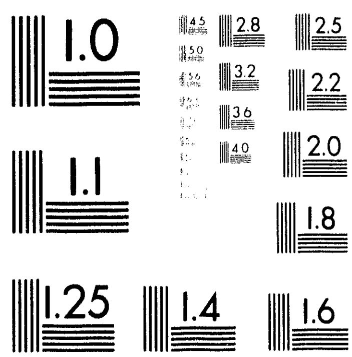
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Title: SIMULATION MODELING OF THE PROBABILITY OF MAGMATIC DISRUPTION OF THE POTENTIAL YUCCA MOUNTAIN SITE

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SIMULATION MODELING OF THE PROBABILITY OF MAGMATIC DISRUPTION OF THE POTENTIAL YUCCA MOUNTAIN SITE

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ABSTRACT

The first phase of risk simulation modeling was completed for the probability of magmatic disruption of a potential repository at Yucca Mountain. E1, the recurrence rate of volcanic events, is modeled using bounds from active basaltic volcanic fields and midpoint estimates of E1. The cumulative probability curves for E1 are generated by simulation modeling using a form of a triangular distribution. The 50% estimates are about 5 to 8 x 10^{-8} events yr^{-1} The simulation modeling shows that the cumulative probability distribution for E1 is more sensitive to the probability bounds then the midpoint estimates. The E2 (disruption probability) is modeled through risk simulation using a normal distribution and midpoint estimates from multiple alternative stochastic and structural models. The 50% estimate of E2 is 4.3 x 10^{-3} The probability of magmatic disruption of the potential Yucca Mountain site is 2.5 x 10^{-8} yr^{-1} This median estimate decreases to 9.6 x 10^{-9} yr^{-1} if E1 is modified for the structural models used to define E2. The Repository Integration Program was tested to compare releases of a simulated repository (without volcanic events) to releases from time histories which may include volcanic disruptive events. Results show that the performance modeling can be used for sensitivity studies of volcanic effects.

INTRODUCTION

An assessment of the risk of volcanism with respect to isolation of radioactive waste at the potential Yucca Mountain site has been a topic of considerable debate for over a decade.[1-8] Volcanism studies focused on establishing the minimum and maximum bounds of the probability and consequences of disruption of a potential repository should a magmatic event penetrate a repository.[2,9-10] This problem can be summarized in the form of several questions:

1. What is the likelihood that a future volcanic event will occur in the Yucca Mountain region (YMR) during the next 10,000 yrs?

2. Given that a volcanic event occurs, what is the likelihood that it will penetrate a repository or the isolation system encompassing a repository?

3. Would such an event lead directly or indirectly to substantial releases of radioactive waste in the accessible environment?

The answers to these questions must be considered from two perspectives. First, if the risk of volcanism is sufficiently high, the Yucca Mountain site should be eliminated from consideration as a potential repository. Here risk is defined as a product of probability and consequences of future volcanic events. Second, if the site is not eliminated from consideration solely from the risk of volcanism, studies must still be conducted to assess a complete range of future volcanic processes and their possible impact on the repository and waste isolation system. The first perspective of site elimination was assessed for the Environmental Assessment[11], the Site Characterization Plan[12] and the Early Site Suitability Evaluation[13]. A draft report reviewing results of all volcanism studies has been completed and circulated for review comments (Volcanism Status Report[14]). One of the conclusions of this report, like the previously cited reports, is the probability of magmatic disruption of the potential repository is too low to disqualify the site solely on the basis of the risk of future volcanic activity. The support for the decision is the low midpoint estimate of the probability of magmatic disruption of the potential repository ($\approx 10^{-8}$ events yr^{-1} or about 1 in 10,000 in 10,000 years[14]). The distribution of uncertainty about this value has not been evaluated but must extend to > 10^{-8} yr^{-1}. Therefore volcanic processes (scenarios) that could contribute to release of radioactive waste must be considered in future site characterization studies. These volcanic processes include releases associated with volcanic eruptions as well as the releases from the coupled effects of subsurface disruption of the waste isolation system.[15-16]

The purpose of this paper is twofold. We first examine the range of calculated values of the attributes for the probability of magmatic disruption of the potential repository. These data are bounded using logical numerical limits for the rates and spatial distribution of volcanic processes. Risk simulation is used to assess the uncertainty of the probability of volcanic disruption of the potential repository. Second, using the Repository Integration Program (RIP),[17] we provide preliminary calculations to test the applicability of using the RIP code to assess system responses or sensitivity to revised subsets of volcanic events.

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PROBABILITY MODEL

The probability of magmatic disruption of a repository and release of radionuclides to the accessible environment is modeled as a conditional probability:[8]

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

where E1 is the recurrence rate of volcanic events, E2 is the probability that a future volcanic event intersects the potential repository, the controlled area of the YMR, and E3 is the probability that a volcanic event leads to release of radionuclides to the accessible environment. For the case of disqualification of the potential repository, E2 is evaluated for the repository area, and E3 is evaluated for eruptive (direct) releases. For the case of site licensing, volcanism is evaluated as one of a combination of processes that could lead to loss of waste isolation. Here E2 is evaluated for the potential repository, the controlled area and the YMR, and E3 is evaluated for both eruptive and subsurface releases.[16]

The mathematical model used to model the conditional probability is:

$$\text{Pr[no disruptive event before time } t] = e^{-\lambda t p},$$

where λ is the recurrence rate (E1), t is time and p is the disruption probability (E2).[2] This probability is expressed in the form of a homogeneous Poisson distribution assuming that the probability of n eruptions over time t is constant, the eruptions occur independently and the time between events is exponentially distributed. Crowe et al.[8] reviewed possible models for λ. They concluded that a variety of distribution models are permissible and there is no consensus concerning the most applicable model for volcanic systems primarily because of the limited data for attempting to discriminate time-distribution models. A homogeneous Poisson model was chosen because it represents the most direct approach to probabilistic assessment using a small data set.

