event rate (events/yr)
- Does the event disrupt the repository?
  E2 - Disruption probability
  (disruptions/events)
- Disruptive event rate
  E1*E2 - Disruptive events/yr
- Consequences of disruption

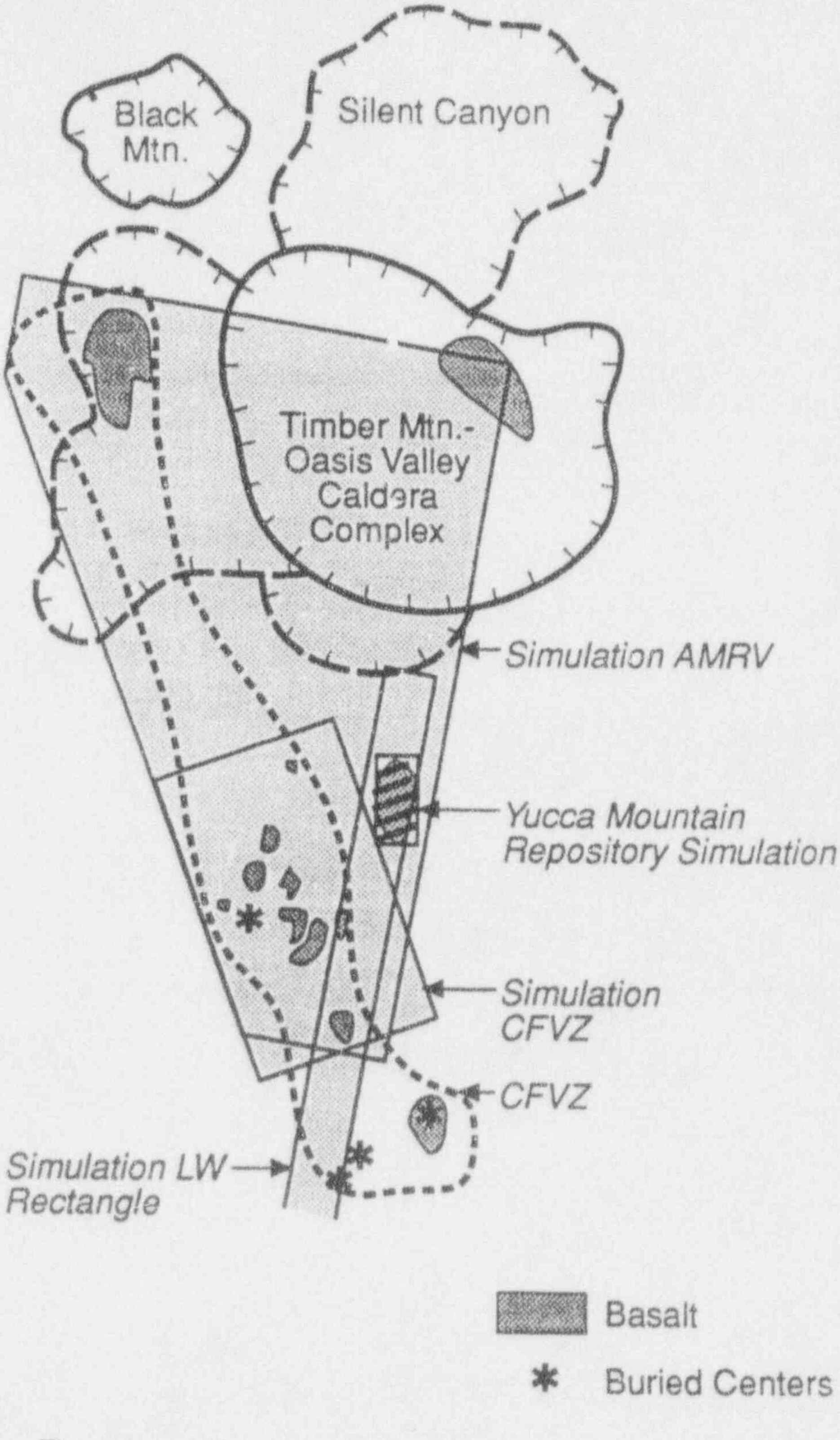


Figure 1. Location map for post-caldera basaltic volcanism in the Yucca Mountain region.

FracMan Discrete Feature Model

- Discrete feature analysis and generation program
- Used in fluid flow fracture network modelling at Stripa and Äspö sites in Sweden, Kamaishi Mine in Japan, Yucca Mountain in USA
- Contains multiple distributions for fracture radius and orientation, and multiple models for spatial distribution of fracture centers

rea weighted??

Golder Associates

Model Simulations

- Fracture centers represent "initiation point" for dike propagation; each generated feature represents 2 dikes propagating in opposite directions

Homogeneous?? Apparently so

- Poisson distribution for "initiation points"
- 10 realizations of 10,000 fractures simulates 200,000 dikes [illegible]

3D. : Region Extend to 3 km's.
- Not Mechanistic for dike Propagation

Golder Associates

Example FracMan Dike Simulations

- **Dike Orientation**
  - Bivariate Normal Distribution

    Mean Pole (Trend, Plunge) = 110°, 0
    1 StdDev Trend = 20°
    1 StdDev Plunge = 10°

~ Regional stress field T, ω ~110

- **Dike Length***
  - Uniform Distribution

    Mean = 7500 meters
    Maximum Deviation = 6500 meters

*Single feature in FracMan; represents 2 dikes

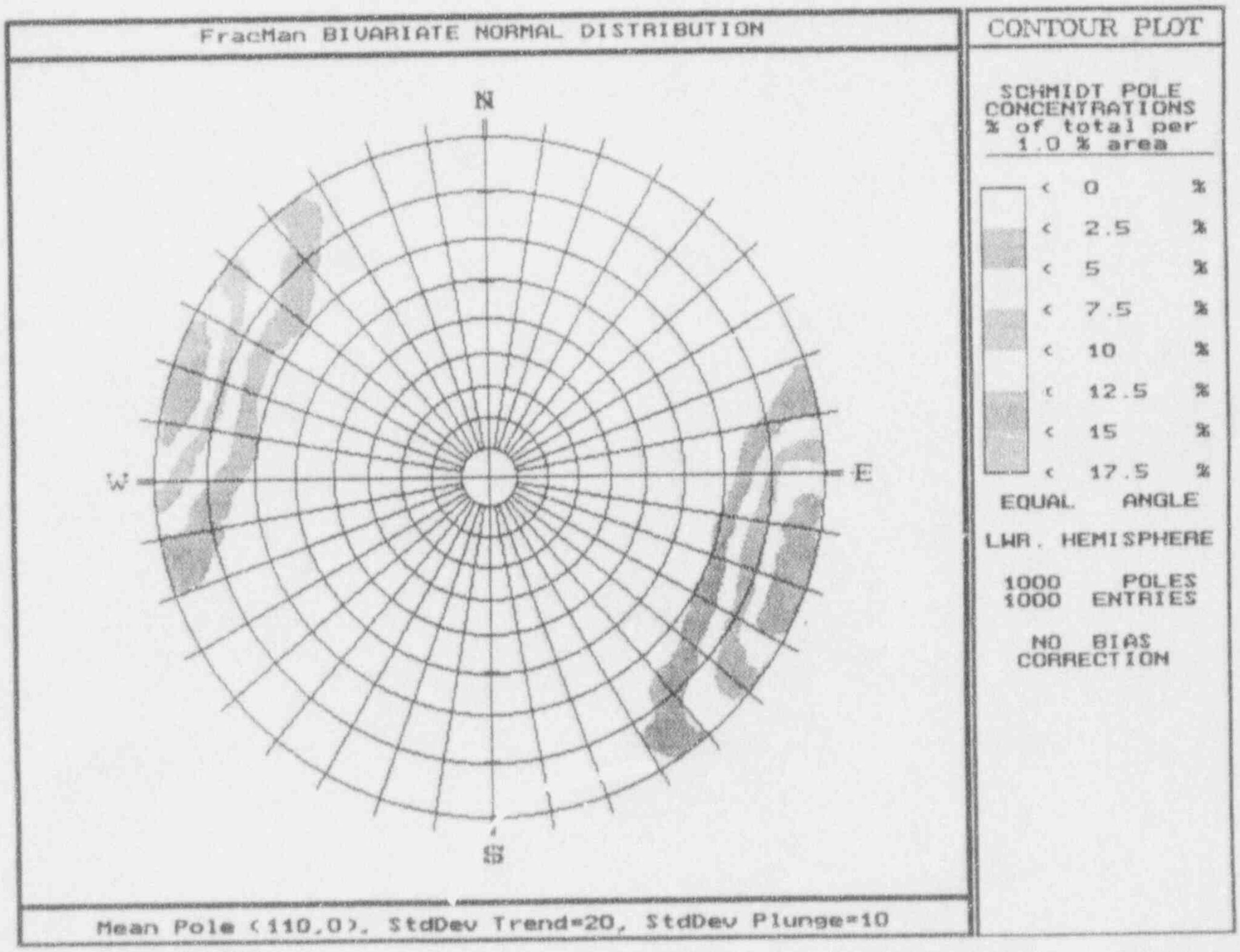
500 m to 7000 m long (?)

