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TITLE: RECURRENCE MODELS OF VOLCANIC EVENTS: APPLICATIONS TO VOLCANIC RISK ASSESSMENT

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RECURRENCE MODELS OF VOLCANIC EVENTS: APPLICATIONS TO VOLCANIC RISK ASSESSMENT

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INTRODUCTION

An assessment of the risk of future volcanism has been conducted for isolation of high-level radioactive waste at the potential Yucca Mountain site in southern Nevada.[1] Risk used in this context refers to a combined assessment of the probability and consequences of future volcanic activity. Past studies established bounds on the probability of magmatic disruption of a repository. These bounds were revised as additional data were gathered from site characterization studies. The probability of direct intersection of a potential repository located in an eight km^2 area of Yucca Mountain by ascending basalt magma was bounded by the range of 10^{-8} to 10^{-10} yr^{-1}.[2] The consequences of magmatic disruption of a repository were estimated in previous studies to be limited. The exact releases from such an event are dependent on the strike of an intruding basalt dike relative to the repository geometry, the timing of the basaltic event relative to the age of the radioactive waste and the mechanisms of release and dispersal of the waste radionuclides in the accessible environment.[3,4] The combined low probability of repository disruption and the limited releases associated with this event established the basis for the judgement that the risk of future volcanism was relatively low. It was reasoned that the risk of future volcanism was not likely to result in disqualification of the potential Yucca Mountain site.[5]

Volcanism studies for the Yucca Mountain Site Characterization Project have progressed to a sufficient degree that it is now prudent to work toward concluding aspects of the work. An advantage of a probabilistic approach to volcanic risk is that it assigns a structured formalism to the problem. This formalism subdivides a complex issue into logical sections. The significance of uncertainty or differences in scientific opinion concerning volcanism issues can be tested for each section of a probabilistic problem. The perspective for making judgements of significance for volcanism studies are the regulatory requirements for assessing the suitability of the potential Yucca Mountain site.

This paper attempts to begin the process of helping establish the probabilistic framework for making those judgements. There are three objectives. First, we describe the tripartite probability used to define the risk of volcanism and the geologic assumptions required for the probability model. Second, we examine and define the first part of this probability, the recurrence of volcanic events. Studies are reviewed from the volcanological literature where time-volume behavior of volcanic centers and fields have been evaluated. These evaluations include both conventional statistical analysis of time-series of volcanic events and applications using newly developing concepts of fractal analysis and deterministic chaos. Third, we tabulate past calculations and derive new values for the recurrence of volcanic events using a simple Poisson model.

The primary conclusion of this paper is that the most reasonable approach to estimating the recurrence of volcanic events in the Yucca Mountain region is through application of a simple Poisson model. This model is justified based on the current state of knowledge of the complex dynamics of volcanic processes and the limited record of past volcanic events in the Yucca Mountain region. The approach introduces a degree of uncertainty into the problem, but the uncertainty can be bounded by examining the recurrence of volcanic events in more active basaltic volcanic fields of the southwestern United States.

PROBABILITY MODEL

The probability of magmatic disruption of a repository and release of radionuclides to the accessible environment during the 10,000-yr isolation period (Pr_{dr})

is modeled as a tripartite probability:

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

where E1 denotes the recurrence rate of volcanic events in the Yucca Mountain region, E2 denotes the probability that the future magmatic event intersects the repository, and E3 denotes the probability that magmatic disruption of the repository leads to direct releases of radionuclides to the accessible environment. Only those events that result in formation of new volcanic centers are included in Pr(E1). Such events have a defined probability (Pr(E2)) of disrupting the potential Yucca Mountain site. Studies in progress[6,7] suggest that there may be more than one time-distinct event (polycyclic activity) at individual centers. However, polycyclic activity is not factored into the Pr(E1) because these succeeding eruptions occur at an existing volcanic center. They do not represent a unique breaching event. The possibility of polycyclic volcanism is used in calculations of Pr(E3).[8] The tripartite probability assumes that each successive event is dependent on the occurrence of the previous event(s).