E1: The Recurrence Rate of Volcanic Events.

A range of midpoint estimates for E1 is possible for several reasons. First, there are only a small number of past volcanic events in the YMR. An event is defined as the formation of a new volcanic center and may consist of multiple volcanic vents. Volcanic events have attributes of age, location, eruptive volume, eruption mechanism(s) and magma composition. There were only three sets (clusters) of volcanic events that formed seven volcanic centers during the Quaternary. This is an insufficient number to select either distribution models using tests for goodness of fit, or to provide statistically robust calculations of the time-space properties of the events. Thus while rates for E1 are generally low[8] ($<< 10^{-5}$ yr^{-1}), there is considerable uncertainty in assigning and bounding the rates. Second, different ages of volcanic events have been used because of the measurement uncertainty of established and developmental geochronology methods[14]. Finally, the most significant model differences result from selection of values for E1 that satisfy vaguely defined concepts of "reasonable assurance" and "conservatism". The problem can be solved through the application of risk analysis[18,19] using elements of subjective judgment to translate uncertain data into probability distributions. We adopt this approach and combine estimates of E1 with risk simulation to calculate the distribution of E1 in probability space. The calculations are made recognizing that the exact form of the distribution cannot be defined. The intent of the risk simulation is to provide an unbiased assessment of E1. This is attempted through evaluation of the record of volcanism in the YMR, inclusion of all alternative models for past volcanic patterns and consideration of the limits imposed by natural variability in volcanic processes.

Figure 1 is a plot of the distribution of published values of E1 (events yr^{-1}) using homogeneous, modified homogeneous and nonhomogeneous Poisson models. An upper bound for E1 can be used from the regulatory guidelines of 10 CFR60. An adverse condition is defined as the presence of igneous activity in the Quaternary or 2 Ma using the regulatory definition. Formulated probabilistically, the risk of volcanism becomes a concern for siting a repository when there is at least one volcanic event in the Quaternary (1 event/2 x 10^6 yrs or $\approx 5 \times 10^{-7}$ events yr^{-1}; ***regulatory perspective***; Fig. 1). An upper bound to rates of volcanic events can be defined by event rates in large volume, very active basaltic volcanic fields of the basin-range province

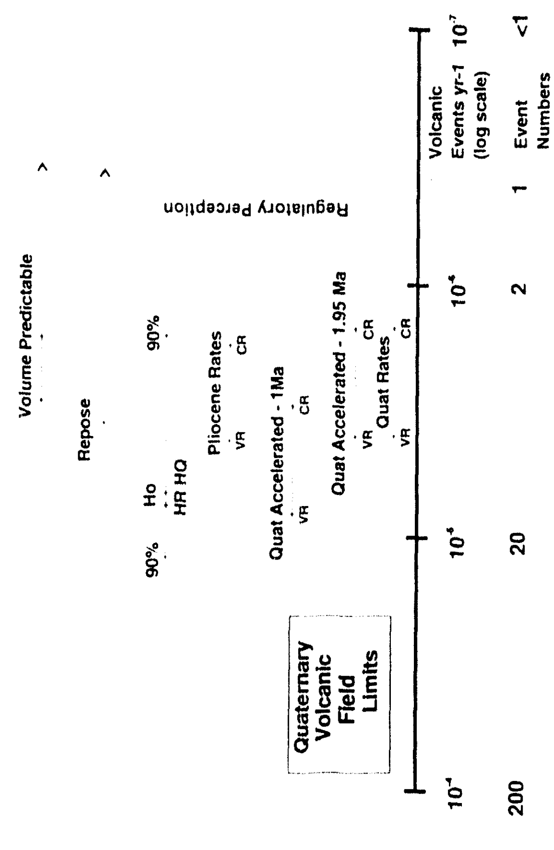

Figure 1: Distribution of Calculated Values of of E1. The y-axis has no scale and provides space to plot values. Labels on Fig. 1 and the following figures are described in the text.

(choosing fields in reasonable proximity to the YMR). The Yucca Mountain site is **not** located in a major volcanic field. Therefore recurrence rates in the YMR must be *less* than rates in large, more active fields (Quaternary volcanic events > 20). Recurrence rates for these fields have been estimated assuming a homogeneous Poisson model[8] (Cima volcanic field, California; Lunar Crater volcanic field, Nevada). The Lunar Crater has a maximum of 82 vents occurring in 28 clusters of probable Quaternary age (a cluster is a closely spaced group of basaltic vents that could be fed from a *single dike system*). The Cima volcanic field has 29 vents in 22 clusters (Quaternary age). The event counts for both fields give recurrence rates of 4.5×10^{-5} to 1.1×10^{-5} events yr^{-1} (a homogeneous Poisson model is used because the chronology of individual events is too poorly established to test other distribution models). These rates are shown in the box labeled ***Quaternary volcanic field limits*** on Fig. 1.

What constraints are provided from the volcanic record for the YMR? There are 7 Quaternary volcanic centers in the YMR. These can be viewed as a minimum of 3 events (cluster model[20]) or as many as 8 events where a spatially separate vent is counted as one event.[14] Corresponding rates are 1.5×10^{-6} to 4×10^{-6} (***Quaternary rate; CR*** = cluster rate, and ***VR*** = vent rate on Fig. 1). A separate calculation is made applying the concept of a volcano-tectonic cycle (inception, evolution, and decline of a thermal anomaly producing basaltic melt that ascends episodically through the upper mantle and crust). The record of basaltic volcanic events in the YMR, using this criterion, extends from about 4.7 Ma to the present.[8,21] There were 8 Pliocene and Quaternary events (cluster model) and 20 Pliocene and Quaternary events (vent model; includes aeromagnetic anomalies suspected or confirmed to be volcanic centers[14]). These event counts correspond to occurrence rates of, respectively, 1.7×10^{-6} and 4.3×10^{-6} events yr^{-1} (***Pliocene rate***; ***CR*** and ***VR*** on Fig. 1). Note the similarity of the ***Pliocene*** and ***Quaternary*** rates. (Fig. 1).