- **Dike Height**
  - Uniform Distribution

    Mean = 1500 meters
    Maximum Deviation = 500 meters

Golder Associates

Bivariate Normal Distribution

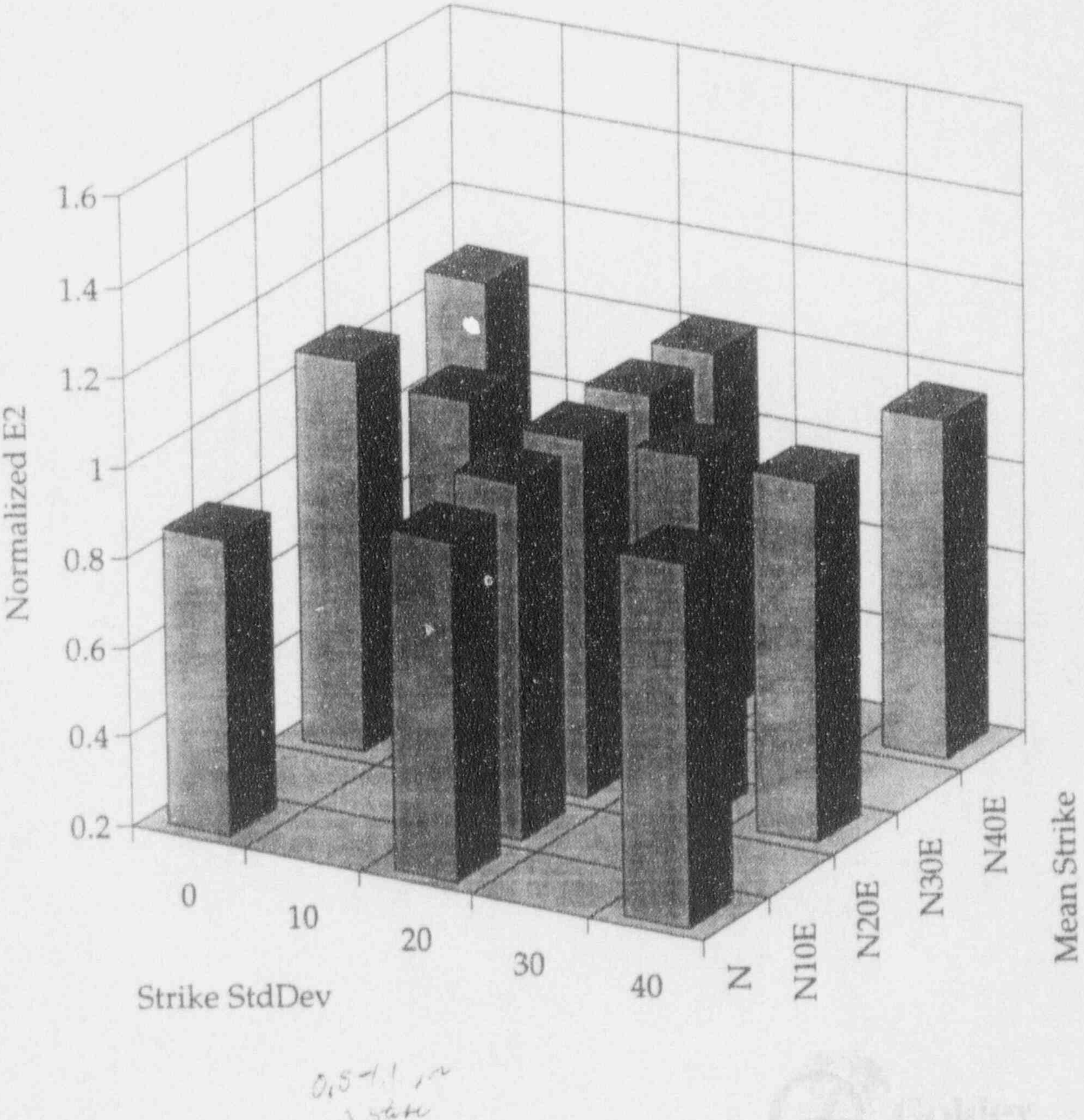


Mean Pole (110,0), StdDev Trend=20, StdDev Plunge=10

TREND : 110° (±)

AMRV Model

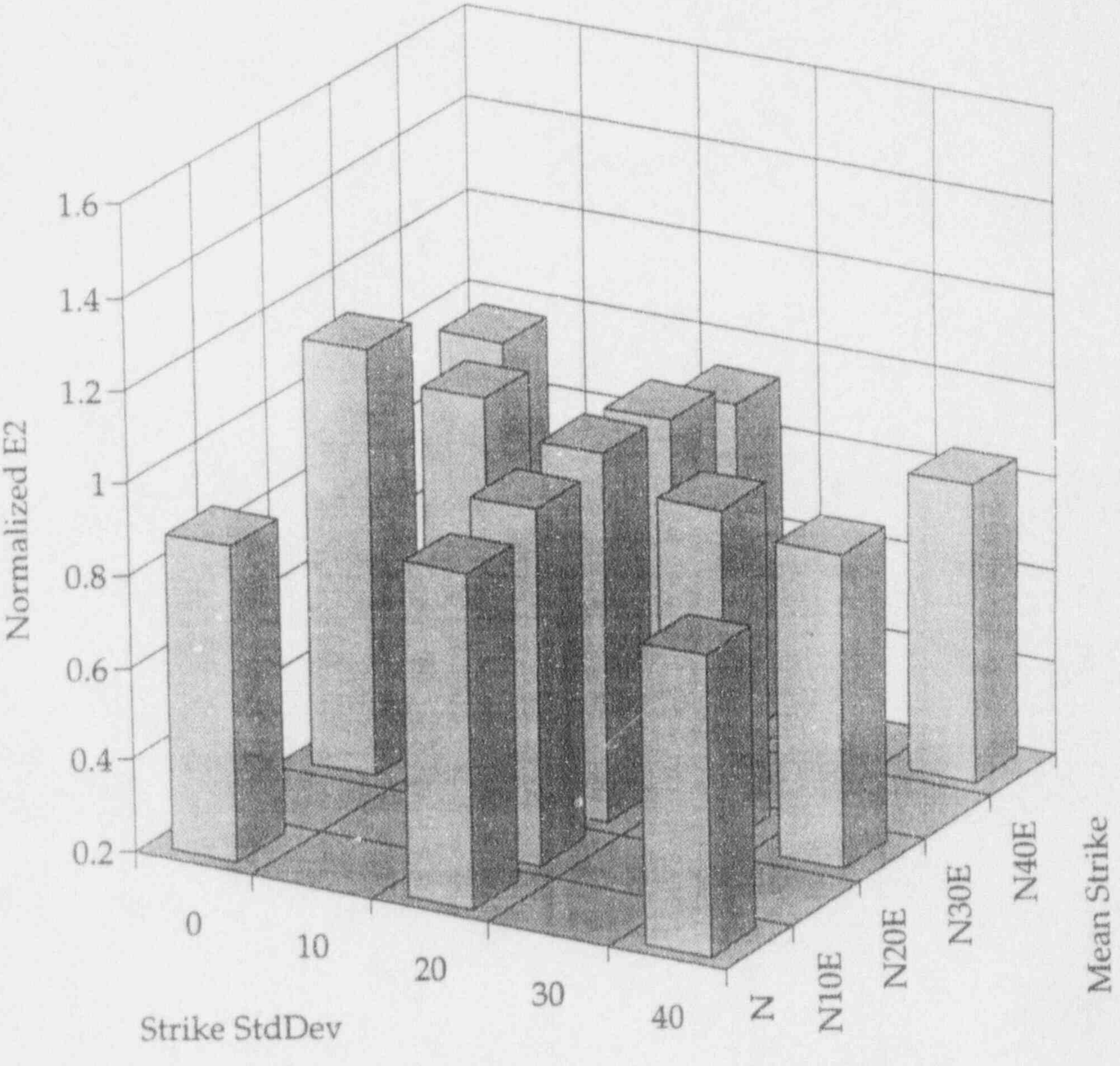
(Smith et al.)



0,5 - 1,1 m
[illegible] strike

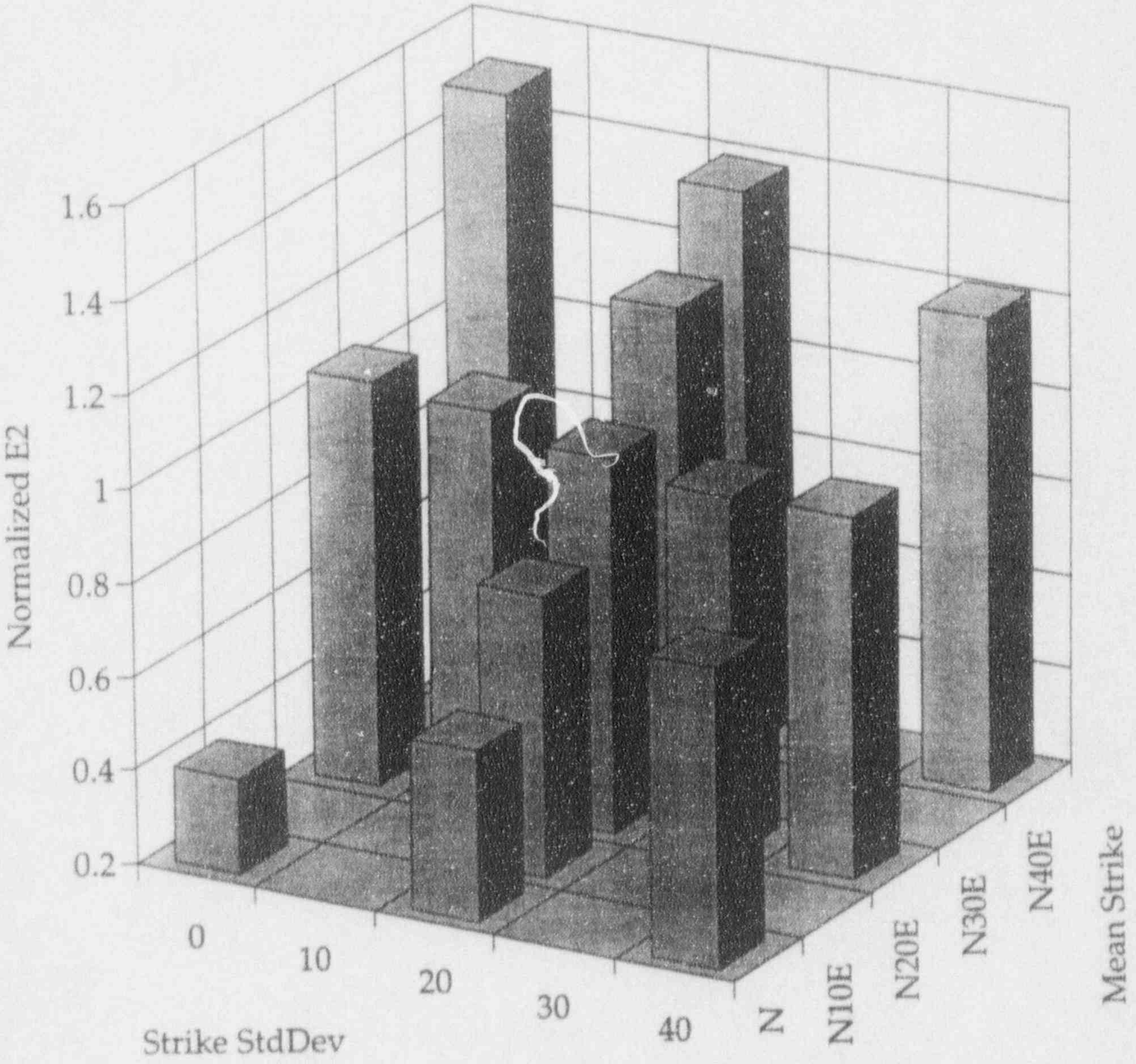
LW Rectangle Model

(Smith et al.)