We use the most current data from site characterization studies for revised probability calculations. Information on the distribution and chronology of volcanic activity is used from Crowe,[6] Wells et al.[7], Smith et al.[9] and Turrin et al.[10] Data for the volume of volcanic units is modified from Crowe et al.[3] using the revised geologic mapping of Crowe et al.[11] and Crowe and Perry[12] for respectively, the Lathrop Wells volcanic center and the Sleeping Butte volcanic centers. Our new calculations use mean values for geologic data. Past studies used conservative data assumptions to establish probability bounds. Conservative data assumptions are defined as numerical assignments that, because of uncertainty in data distribution, are skewed toward estimates which produce a higher level of risk. This approach, while useful in establishing probability bounds, introduces a systematic but unquantified bias toward higher probability values.

Several assumptions are required to estimate Pr(E1). First, the past record of basaltic volcanic activity in the Yucca Mountain region is judged to provide the most reliable indicator of the rates of future volcanic events. This assumption is supported by the consistency of the record of volcanism in the region during the last 10 Ma.[6] During this time, all volcanic centers formed from eruption of small volumes (< 1 km^3) of basaltic magma. This activity produced spatially isolated centers composed of scoria cone(s) and associated lava flows. The only variability in the past patterns has been in the basalt centers, with one exception, occur in a narrow northwest-trending zone located southwest of Yucca Mountain. This zone has been named the Crater Flat volcanic zone (CFVZ).[13] The one exception is the basalt of Buckboard Mesa which crops out in the northeast part of the moat zone of the Timber Mountain caldera, 37 km from the exploratory block of the Yucca Mountain site. Another assumption used in evaluating Pr(E1) is that interpretations of the geologic record are reliable, an assumption that is difficult to quantify. An increased degree of confidence in the continuity of the geologic record is provided by the length of the observed geologic record. The past volcanic events in the CFVZ span a period of about 4 Ma. However, as the observation length increases, the likelihood of recognizing small or short-term events may decrease. For example, interpretations can be hampered where the geologic record has been obscured. This is especially true at polycyclic centers, where more recent events may bury older events. Currently available geochronology methods lack the resolution to distinguish closely spaced events (times scales of a few thousand to tens of thousands of years). This uncertainty is mitigated because the estimations of Pr(E1) require only recognition of Quaternary volcanic centers, for a simple Poisson model. This is a relatively easy field task. Finally, use of the geologic record for predictions presumes that there have not been recent (Holocene or Pleistocene) drastic changes in the rate of operation of processes which drive the overall magmatic system. Perry and Crowe[14] summarized morphological and geochemical evidence indicating the processes controlling magma production, ascent and eruption have waned through time in the Yucca Mountain region.

E1: RECURRENCE OF VOLCANIC EVENTS

The first part of the tripartite probability concerns the recurrence of volcanic events. Here, there is a logic paradox. The primary problem is the small number of Pliocene and Quaternary volcanic centers in the region (7 Quaternary centers, 13 to 16 Pliocene and Quaternary centers). It is impossible, with this number of centers, to develop and test conceptual or statistical models of the time-distribution of events. Conversely, if there were more volcanic centers, there would be a more robust data set to develop and thoroughly test time-distribution models. Because of the increased number of centers however, there would be an increased risk of future volcanism. This paradox can be examined in reverse. If a potential repository site were located in an area that had no record of Cenozoic volcanism, volcanism would arguably be regarded as not an important issue. But by virtue of the absence of data, it would be difficult to establish a numerical basis data set applies equally to the second probability (Pr(E2)). We will consider this problem in a subsequent paper.

There are clear elements of uncertainty introduced by applying a probabilistic approach to such a small data set. Unfortunately the current level of knowledge of volcanic processes precludes the use of a fully deterministic approach to predicting volcanic events over periods of thousands of years. The strengths and weakness of using a probabilistic approach to risk assessment have been debated for many applications. However, rather than digress on this issue, it is more important to evaluate three questions for assessing the recurrence of volcanic events for the region encompassing the potential Yucca Mountain site. First, what are reasonable time-distribution models of volcanic events to use with the small data set? Second, can those models be structured to not underestimate volcanic risk? Third, can the uncertainty of a small data set be bounded by comparison with analogue studies of more active volcanic fields in the southwestern United States?