Have other event rates been calculated? Ho et al.[5] and Ho[6] used a nonhomogeneous Poisson process with Weibull intensity to estimate recurrence rates and a homogeneous Poisson process to predict future eruptions in the YMR. They obtained rates of 5×10^{-6} events yr^{-1} ($\beta = 2.29$) for the Pliocene epoch and 5.5×10^{-6} events yr^{-1} ($\beta = 1.09$) for the Quaternary (***Ho***; ***HP*** and ***HQ***, respectively on Fig. 1). The 90% confidence limits for the Quaternary events were also calculated[6] (1.85×10^{-6} to 1.26×10^{-5} events yr^{-1}). Are these event rates different from homogeneous Poisson rates? The maximum 90% confidence limit for the instantaneous recurrence rate is nearly identical to the volcanic field limits (Fig. 1). The difference in midpoint estimates results from the use of only maximum event counts and a time interval of 1.6 Ma versus 2.0 Ma (geologic versus regulatory definition of the Quaternary). The β of 2.29 for the Pliocene epoch results from the construction of the calculation; the time interval used was 6.0 Ma and the volcanic events used are ≤ 3.7 Ma. The β for the Quaternary is ≈ 1 and is therefore equivalent to the homogeneous Poisson model.

An important element in assessing the suitability of the distribution of values of E1 is the pattern of volcanic events through time. A homogeneous Poisson process modeled in the form of an exponential distribution for a continuous random variable underestimates recurrence rates for a system in a waxing state and overestimates rates in a waning state.[5-6,8] The former is not acceptable; the latter represents a conservative model that could be acceptable for risk assessment.[8] The β value of ≈ 1 for the Weibull distribution for Quaternary events[6] is consistent with a homogeneous Poisson process.

Figure 2 is a plot of magma volume versus time for the YMR using all Pliocene and Quaternary volcanic events. There has been an exponential decrease in the volume of erupted magma through time (magma output rate). Modified homogeneous Poisson event rates can be calculated using magma output rates through time using the formula[2,14,25]

$$N_e = (R_v / O_p) - L_t$$

where N_e is the estimated time of the next volcanic event, R_v is the representative volume of a volcanic event, O_p is the magma output rate and L_t is the time since the last volcanic event. Values for these variables are used from Crowe et al.[2-3,14] The calculated values of N_e using mean Pliocene and Quaternary event volumes are >1 Ma and are physically unrealistic. The calculated values for N_e using mean Quaternary event volumes are $< 1.7 \times 10^{-6}$ events yr^{-1} and are **less** than all estimated event rates (Fig. 1). Exceeding small and unrealistic values of N_e are obtained if the smallest volume of a volcanic center is used

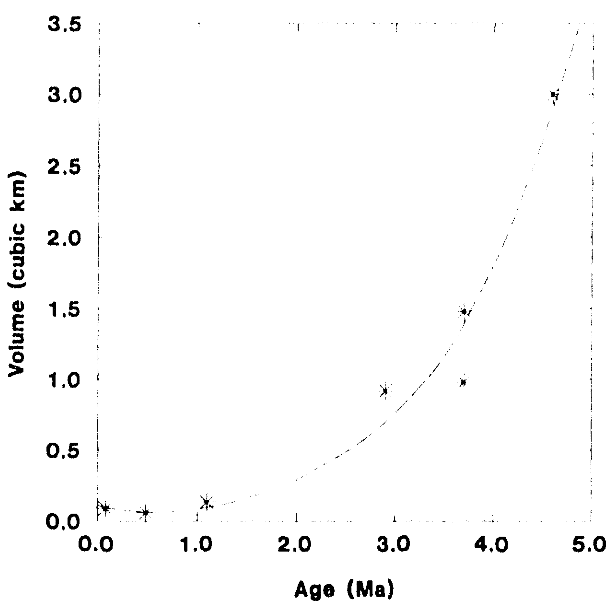

Figure 2: Magma volume versus time for the Pliocene and Quaternary volcanic rocks of the YMR. The 3.7 Ma event includes the drilled aeromagnetic anomaly of Amargosa Valley. The second point plotted above the 3.7 Ma point adds the volume of two aeromagnetic anomalies of the Amargosa Valley. The dashed line is a distance weighted least squares fit of the magma volumes and the solid line is the linear regression fit (both fitted with the lower point for the 3.7 Ma event).

(Little Cones center or the volume of the individual cones of the Little Cones centers ≈ 7.5 x 10^{-4} events or equivalent to 1,500 Quaternary events!). The only physically plausible results for recurrence rates for magma-volume calculations are obtained by assuming values of R_v that are equal to the volume of pulses of magma that produced clusters of events. Using the volumes of Quaternary events for the 1 Ma cluster, the Sleeping Butte cluster and the Lathrop Wells center gives estimated values for N_e of 2.76 x 10^{-6} to 1.6 x 10^{-6} (***Volume Predictable*** of Fig. 1; all values from Crowe et al.[14]).