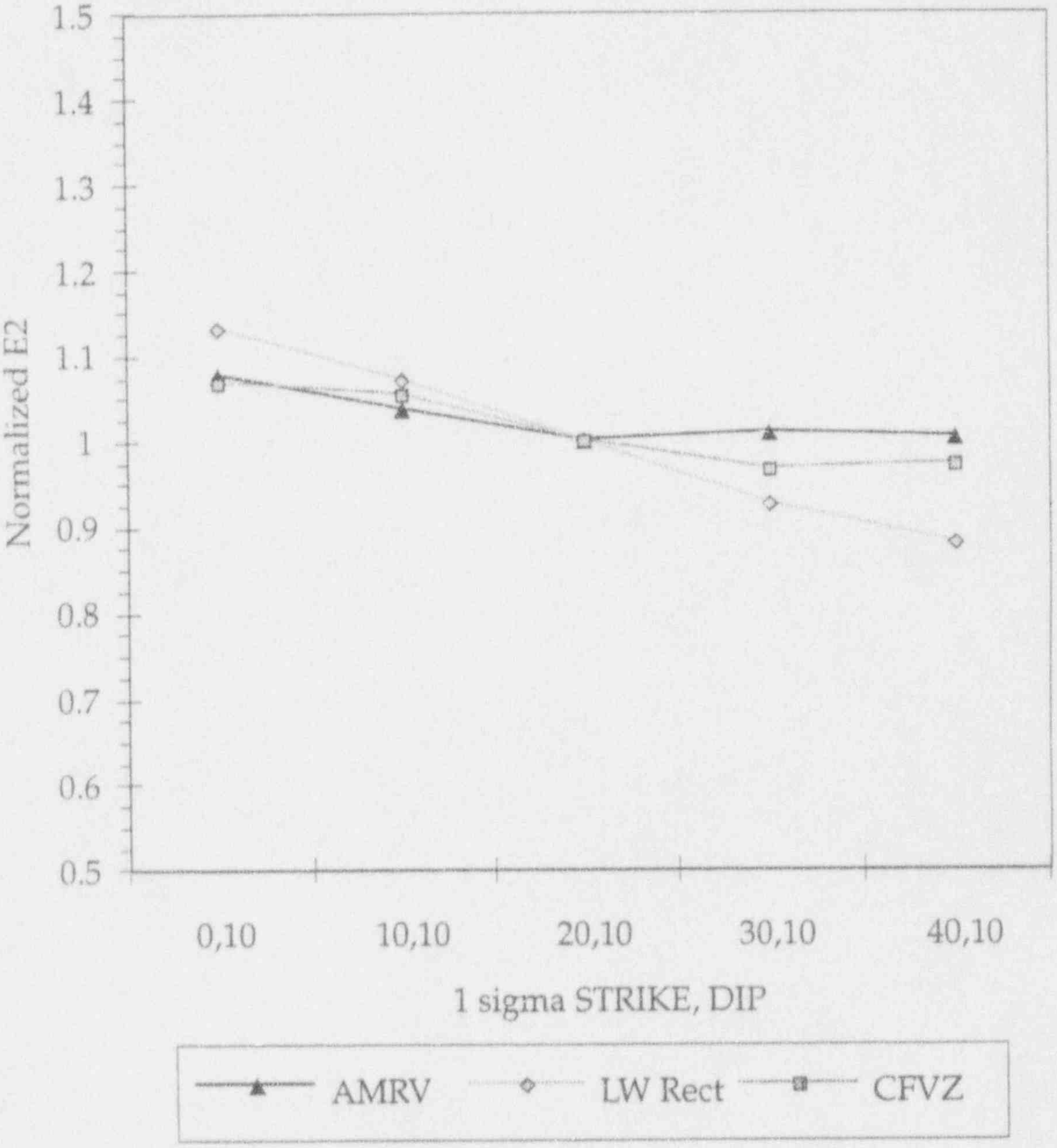
CFVZ Model

(Crowe and Perry)

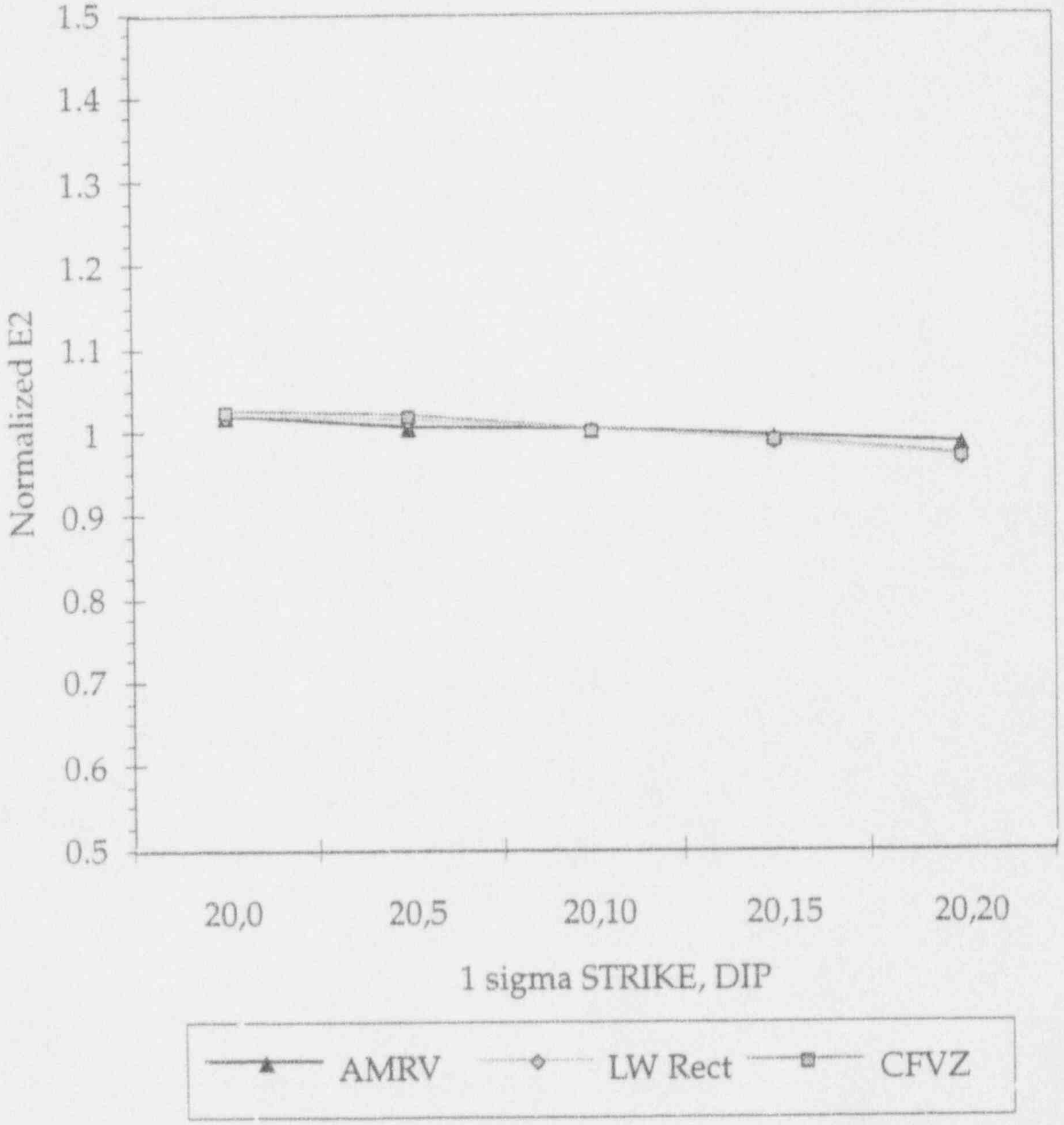


STRIKE Variation

(Normalized to Base)

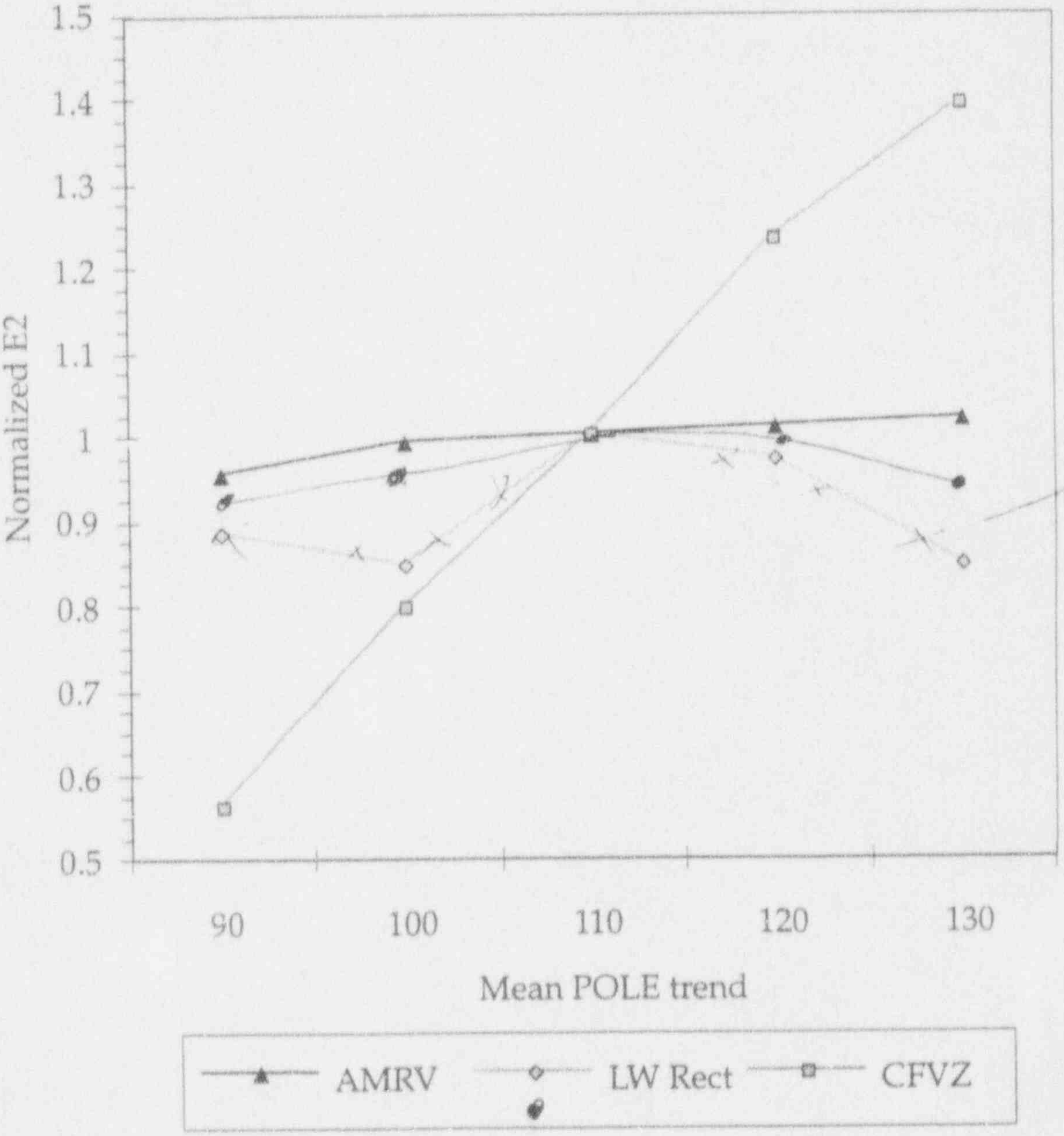


DIP Variation
(Normalized to Base)