Time-Distribution Models: The subject of time-distribution models or repose-period patterns of volcanoes has been discussed extensively in the geologic literature. The topic has received increased attention in the last several years primarily because of both improved field and chronology data for past volcanic events and increased interest in eruption forecasting. We present a general survey of this literature focusing on data concerned with estimating Pr(E1). Wickman[15,16,17] argued that the distribution of volcanic events in time can be treated as a stochastic phenomena. He suggested that volcanic events should be treated as independent Poisson processes with time-independent rates. He also modified the simple Poisson model using six renewal-type Markov models and applied these models to data sets from five active volcanic centers. Klein[18] treated eruptions of Hawaiian volcanoes as random phenomena with no periodicity. He suggested that a random behavior is produced by multiple simultaneous processes effecting the timing of eruption events. He also noted, however, that large-volume eruptions tend to be followed by longer repose periods. He suggested that eruptions associated with the longest repose periods of Kilauea and Mauna Loa volcanoes are nonrandom phenomena with activity at one volcano possibly affecting the other.

Crowe et al.[2] used a Poisson-distribution model to assess the probability of disruption of a repository at the potential Yucca Mountain site. They assumed the probability of n eruptions over time t is constant and the individual eruptions occur independently. This assumes also that the times between events are exponentially distributed and the number of events in time intervals of t are Poisson distributed with mean λt. The mathematical model used is

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

where p is the probability that an event is disruptive. This model was developed for the case of disruption of a repository by a single volcanic event. Scandone[19] reviewed volcanic risk studies. He regarded the timing of eruptions as a Poisson process but noted this model could be used only for volcanoes where it could be demonstrated that eruptive rates are independent through time. He summarized data for Vesuvius volcano where the duration of each state of activity could be described by an exponential distribution and transitions from one state to another were constant in time. Predictions of volcanic activity for this case can be made if eruption patterns remained constant over a long period of time.

Mulargia et al.[20] analyzed the time-series of flank eruptions of Etna volcano. They used the Kolmogorov-Smirnov statistic for a goodness of fit test and concluded that the data could be fitted to a Poisson distribution. They correlated eruption durations with extrusion volume and applied extreme value statistics, with duration as a dependent variable, to estimate the probability of major eruptive events. Chester[21] argued that the approach used by Mulargia et al.[20] is invalid primarily because the time-volume data for the volcano may be nonstationary. He suggested there is a strong chance of nonstationarity in the data when event times are combined with the magmatic volume of both summit and flank eruptions. In response, Mulargia et al.[22] noted their data set met standard statistical tests for randomness. They emphasized that their analysis was confined to event times and were consistent with a stationary Poisson process. They emphasized the statistical difficulty of identifying different regimes in a set of data and argued that these concerns were reduced by focusing their analysis on flank eruptions. The questions of stationary versus nonstationary Poisson processes and correlations between the timing of eruptive events and the volume of magma discharged are recurring topics of controversy in probabilistic studies of volcanic events.

Some statistical studies of time-series of volcanic events have considered the problem of nonstationary rates by attempting to identify change states in eruptive behavior. Mulargia et al.,[23] examined the problem of identifying different regimes in eruptive activity for data sets from Etna volcano. They argued that plots of cumulative magma volume versus time provide only a subjective basis for evaluating volcanic trends. They examined the trends of Etna volcano using inter-event times, magma output, and mean effusion rates and applied change-point (stability analysis) statistical methods to time-series analyses of these data. They concluded that the inter-event times of flank eruptions define two regimes, the magma output rates of flank eruptions define three regimes, and the effusion rates define two regimes. Further, they noted that the change points in these data sets do not coincide. Eruptive activity was considered to be controlled by a balance of several contributing factors with the net history of eruptive events behaving as random nonstationary events. Significantly, they[23] recognized no correlation between the volume of large flank eruptions and subsequent inter-event times.