The magma output rate has declined exponentially through time (Fig. 2). There is also a slight tendency for more frequent events (but smaller volume) through time.[22] This may be attributed to a decreasing degree of partial melt[23] resulting in a higher volatile content in the melt and a greater tendency for the ascending magmas to erupt. The data set is too small to evaluate using time-series analyses but can be assessed qualitatively from Fig. 3, a plot of repose intervals versus time. The plot is consistent with variation about a mean that decreases slightly through time (linear regression fit; Fig. 3). A permissive alternative model is that the repose intervals have decreased in the Quaternary (distance weighted least squares fit; Fig. 3). Neither trend can be tested statistically because of the small number of events. Two models are used to account for these possible trends. First, the recurrence rate is calculated as the **minimum** observed, repose interval (290 ka or 3.4 x 10^{-6} events yr-1; ***Repose*** of Fig. 1). Second, recurrence rates can be calculated for only the interval of the possible increase in event rates. The interval of the calculation is somewhat arbitrary because of the long time between the age of the onset of increased event rates (1 Ma) and the age of the preceding volcanic event (2.9 Ma or 3.7 Ma dependent on structural models). Moreover, there is uncertainty in identifying the cause of changed rates. We use, therefore, two calculations to bracket this event. The first is the 1 Ma interval (***Quaternary accelerated 1 Ma***; Fig. 1) and the second is the midpoint of the interval between the accelerated events and the preceding event (1.95 Ma; ***Quaternary accelerated 1.9*** Ma; Fig. 1). The latter rate is nearly identical to the ***Quaternary cluster*** and ***event*** rates (Fig. 1).

The Table 1 lists minimum and maximum bounds, midpoint estimations of E1 and descriptive statistics derived from the midpoint estimations. These values were used to generate cumulative probability distributions through simulation modeling (@RISK computer program[24], Latin Hypercube sampling, 10,000 iterations). We calculated cumulative probability distributions for all sets of E1 estimations from Table 1. A trigen distribution model was used that is a variation of the triangle distribution model. The trigen model allows input of estimated occurrence probabilities for bounding values and does not require the minimum and maximum values to be zero. Figure 4 is a plot of the cumulative probability distributions labeled with the symbols from Fig. 1. These cumulative distributions span a limited range of probability space. The 50 percentile estimates for E1 range from 5.2 to 8.4 x 10^{-6} events per year. These are slightly higher values than previous estimates[2,6,25] because we added the Quaternary accelerated model. Additionally, the lower boundary limits chosen for the trigen distribution skew the values toward higher median estimates. The median estimates equal or exceed all published midpoint estimates for E1. The 50 percentile values, based on sensitivity analysis, are more dependent on the probability bounds than either the midpoint estimations or the assumed distribution models. This is illustrated on Fig. 1 by the cumulative curve obtained through risk simulation using a normal distribution and univariate statistics from Table 1.

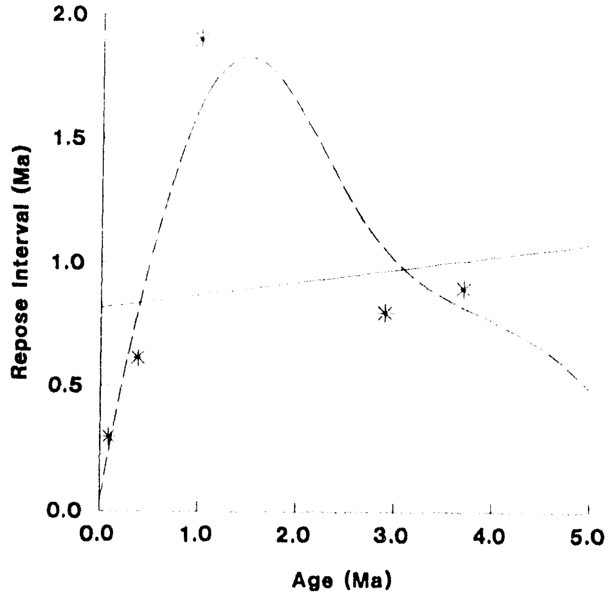

Fig. 3: Repose intervals versus time for Pliocene and Quaternary volcanic events of the Yucca Mountain region. The dashed line is a linear fit to the data points (5 points). The dotted line is fitted by distance weighted least squares.

Table I: Calculated Values for E1, the Recurrence Rate of Volcanic Events			
	Max Cluster	Max event	E1
Rate Model	Count	Count	(events yr-1)
Quaternary Cluster	3		1.50E-06
Quaternary Event		8	4.00E-06
Quaternary Accel Cluster/1 Ma	3		3.00E-06
Quaternary Accel Event/1Ma		8	8.00E-06
Quaternary Accel Cluster/1.9 M	3		1.54E-06
Quaternary Accel Event/1.9 Ma		8	4.10E-06
Pliocene Cluster	8		1.74E-06
Pliocene Event		20	4.35E-06
Weibull Quaternary/Ho 1992			5.50E-06
Weibull Pliocene/Ho 1992			5.00E-06
Repose Interval			3.45E-06
Volume Predictable			2.10E-06
GEOMEAN	3.25E-06		
STD	1.92E-06		

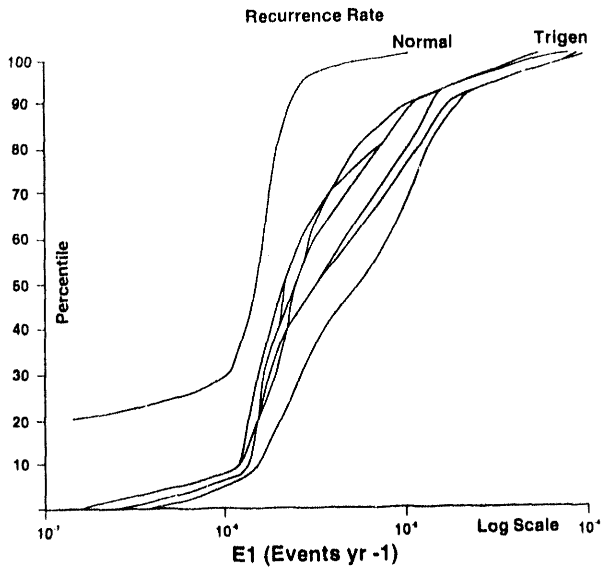

Fig. 4: Simulation-generated cumulative probability distributions for the 12 models of volcanic events in the YMR. The curves overlap so all distributions cannot be shown as separate lines.