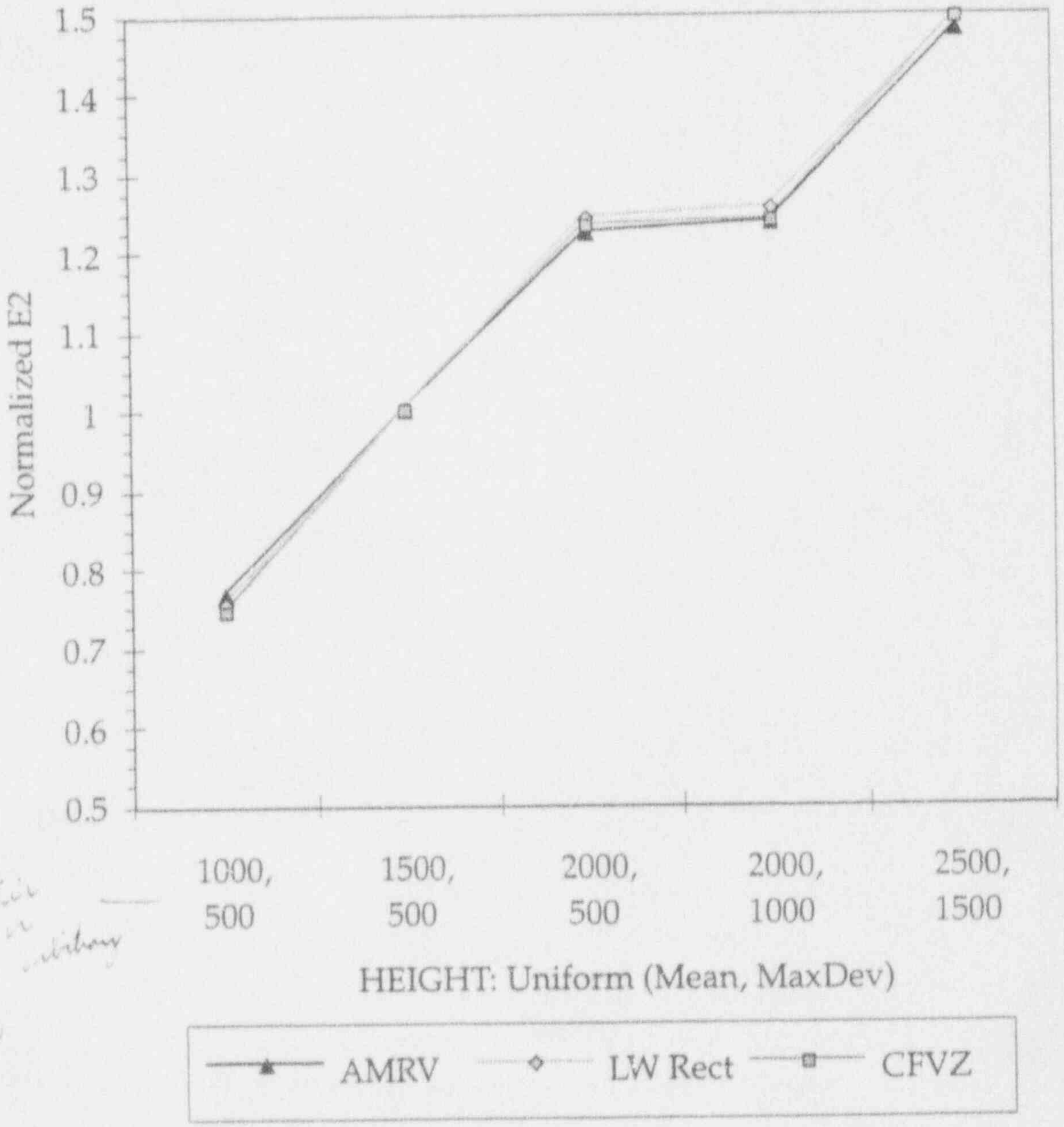
Mean POLE Variation

(Normalized to Base)



'Δ, wrong in Fig'

HEIGHT Variation
(Normalized to Base)

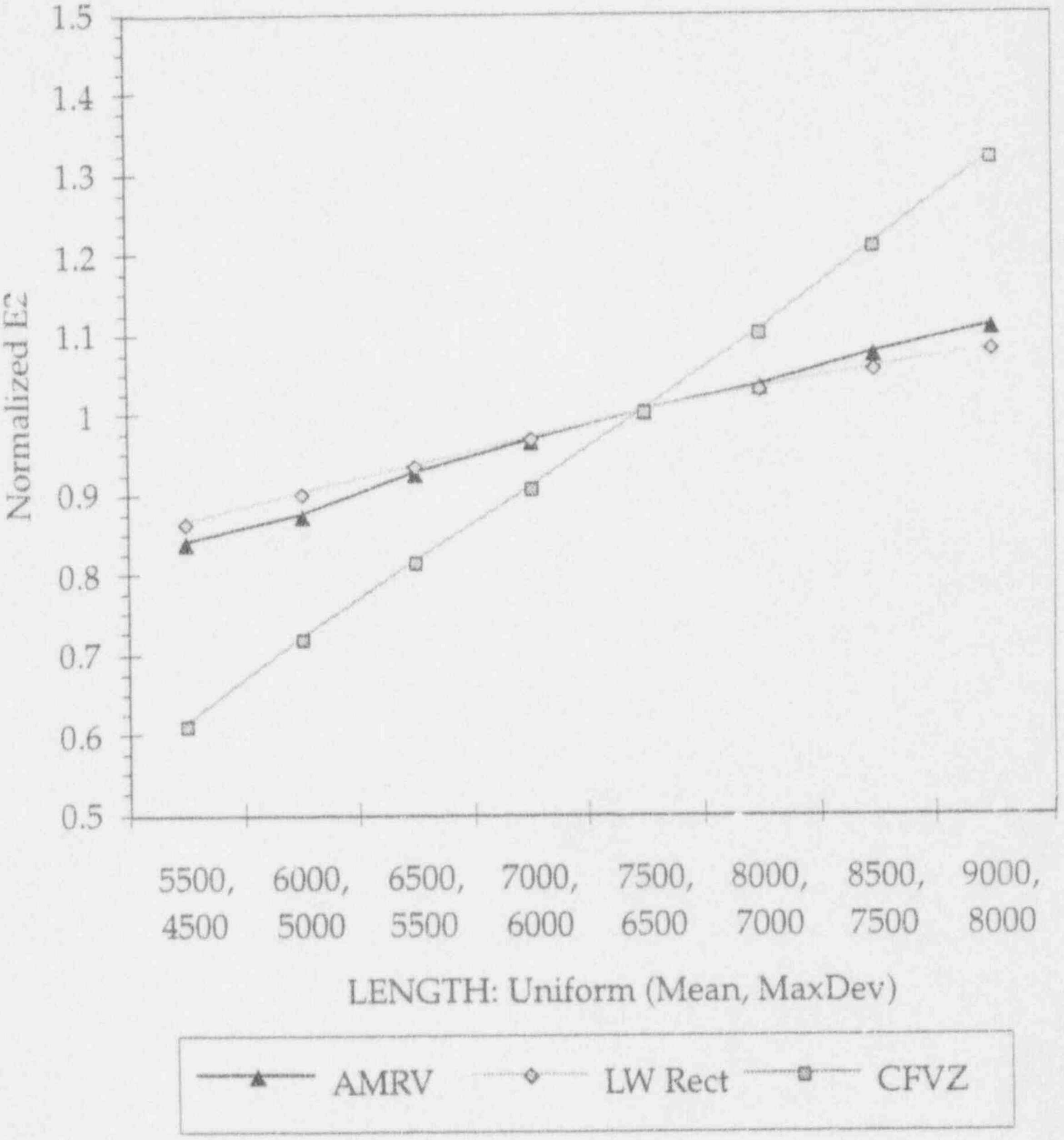


[illegible] [illegible] conditions

"Fracture tortuosity"

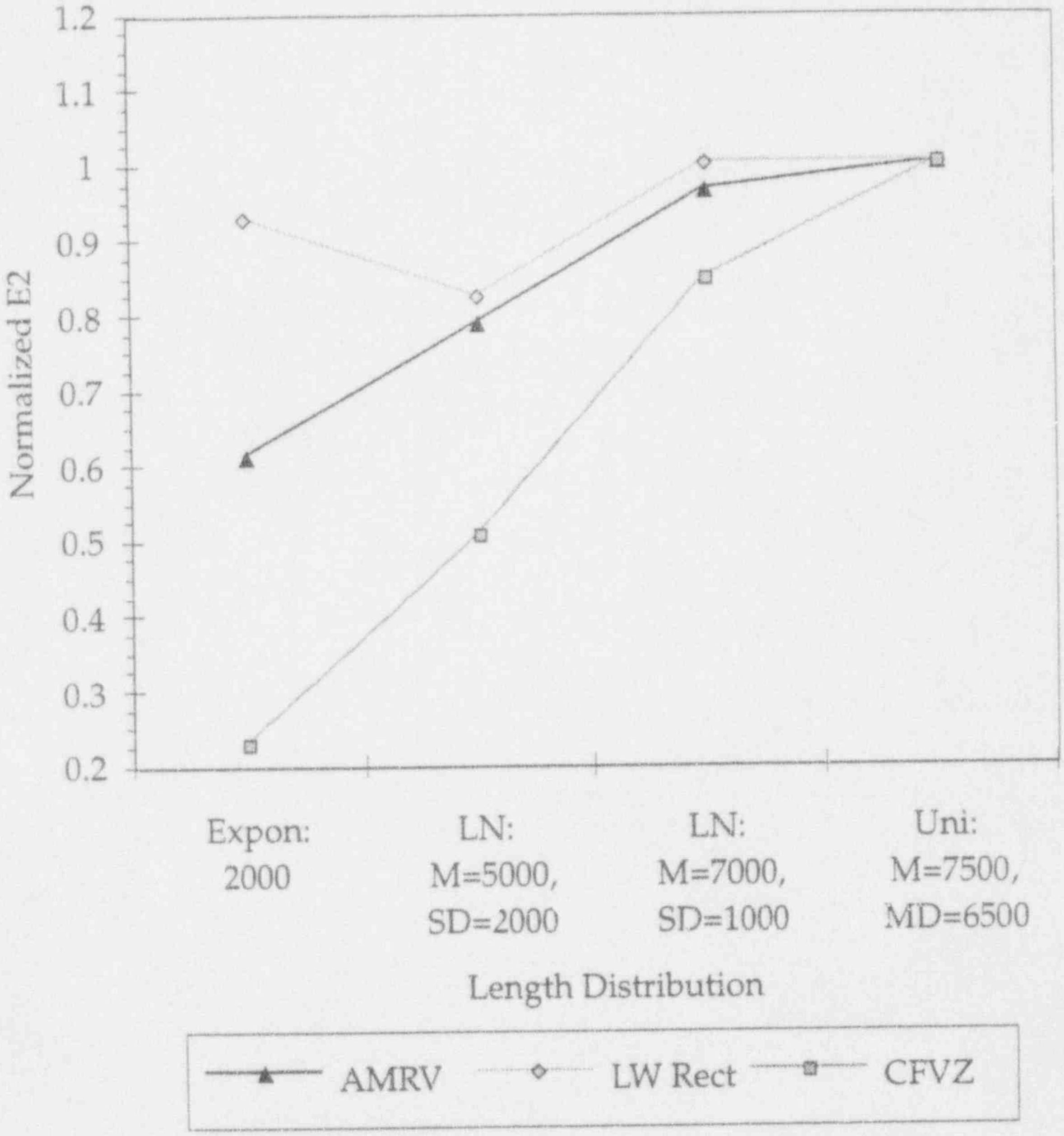
LENGTH Variation

(Normalized to Base)