A number of approaches to estimation of volcanic recurrence rates have been based on assessments of the time-volume relationships of eruptive events at volcanic centers and for volcanic fields. Bacon[24] suggested that basaltic and rhyolitic volcanism in the Coso volcanic field of east-central California exhibits time-predictable behavior analogous to time-predictable seismic models. He related these observations to the tectonic controls of the extensional patterns of deformation for the setting of the volcanic field. Kuntz et al.,[25] presented data indicating the Holocene and Pliocene eruptions of the Great Rift in the Snake River plains of Idaho, show steady-state volume-predictable behavior. He identified a possible change in magma output rates on a plot of cumulative magma volume versus time for the Great Rift basalts. Similar plots were used by Wadge[26] to describe steady state behavior of polygenetic volcanoes. King[27] described volume predictability for the cumulative magma volumes of the historical eruptions of Kilauea and Mauna Loa volcanoes. He suggested the volcanic events respond to pressure drops produced in a reservoir from preceding eruptions. Similar behavior has been documented for the historic activity of Piton de la Fournaise on the island of Reunion[28] and close analogies were drawn between this volcano and the Kilauea volcano. Past behavior of Piton de la Fournaise was inferred to be described statistically by a Poisson process.[28] The eruptions were linked to refilling of magma reservoirs modified by external processes such as earth tides. An essential difference between the eruptive patterns of Eta and the Kilauea, Mauna Loa, and Piton de Fournaise volcanoes may be the presence, for the latter, of shallow magma chambers.

Ho[29,30] examined the applicability of the simple Poisson model (homogeneous Poisson process) for eruption forecasting. He noted that while the simple Poisson model can be used for modeling eruptive events from some volcanoes, it may not be appropriate in all cases. He proposed two alternative models. The first is a negative binomial distribution where the Poisson process is expanded to include a gamma-mixing distribution on λ.[29] The second is for a nonhomogeneous Poisson process with a Weibull intensity.[30] This model can accommodate volcanoes exhibiting decreasing rates of eruptions, increasing rates of eruption, or steady state (similar to the homogeneous Poisson process). Ho[29,30] modeled published eruption data for a range of volcanoes using the nonhomogeneous Poisson models. These modified Poisson processes provide alternative models to the approach used by Mulgaria et al.,[23] where regime changes are identified for volcanoes and each regime is treated as independent with a uniform λ.

In a related paper, Ho[31] attempted time-trend analysis of past patterns of basaltic volcanism in the Yucca Mountain region. He estimated the instantaneous recurrence rate of volcanic events using a nonhomogeneous Poisson process with Weibull intensity. The time-trend analysis was based on episodes and age cycles for the region. The observational interval ranged from 12 to 1.6 Ma and varied assumptions were used for the nature and chronology of volcanic events at basaltic centers. Using the nonhomogeneous Poisson model, Ho[31] estimated midpoints of the time interval for the next eruption. These intervals ranged from 4.2 to 0.6 million years. For all but one estimation, a slight developing trend was identified (β values of 1.09 to 2.55). Ho[31] concluded, on this basis, that a simple Poisson model could underestimate the risk of volcanism for the potential Yucca Mountain site. However, the β values of > 1 were obtained in part by assuming polycyclic eruptions at some or all of the Pliocene and Quaternary volcanic centers. This usage no longer meets the definition of the tripartite probability. Succeeding eruptions at a volcanic center are dependent on the preceding formation of a new volcanic center. It is the formation of a new volcanic center that is of concern to siting of a potential repository at Yucca Mountain. Ho[31] argued that the volume combined with the timing of volcanic events are not required attributes for predicting the frequency of future volcanic events despite a significant negative correlation between these attributes.[2,13] This same concern was addressed by Mulgaria et al.[26] for Etna volcano. They demonstrated, for a much larger data set, that points of change in regimes in the time series of the inter-eruption times and outputs of magma volumes do not coincide. This in part, lead to the suggestion that eruptive events are controlled by a balance of several contributing factors. Finally, Ho[31] suggested that volcanic risk for the potential Yucca Mountain site should be expressed as a percentage relative to the required isolation time of high-level radioactive waste (10^4 yrs). He estimated that the risk of volcanism for the potential site for 10^4 yrs is about 5%. However Ho[31] misused the term volcanic risk, which requires an assessment of $Pr(_{ab})$, not just of Pr(E1), the probability of recurrence.