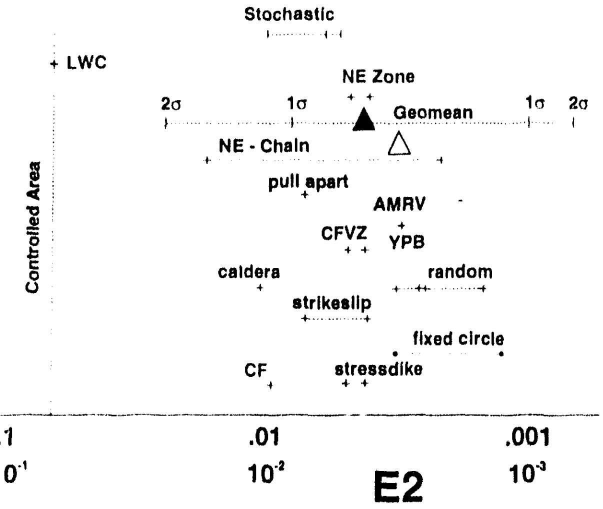

Fig. 5: Distribution of values of E2 (dimensionless ratio) for the YMR. The y-axis has no scale and is used for plotting space. The filled triangle is the geomean with one and two sigma errors The open triangle is the calculated geomean without the outlier value of Smith et al.[4]

E2: The disruption ratio.

Two slightly different approaches have been used to calculate E2, the probability of repository disruption (Fig. 5). The first approach assumes a random distribution of volcanic events recognizing that visual examination shows the spatial distribution of events to be nonrandom. Bounding values for E2[2-3,14,26-27] are used that encompass the uncertainty of the assumption of a homogeneous Poisson distribution. The advantage of a random model is that it is easily extended to include the repository and controlled area and is a conservative assumption for structural models that do not include the potential Yucca Mountain site. The second approach assumes some spatial (structural) control of volcanic events and attempts to factor this control into E2.[4,6,28] This approach allows the application of nonhomogeneous Poisson models to the Yucca Mountain setting. The disadvantages are several. First, the statistical validity of nonhomogeneous models cannot be tested with the limited data set. Second, volcanic centers show an inconsistent relationship to structural features. Some centers follow structural features (fault systems, caldera ring-fracture zones); others appear completely independent of local or regional structure.[21] Third, it is difficult to adapt these models to the Yucca Mountain site when the structural models do not include the site. Fourth, and most important, structural models for E2 assume the past locations of volcanic events provide information that constrains the location of future events. The geologic record shows however, that it is difficult to identify consistent patterns in the time-space distribution of volcanic events. Sequential plotting of volcanic events in the YMR reveals no consistent relationship between the location of individual events relative to successive events (Fig. 6). The only spatial relationships between events are their tendency to occur within a northwest-trending zone[25] (irregular jump directions and distances between events) and a secondary elongation of

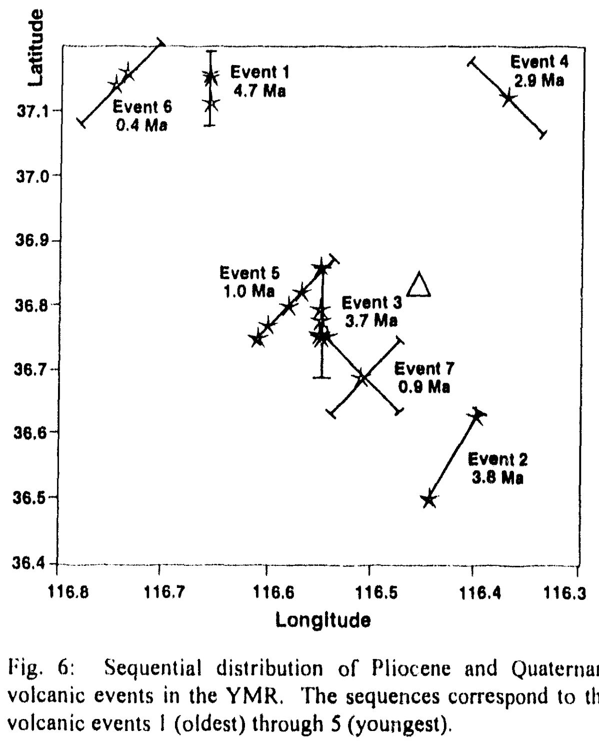

Fig. 6: Sequential distribution of Pliocene and Quaternary volcanic events in the YMR. The sequences correspond to the volcanic events 1 (oldest) through 5 (youngest).

age-grouped clusters of scoria cones (northeast-trending direction, maximum half-length = 6 km[4,25]). The only spatial overlap between past events is for the 3.7 Ma and 1 Ma basalt of Crater Flat.

We attempt to bound the values of E2 in probability space using the same approach applied to E1 (Fig. 5). Simple geometric constraints are placed on E2. First, the ratio must be smaller than the approximate ratio of the controlled area and the repository area since there are no Pliocene or Quaternary volcanic events in the controlled area. The distribution centroid of post-Miocene basalt centers is located in Crater Flat.[14] Thus it is unlikely that future basaltic activity will center on the potential repository (E2 << .1; the value is a dimensionless ratio). Second, a midpoint estimate of E2 can be approximated by the area enclosing the location of all volcanic events through time. Initial events (4.7 and 3.7 Ma) are aligned in a northwest-direction (Fig. 7). The next event (basalt of Buckboard Mesa) extends the distribution space to the northeast. Subsequent events fill the previously defined space. On the basis of the demonstrated stability of this distribution space through time, the ratio between the repository area and the area bounding the locations of the Pliocene and Quaternary volcanic events provides an approximation of a midpoint estimate of the E2 ratio. It is about 2 to 3 x 10^{-3}.