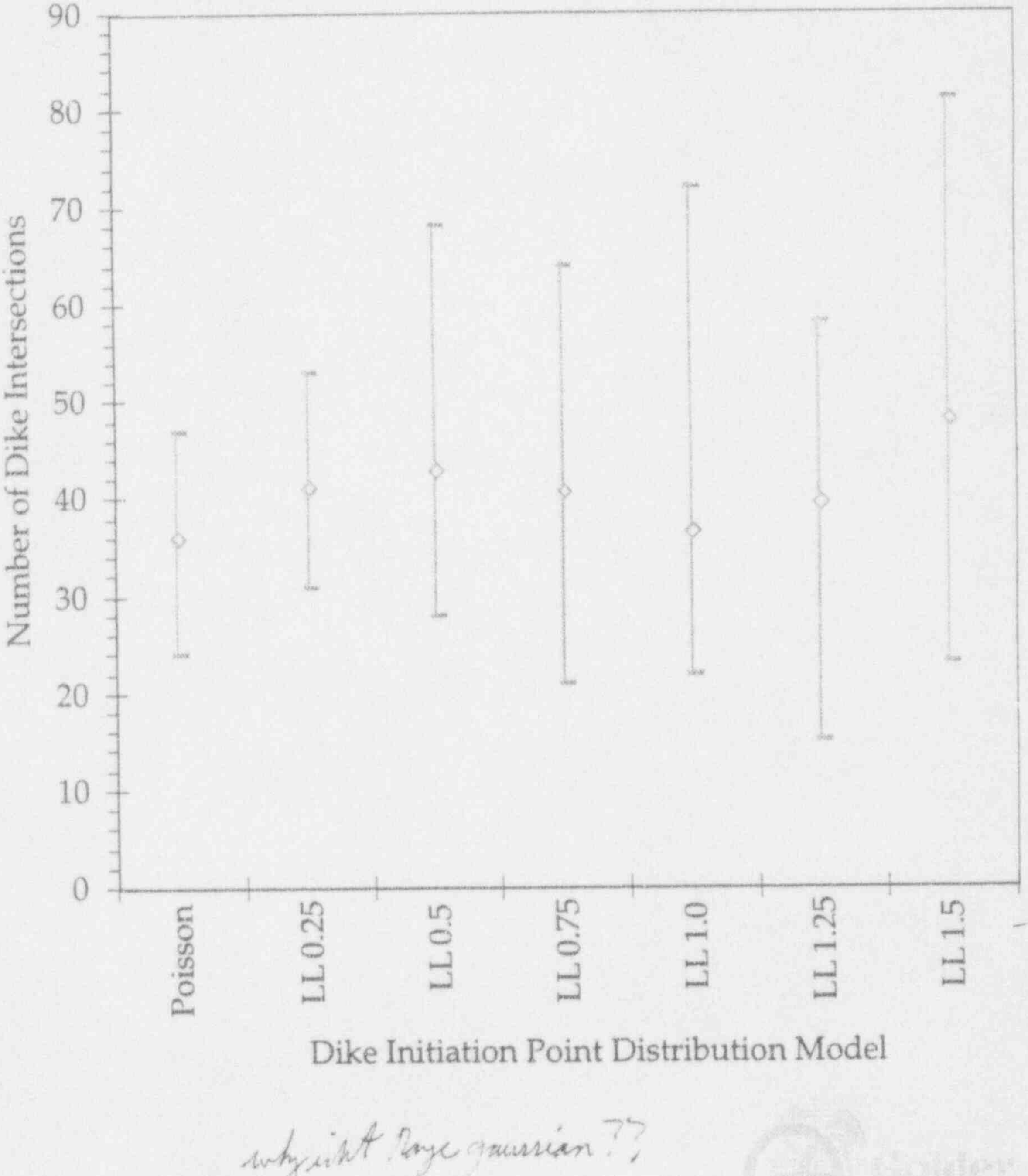


DISTRIBUTION Variation

(Normalized to Base)



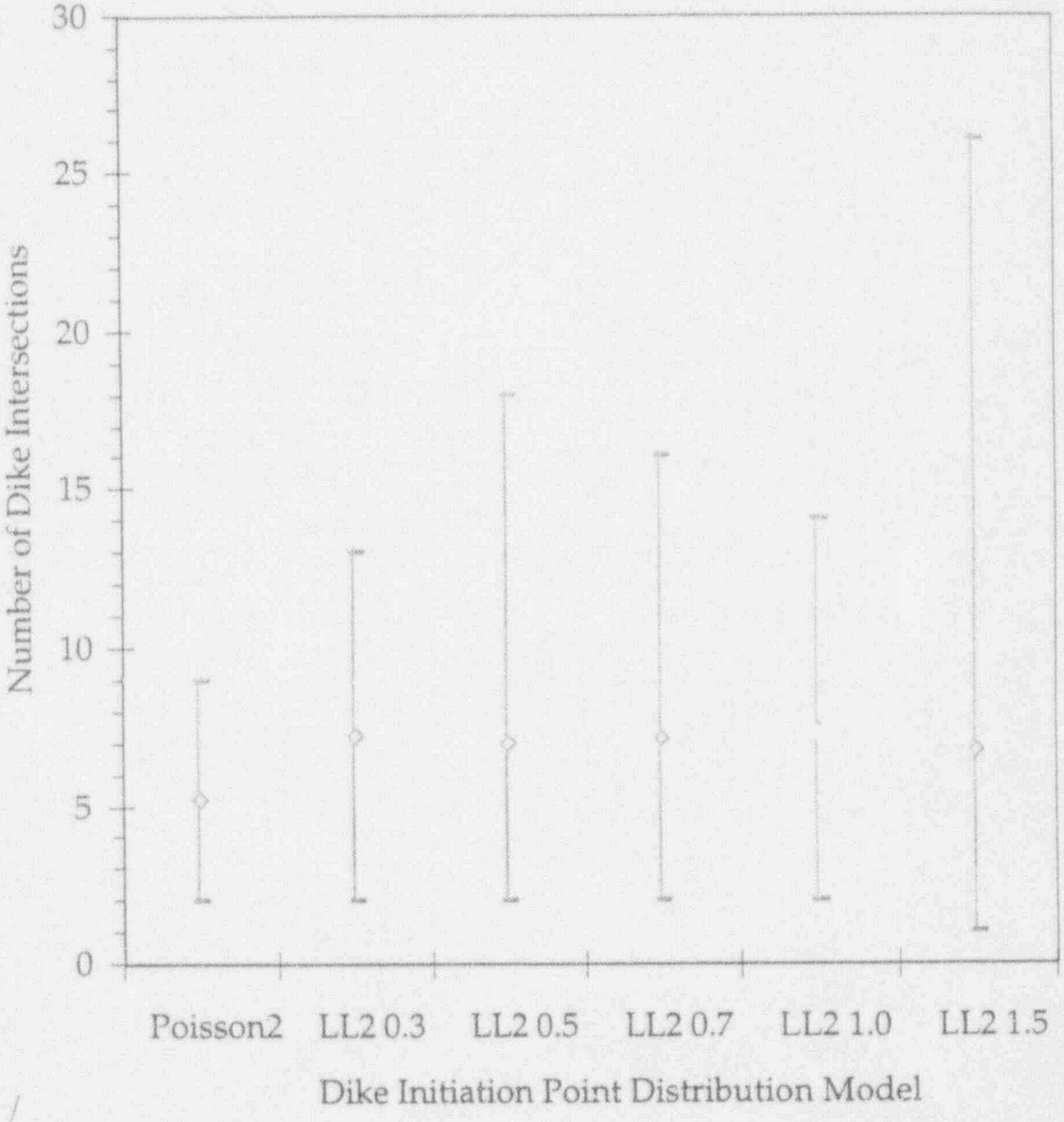
Poisson vs Clustering Models



— Cluster Factor

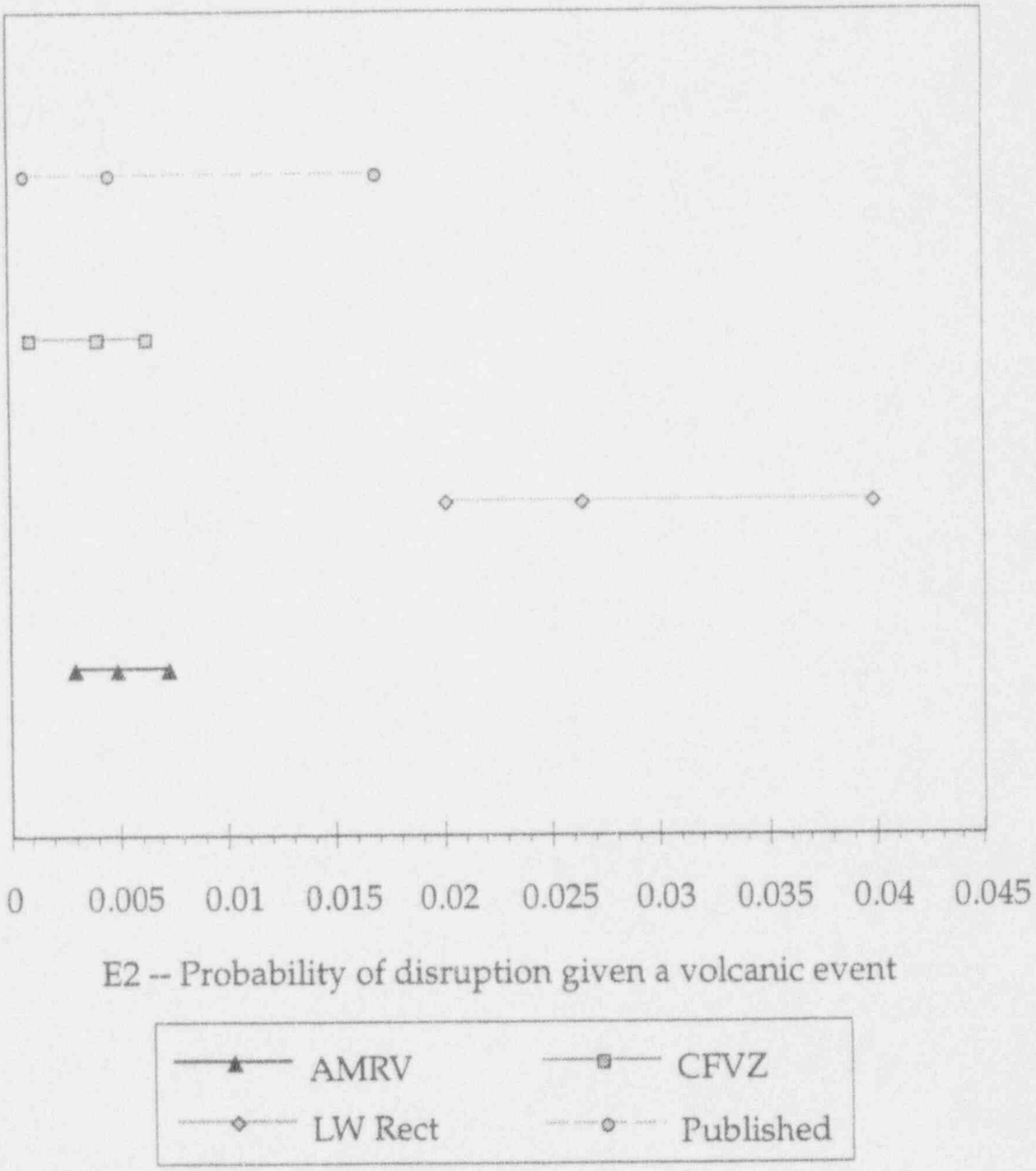
why isn't large gaussian??