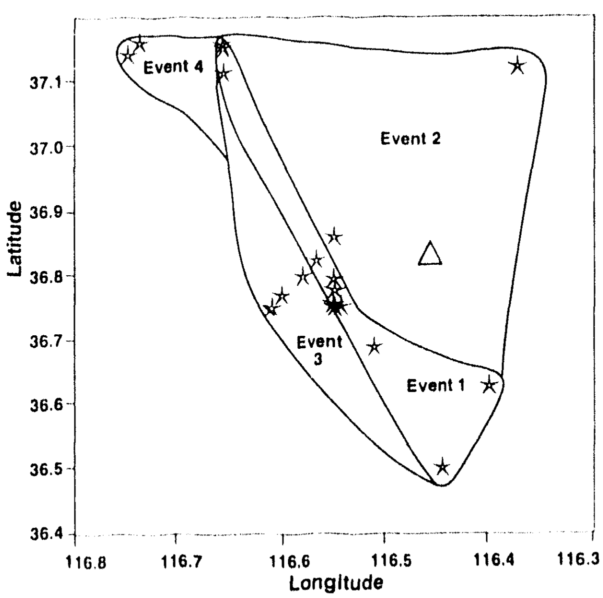

Fig. 7: Space-filling patterns of successive volcanic events in the YMR.

Table 2 is a compilation of published estimations for E2. These estimations (24 structural models) are near-normally distributed (probability plot). The mean is equal to the median and only one estimation is identified as an outlier (Lathrop Wells chain model of Smith et al.[4]). We model the distribution of E2 as a normal distribution using the univariate statistics from Table 2 (geomean = 4.3 x 10^{-3} ± 3.5 x 10^{-3}; 4.0 x 10^{-3} ± 2.6 x 10^{-3} with outlier removed). The cumulative probability distribution of E2 is computed using risk simulation similar to the calculations made for E1. The cumulative probability distribution is shown on Fig. 8.

Table II: Stochastic and Structural Models for E2, the Probability of Repository Disruption

Structual Model	Publication	Event Area (km2)	Disruption Ratio
Fixed Circle- 25 km	Crowe and Carr 1980	1963	3.10E-03
Fixed Circle- 50 km	Crowe and Carr 1980	7845	1.30E-03
Random Circle	Crowe et al. 1982	2437	2.50E-03
Random Ellipse	Crowe et al. 1982	4419	1.40E-03
Random Circle	Crowe et al. 1982	2470	2.40E-03
Random Ellipse	Crowe et al. 1982	1953	3.10E-03
AMRV	Smith et al. 1990	1955	3.00E-03
NE Chain Model	Smith et al. 1990	375	2.20E-03
CFVZ	Crowe and Perry 1989	1260	4.80E-03
CFVZ	Crowe and Perry 1989	1480	4.10E-03
YPB	Crowe 1990	1955	3.00E-03
Crater Flat Field	Crowe et al 1994	650	9.20E-03
Strike Slip Quat	Swchweickert, 1989	855	7.00E-03
Strike Slip Plio-Quat	Swchweickert, 1989	1460	4.10E-03
Stress Field Dike-Q	Crowe et al. 1994	1260	4.80E-03
Stress Field Dike-P	Crowe et al. 1994	1480	4.10E-03
Lathrop Chain Model	Smith et al. 1990	360	1.70E-02
Pull-apart Basin	Fridrich and Price 1992	855	7.00E-03
Caldera Model	Carr 1990	585	1.02E-02
NE Structural Zone	Carr 1990	1500	4.0C.-03
Crater Flat/Buckboard	Crowe el al. 1994	1300	4.62E-03
Stochastic Dike/NW-NE	Sheridan 1992		6.00E-03
Stochastic Dike/NE-NE	Sheridan 1992		1.00E-02
Lathrop Wells Dike	Sheridan 1992		5.30E-03
	GEOMEAN		4.29E-03
	STD		3.54E-03

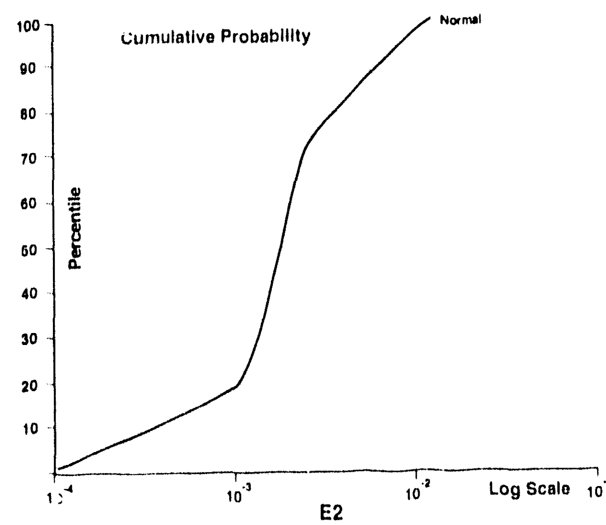

Fig. 8: Simulated cumulative probability distribution for E2, the disruption ratio. The distribution was calculated using a normal distribution with a mean of 4.3 x 10^{-3} and a standard deviation of 3.5 x 10^{-3}.

Probability of magmatic disruption of the potential repository.

A cumulative probability distribution of the magmatic disruption of a potential repository (Pr_{md} = Pr(E2 given E1)Pr(E1)) was obtained by multiplying the cumulative probability distributions for E1 and E2. The E1 probability distribution was integrated using the quartile values from the simulation runs for all distributions except two. The excluded distributions used estimations of only maximum event counts;[5-6] all other distributions were obtained using minimum and maximum cluster and event counts. The cumulative probability distribution of Pr_{md} is shown on Fig. 9. The 50% value for the cumulative distribution is 2.6 x 10^{-8} events yr^{-1}. An unexpected result from simulation modeling is the observation that there are significant modifications to E1 required from selection of structural models for E2, an observation not made in previous calculations. We recalculated E1 for specific structural models, reducing the cluster and event counts where required because they correspond to volcanic events that were **excluded spatially** from the structural model (Table 1). Preliminary simulation modeling was completed for a modified Pr_{md} where the E1 estimations were recalculated without the excluded events. This modified distribution of E1 was multiplied by the simulation values for E2. The 50% estimate for this structurally revised probability of disruption of a potential repository is 9.5 x 10^{-9} events yr^{-1} (*SM*; Fig. 9) This is only a preliminary calculation and is not shown as a cumulative probability distribution. We have not run all the simulation sets for the multiple cases (cluster and vent counts) for the modified E1. However the modified calculations show that variations in E1 required by selection of structural models have a significant effect on Pr_{md}. Also shown for comparison on Fig. 9 is the range in midpoint estimations reported by Connor and Hill[28] for Pr_{md} using nonhomogeneous Poisson models. These values are similar to our calculations.

Conclusions from the simulation modeling:

Risk assessment using simulation modeling combined with multiple alternative estimations of E1 and E2 show that the median rate of the probability of magmatic disruption of a potential repository is about 9.5 x 10^{-9} to 2.6 x 10^{-8} events yr^{-1}. These rates are low and support previous conclusions that the potential repository site at Yucca Mountain **cannot** be disqualified solely on the basis of the risk of volcanism. The uncertainty about the midpoint estimations is sufficiently large (the 75% of Pr_{md} is 4.5 x 10^{-8} events yr^{-1}) that volcanic events must be considered for their potential effect on the performance of the waste isolation system. Such studies are in progress.[15,29] The simulation modeling shows that Pr_{md} is relatively insensitive to the selection of distribution models and variations in midpoint estimates. Alternative models of E1 and E2 show minor differences in attribute estimates that are bounded by the range of cumulative probability distributions. Significant variations in E1 are caused by the selection of different structural models for E2. Not considering these effects can result in overestimation of Pr_{md}.

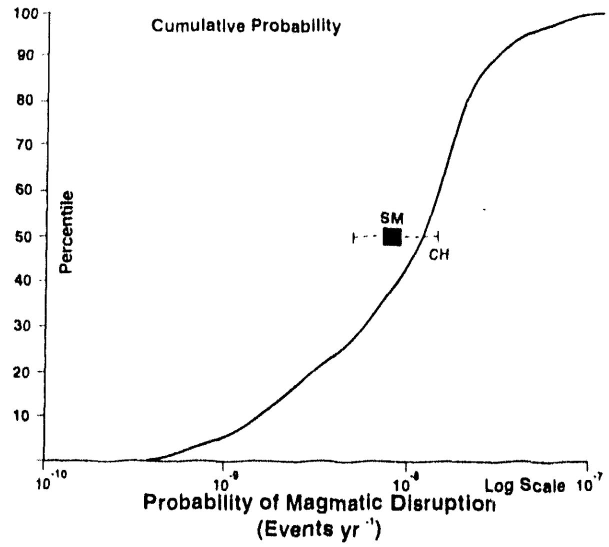

Fig. 9: Simulated cumulative probability distribution for the probability of magmatic disruption of the repository. The box labeled SM is the 50% value for the Pr_{md} using a modified distribution of values for E1 required from consideration of the spatial geometry of individual structural models. The bracketed dashed line labeled C-H is the range of calculated values for Pr_{md} from Connor and Hill.[24]

There are three comments concerning interpretations of the computed probability distributions. First, these estimations are based on inclusion of multiple alternative models for E1 and E2 combined with identification of their bounds in probability space. We made no attempt to evaluate the suitability of individual alternative models except where they were based on inconsistent calculation assumptions. Logically, there is a ranking that could be developed for the likelihood of individual models of E1 and E2. Such a ranking could be used to weigh individual models and produce a modified cumulative probability distribution of Pr_{md}. Second, the cumulative probability distribution for Pr_{md} can be readily modified using the systematic procedures of risk simulation. This is the strategy that will be followed should results from future site characterization studies identify new alternative models for E1 and E2 or result in changed perspectives for the assumptions used to estimate and bound their values. Finally, the derived cumulative probability distribution for Pr_{md} is not necessarily the distribution that will be used in regulatory documents. The Department of Energy may or may not choose to modify the probability distributions in response to regulatory perspectives.

SENSITIVITY ANALYSIS: REPOSITORY INTEGRATION PROGRAM

The Repository Integration Program (RIP) was developed by Golder Associates Inc. as a tool for assessing site suitability through total system performance and as a guide to optimizing site characterization studies.[30-31] One of the three coupled components of RIP is a disruptive events model. This component is used by assigning occurrence rates to disruptive events and choosing descriptive parameters through user input to define the event characteristics. The occurrence rates and event descriptors may be constants, stochastic variables or functions. Event consequences are modeled as an outcome (system performance) of the event characteristics through changes in the component models of the program (waste packages, radionuclide release) and/or through direct releases from the disruptive event. The potential performance impacts of seismic and volcanic events on the potential Yucca Mountain site have been assessed through preliminary simulation modeling using RIP.[27] This modeling showed that there were no significant impacts on the performance of a potential repository from volcanic or seismic events relative to the overall releases for the simulated conditions.