Poisson vs Clustering Models

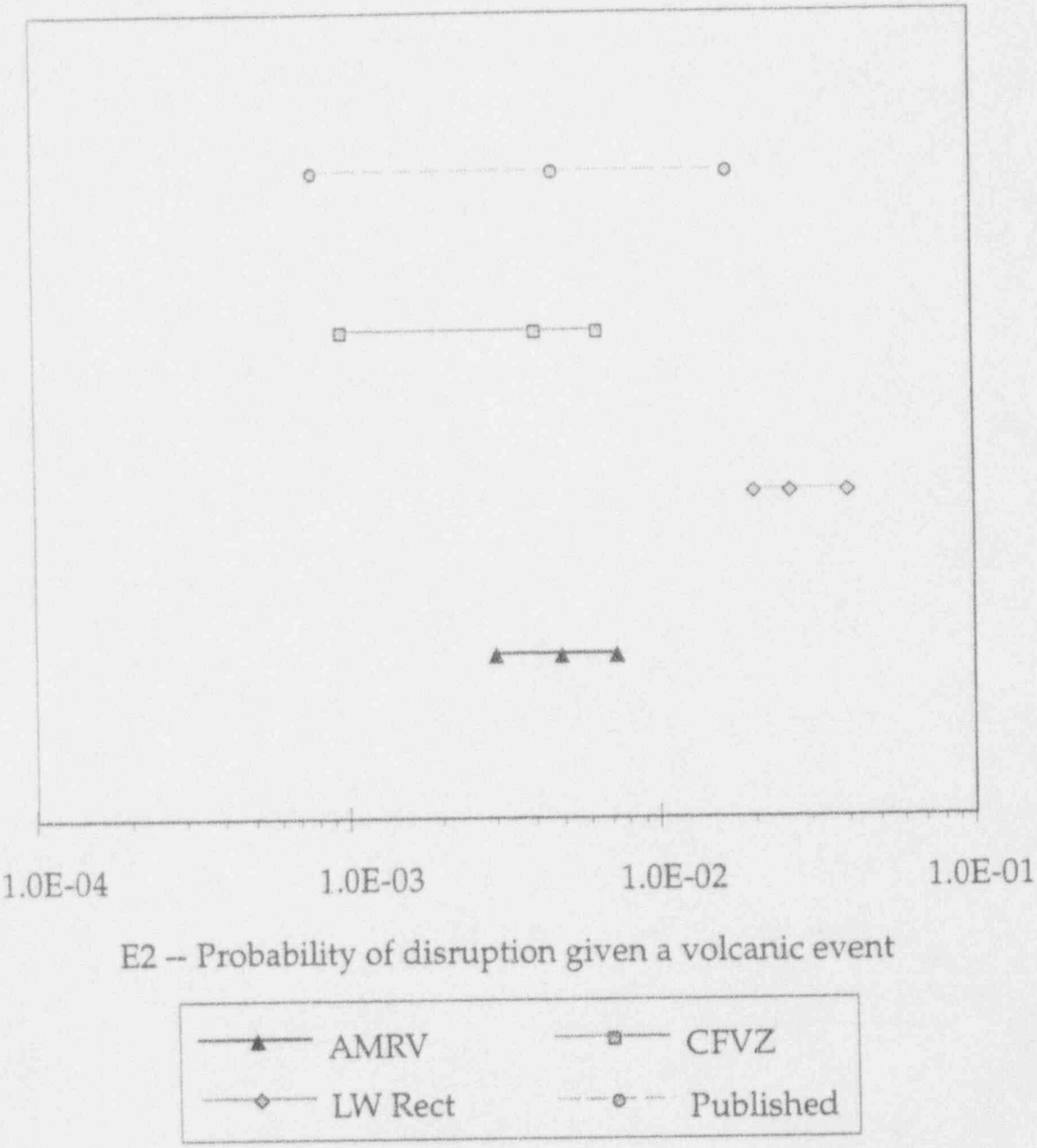


N/A

Range of E2 Values



Range of E2 Values



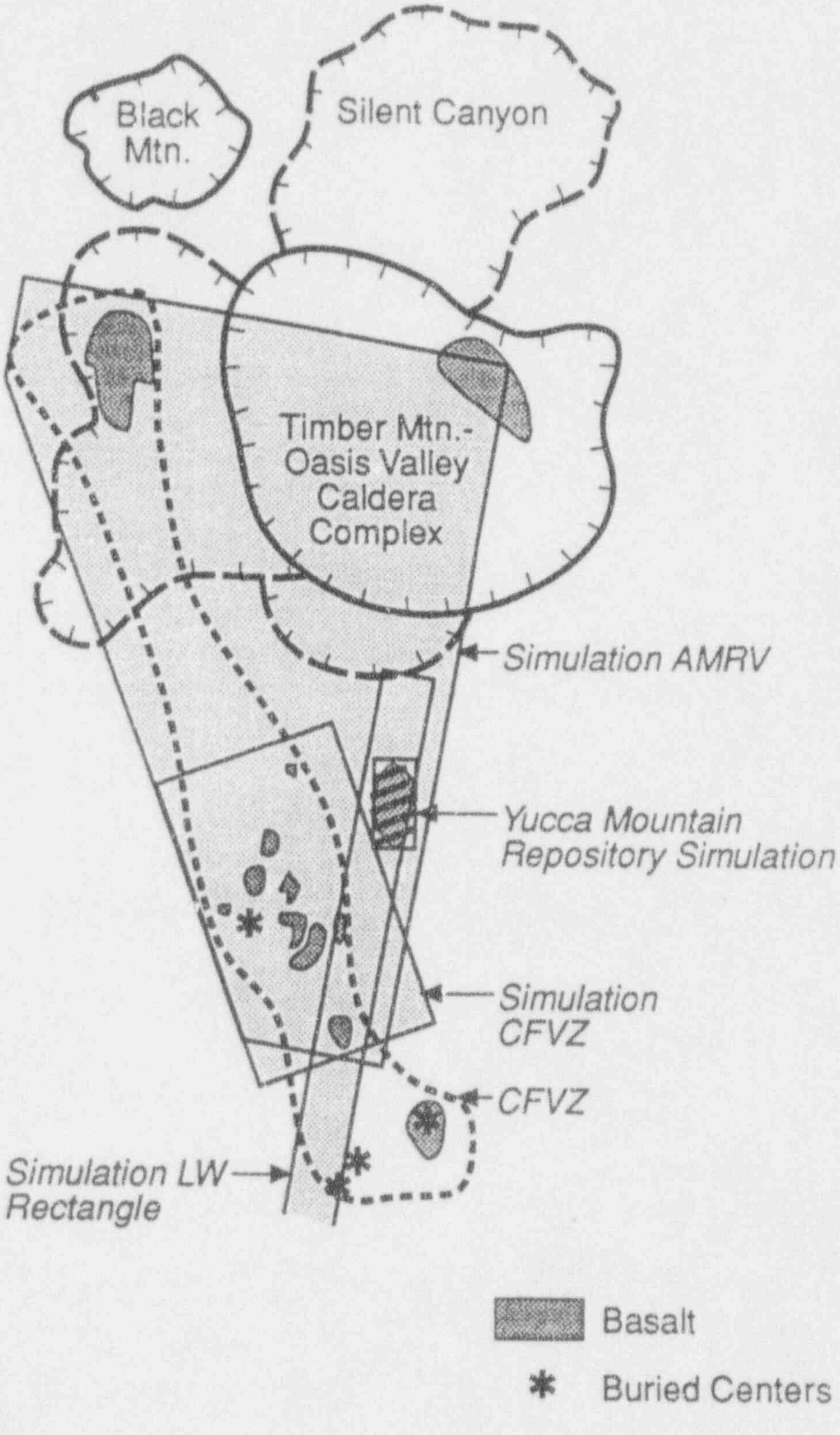
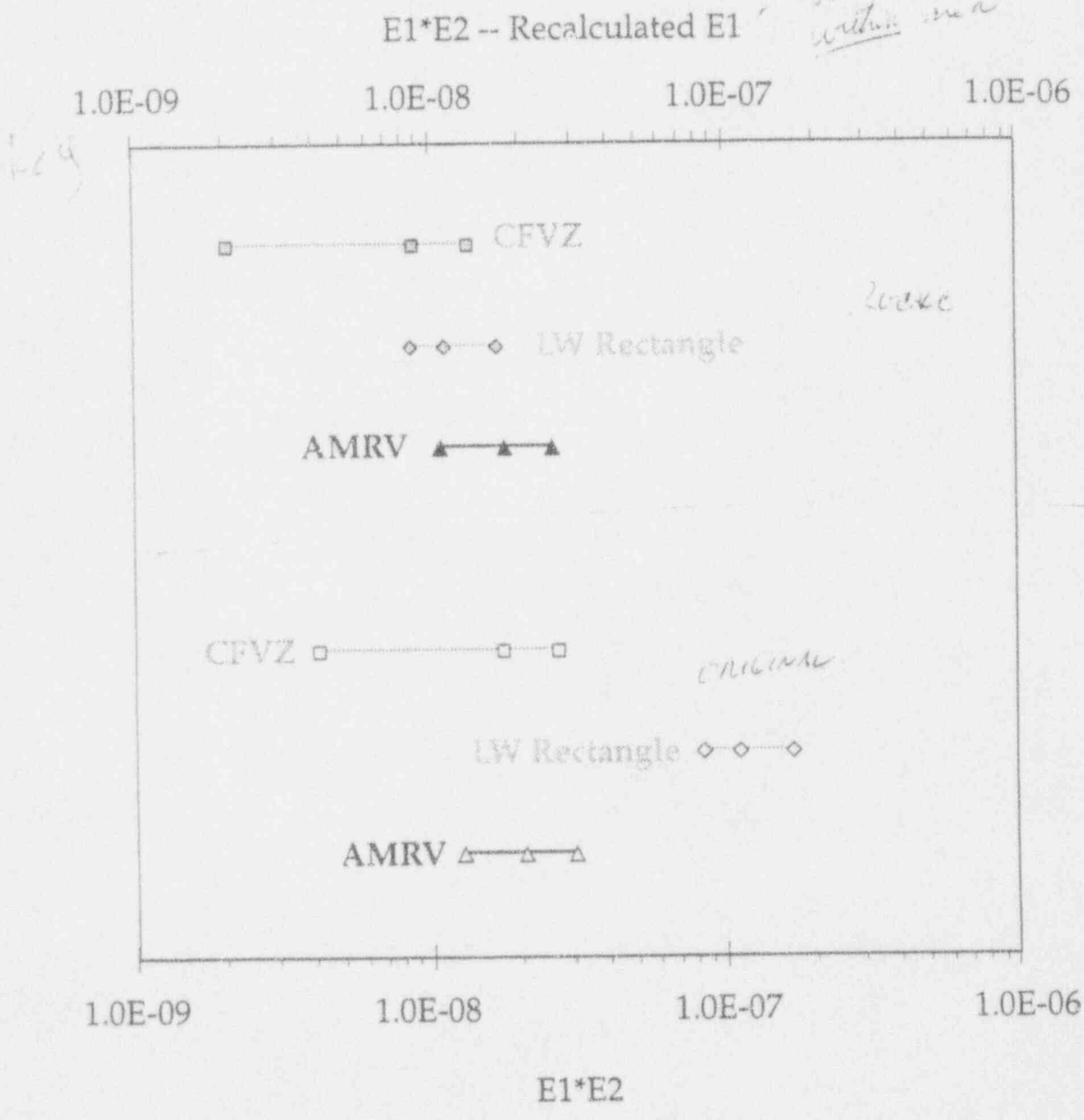
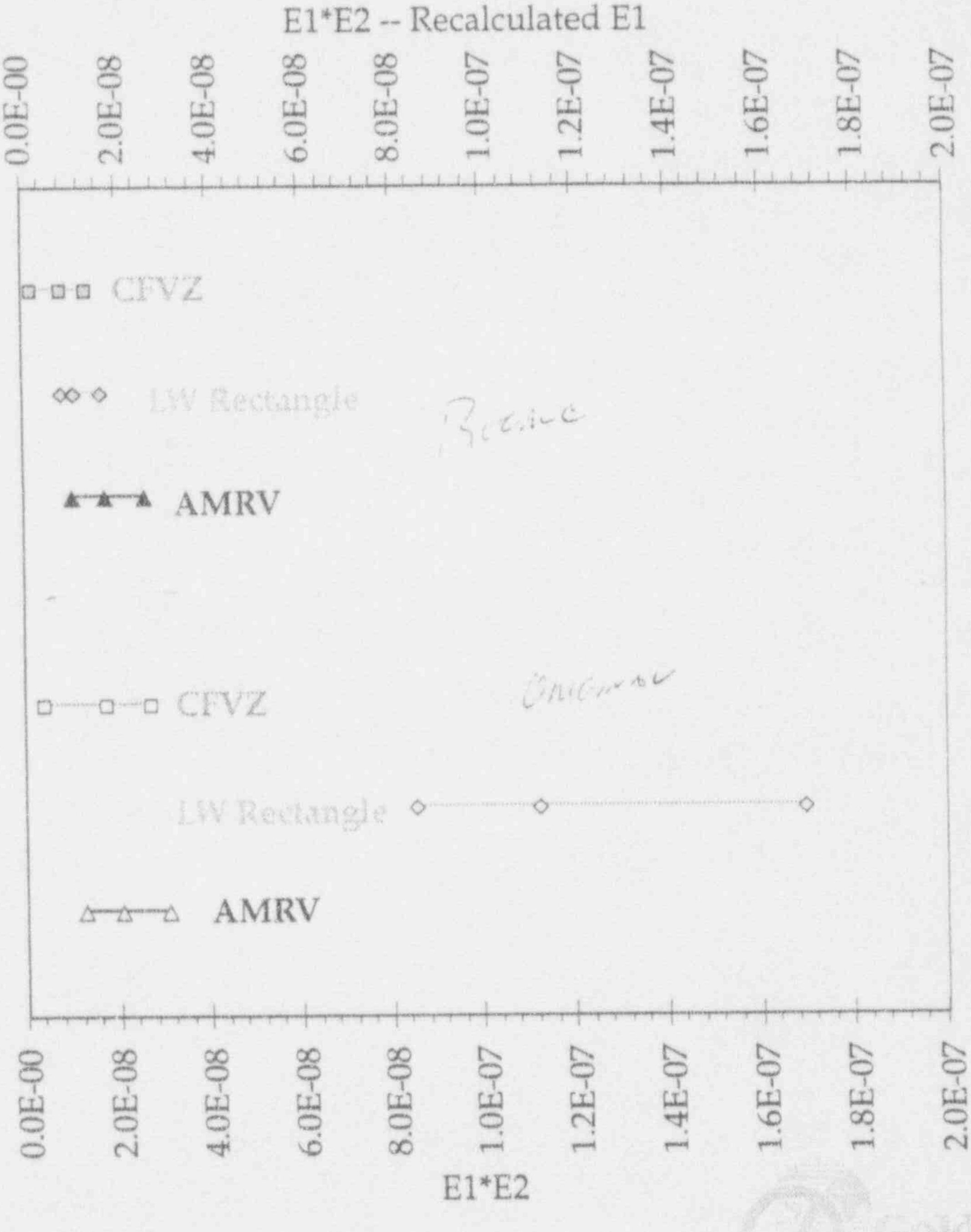


Figure 1. Location map for post-caldera basaltic volcanism in the Yucca Mountain region.

Effect of Recalculating E1 on E1*E2



Effect of Recalculating E1 on E1*E2



Put in 2 CCDF's @ end of Talk.
47 out of 200 [illegible] [illegible] [illegible] [illegible] in CCDF

Conclusions

- Sensitivity of disruptive probability to input parameters dependent on E2 conceptual model
- Simple Clustering does not increase disruptive probability
- Recalculation of E1 given E2 conceptual model is essential for valid disruptive event rate

[illegible] Take [illegible] [illegible] rate + apply to small area

Golder Associates

COMMENTS ON PROBABILISTIC VOLCANIC HAZARD ASSESSMENT

Michael F. Sheridan
Department of Geology
SUNY at Buffalo
Buffalo, NY 14260

(716) 645-6100

Probabilistic Volcanic Hazard Assessment

- Geological Perspectives
- Basic Elements
- Examples of Volcanic Hazard Forecasting
- Methods Used
- Issues Relevant to Yucca Mountain
- Comments on Work Presented Here

SUNY at Buffalo - Geology

PVHA - Geological Perspectives

Volcanic Forecasting

Key Questions:

What? type of event

When? repose frequency, next expected event

Where? at an exicting volcano or a new location

Size ? magnitude