We have initiated a preliminary series of RIP simulations to evaluate the impacts on system performance of revised descriptive parameters for volcanic events. These simulations were run to test the system response or sensitivity to specific subsets of revised volcanic events (sensitivity analyses), not to assess overall site suitability. Our goal is to evaluate changes in system performance from a base case where no volcanic events occur. The event descriptors and consequences of the initial volcanic disruptive event model are based on previous work[27,32] with the following changes:

- the cumulative probability distributions for E1 and E2 from this paper were used to input the event rate and disruptive probability;
- a linear erosion model was used to calculate the fraction of lithic fragments derived from a repository horizon. We assume, based on studies by Valentine et al.,[29] continuous erosion of wall rock and a repository to a depth of 500 m;
- the recurrence rate is modified after the initiation of a volcanic event (formation of a new volcanic center). An updated probability of a second event *at the same location* is used to model the occurrence of polycyclic volcanism using the Lathrop Wells volcanic center as an analog.[14] The event rate is described as a normal distribution with a mean of 1 event in 30,000 years and a standard deviation one order of magnitude smaller than the event mean.

Figures 10 and 11 show the results for 500 computed time histories of the total system performance of a simulated repository. Figure 10 shows releases associated with a waste isolation system that experienced no volcanic events. Figure 11 represents the performance of the waste isolation system with volcanic events using the modified volcanic event descriptors. Note that there is a slight increase in the releases for the simulations with the described volcanic event. The volcanic event simulations were structured in the simulation runs to increase the number of time histories that include a volcanic event resulting in volcanic disruption of a potential repository. We generated this is a test case to determine if minor changes in event descriptors could produce an observed response in the system performance. Such an effect was produced and suggests the RIP simulations can be used for sensitivity analysis. Our goal in simulating these changes is not to define the effects on total system performance but to identify changes in the base case performance to highlight which of a suite of event scenarios produces the most marked performance effects.

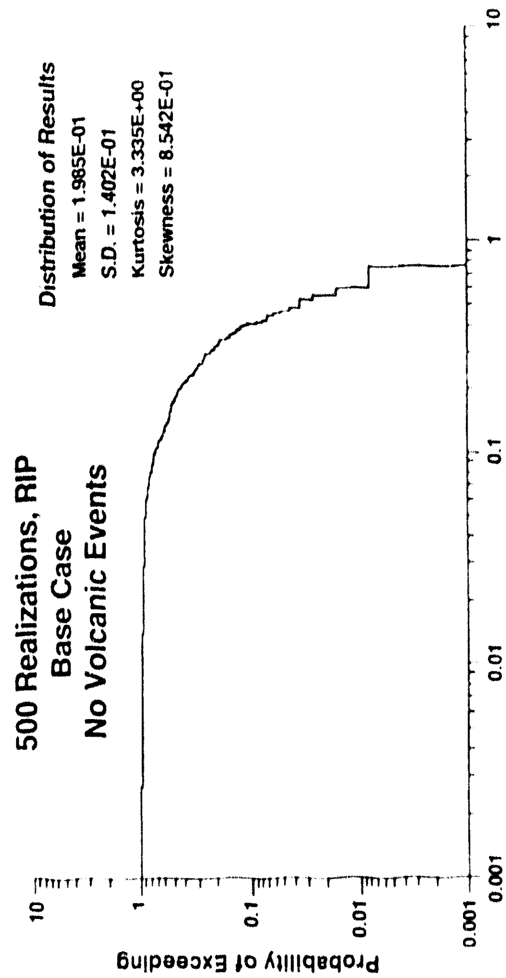

Fig. 10. Release simulations for the base case (no volcanic events) for a simulated repository (500 realizations).

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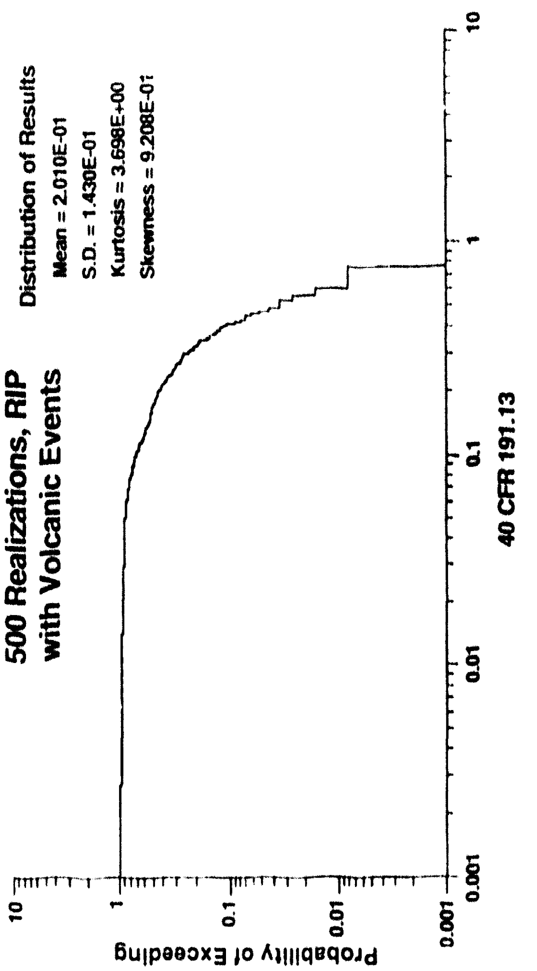

Fig. 11: Release simulations for volcanic events disrupting the repository. A pruning factor was used to produce 47 events in the 500 realizations.

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