Anticipated effects? vulnerability

PVHA - Geological Perspectives

Conceptual Models

Mass eruption rate (energy release rate)

Survivor function = probability that a repose has ended up to a specified time

→ "Still need to be developed with" - what [illegible] length?

age-specific eruption rate

spatial event predictors

SUNY at Buffalo - Geology

BASIC ELEMENTS OF GOOD PVHA

- Define the problem and test the instrument - Need good analyses that are approachable to general public.
- Set limits of acceptability. Policy
- Identify key processes, parameters, & uncertainties
  Deterministic, Probabilistic
- Include all or most possibilities in model
- Arrange according to interdependencies - Need links to evaluate all scenarios
- Perform Sensitivity studies on parameters

Determine interactive effects of all elements on model

- Climate & hydrologic
- Seismicity & Volc

SUNY at Buffalo - Geology

ADVANTAGE OF LOGIC TREES

- Applies to a wide range of problems
- Analyzes sources of uncertainity
- Accomodates interpretations with uncertainties
- Can use probabilities from expert judgement
- Can incorporate extreme interpretations
- Feedback etween nodes is possible

survivor function

$$\mathfrak{F}(x) = \text{prob}\,(X > x) = \int_x^\infty f(u)\,du$$

age-specific eruption rate

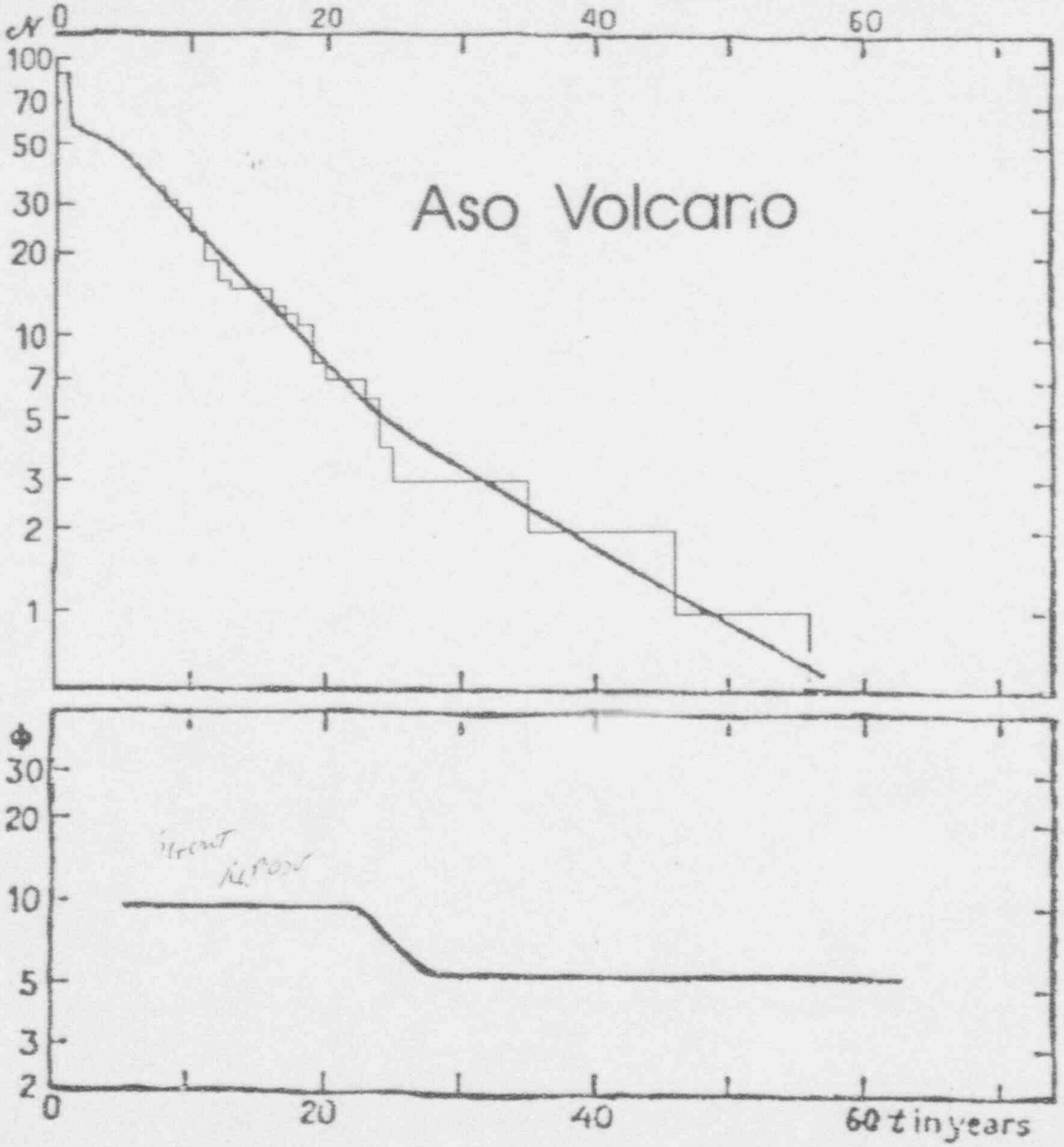
$$\phi(x) = \lim_{\Delta x \to 0+} \frac{\text{prob}\,(x < X < x + \Delta x \mid x < X)}{\Delta x}$$

...at @ Single Volc. Does VF = Volc. eruption rate ??

$$\phi(x) = \frac{f(x)}{\mathfrak{F}(x)} = \frac{\mathfrak{F}'(x)}{\mathfrak{F}(x)} = -\frac{d}{dx}\,[\ln \mathfrak{F}(x)]$$

SUNY at Buffalo - Geology

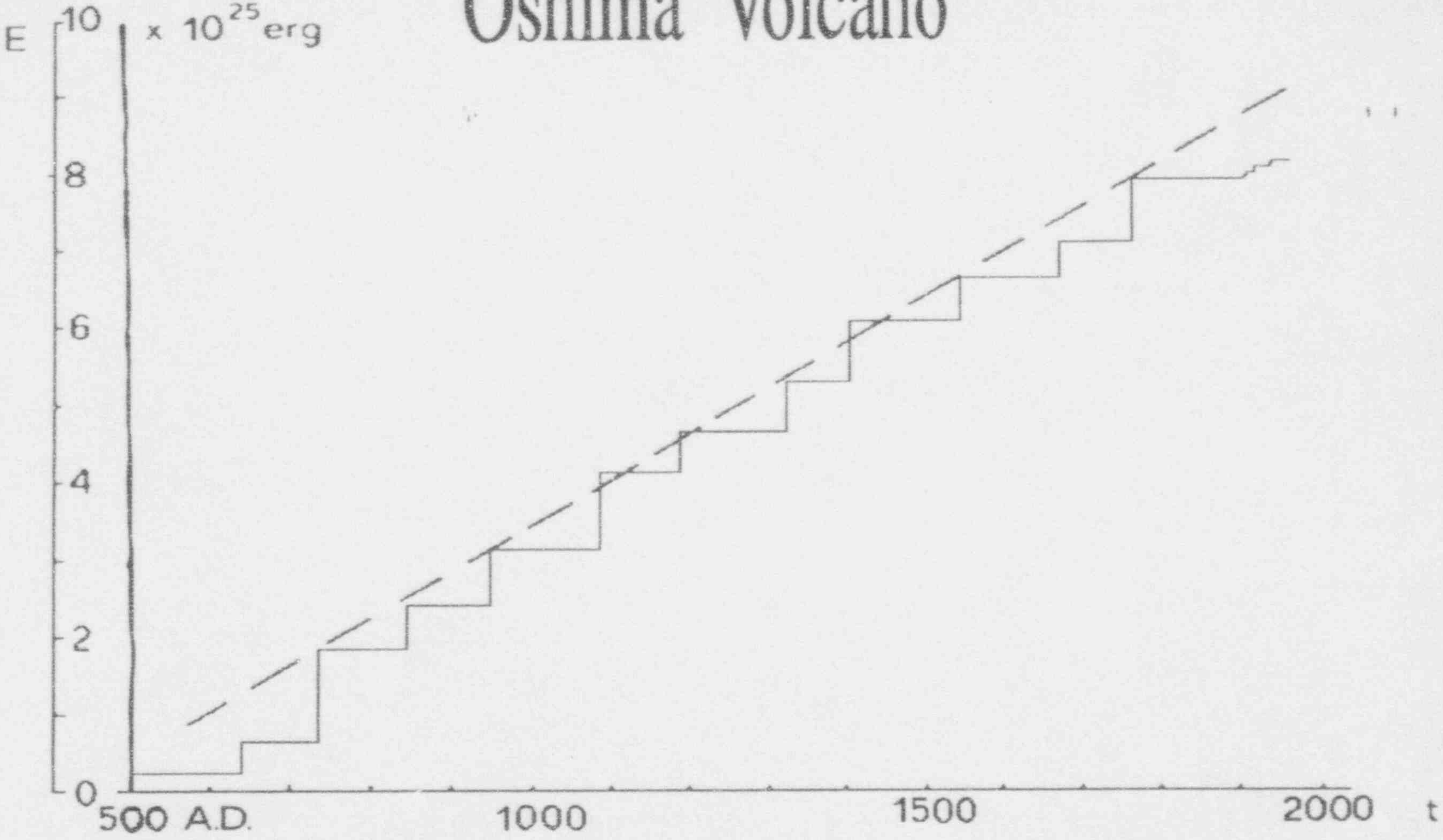
Wickman, 1965



SUNY at Buffalo - Geology

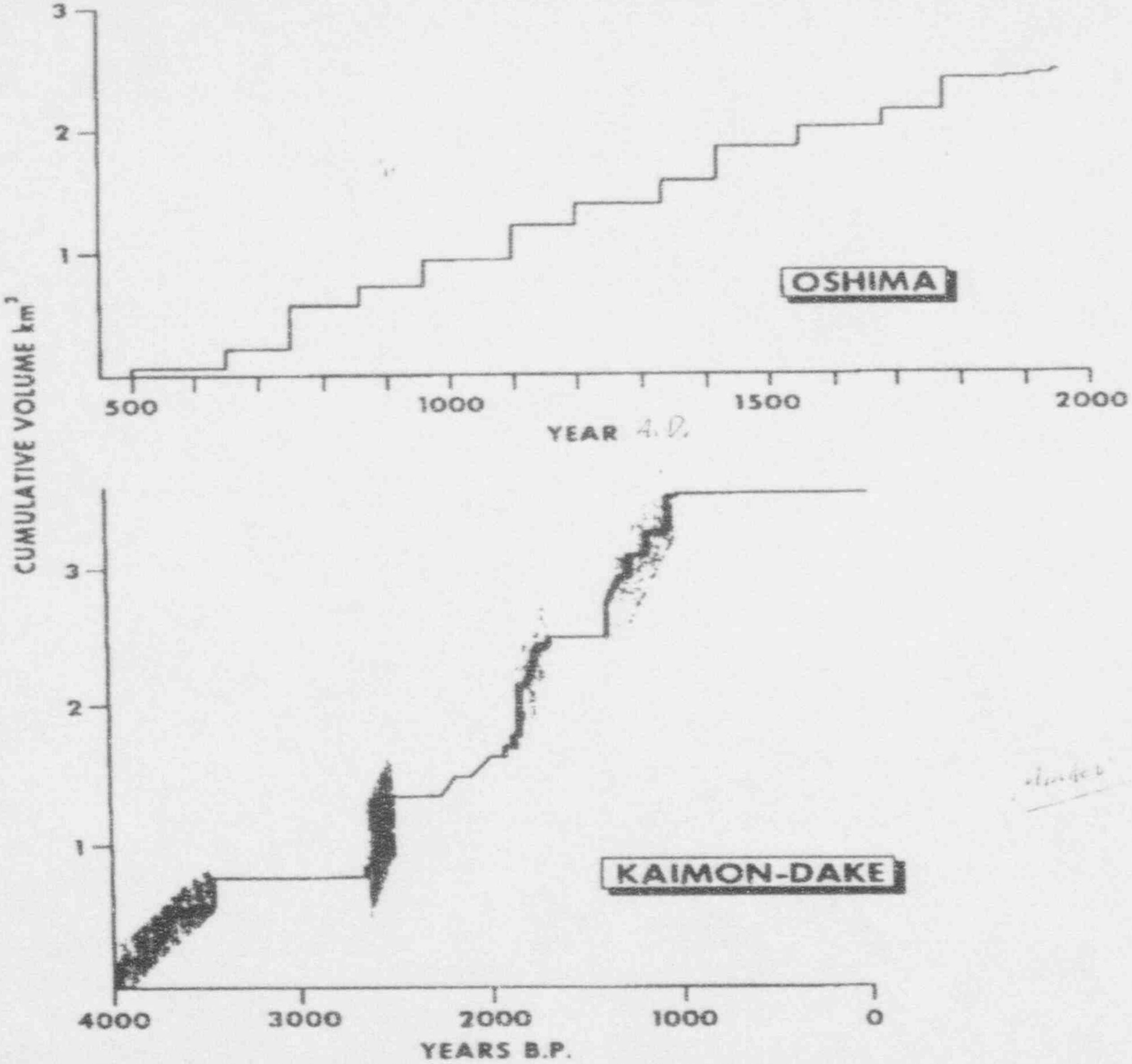
Wickman, 1965

Oshima Volcano



SUNY at Buffalo - Geology

Scandone, 1981



Wadge , 1982

SUNY at Buffalo - Geology

LONG-TERM VOLCANIC HAZARD ASSESSMENT

Scandone (1979) Mexico

Very active volcanoes

Popocatepetl	2.4 x 10-2 yr-1
Colima	5.0 x 10-2 yr-1

Volcanic fields and regions

Mexican volcanic belt		7.0 x 10-2 yr-1
Chichinautzin	236/70,00,00~~0~~	3.1 x 10-4 yr-1
Tlapacaya	12/23,000	5.3 x 10-4 yr-1

YUCCA MOUNTAIN ISSUES

Geologic Questions to be Answered

(put together before [illegible]?)

1. Vulnerability problem:

- What is the minimum sized volcanic event that would present unacceptable safety hazards?
- What is the temporal probability of such an event or a larger one in the relevant volcanic system?
- What is the probability of such an event being close enough to effect the repository?

YUCCA MOUNTAIN ISSUES

Geologic Questions to be Answered

2. Problem resolution

- Put the volcanism problem into a "global" framework. For example: Compare local forecast with that of larger regions (entire Great Basin and larger volcanic fields)

≃ (models)

- Give relatively more weight to qualitative scientific issues. For example: in determination of expected mass eruption rate for volcanoes near Yucca Mountain.

- Use expert judgment to evaluate conceptual issues. For example: the relative probability of various spatial models. or the likelihood of a new volcanic center.