Recent developments that may have important implications for both understanding and modeling complex volcanic systems are derived from fractal analysis and evaluation of deterministically chaotic systems.[32,33,34,35] Shaw[36] examined the time-volume fluctuations of the Puu Oo vent of Kilauea volcano, the historic behavior of Kilauea and Mauna Loa volcanoes, the growth of the Hawaiian Islands and the Hawaiian-Emperor chain. He argued that these volcanic systems show evidence of scaling self-similarity. Shaw[36] modeled these systems using attractor theory with magma transport representing an iterative step in an attractor algorithm. Dubois and Cheminee[37] used fractal analysis for modeling the distribution of repose periods of basaltic volcanoes of Piton de la Fournaise, Reunion, Mauna Loa and Kilauea on Hawaii, and Etna volcano. They applied a Cantor dust model assuming the distribution of volcanic events in time is a scale-invariant process where N_i the number of repose periods of length t_i are related by $N_i = t^{-D}$ (power law) where D is the fractal dimension of the distribution ($0 < D < 1$). For oceanic hotspot volcanism, they[37] found two regimes with short interval eruptions having $D = 0.3$ and eruptions after large intervals having $D = 0.7$. For Etna volcano, they found a single regime with $D = 0.75$. They concluded that the four studied volcanoes do not follow a simple Poisson process and are better modeled using a power law relationship.

Sornette et al.,[38] in a provocative paper, considered the question of whether sequences of volcanic eruptions are deterministically chaotic. They argued that true randomness in a volcanic system could result from two type of dynamics. The first is a system having many degrees of freedom that are coupled and may develop random dynamics. The second is a system with only a few degrees of freedom yet still exhibiting very complex dynamical behavior. The behavior of the second system could be controlled by sensitive dependence on initial conditions and nonlinear processes. Significantly, analysis of time sequences for the second system, which have been called deterministically chaotic,[38] are classified as random processes by all traditional statistical tests. Sornette et al.,[38] applied two tests conventionally used to discover possible deterministic dynamics to repose period data for volcanic eruptions of Piton de la Fournaise and Kilauea and Mauna Loa volcanoes. They computed the dimension D of the attractor as a function of the dimension d of the embedding phase space and found that $D(d)$ saturates to a constant value around 2 for Piton de la Fournaise and 4 for the Hawaiian volcanoes. The higher value for the Hawaiian volcanoes may have resulted from combining, in their analysis, eruption events from both Kilauea and Mauna Loa volcanoes. They used Poincare sections to analyze the eruption intervals and concluded that the resulting return maps represent patterns of a deterministic system, partly overprinted by noise. Lorenz[39] has introduced a note of caution in applying procedures for estimating the correlation dimension of the attractor of complex systems. He suggested use of these approaches for systems such as weather or climate may produce too low values. He provides examples in which the procedures yield systematic underestimates. Lorenz[39] suggests that applications of some procedures may measure the dimension of only a subsystem. Similar arguments must be considered regarding the calculated low dimensionality of the magma systems studied by Sornette et al.[38] The complexity of processes of magma supply, evolution, and eruption from shallow magma chambers which interact with the local stress fields almost certainly requires higher correlation dimensions. Sornette et al.[38] were unable to develop nonlinear forecasting procedures from eruption data largely because of insufficient data. They concluded with the general challenge that further analysis of this type would require obtaining high-quality data for multiple physical parameters which can be related to the dynamics of evolution of a volcanic system.

At present, the number of recurrence models for volcanic centers and fields are varied and there is no consensus concerning the most applicable model for different volcanic systems. Four clear conclusions are apparent. First, the primary difficulty with modeling volcanic events is attributable to limited data. It is difficult to obtain a complete description of past volcanic events. Moreover, the number of events is generally marginal for mathematical analysis. The best opportunity for obtaining large data sets is at historically active volcanic systems. Second, volcanic events have important attributes of timing, spatial location and magnitude, where magnitude is represented as the volume of an eruption. These attributes are often inter-correlated and reflect the complex processes of magma generation, and chamber and eruption dynamics. Modeling of volcanic events by analyzing limited data sets or only the timing of volcanic eruptions may be an oversimplification of the complexity of the systems. Third, specific volcanic centers and fields exhibit a spectrum of behavior. Generalizations of patterns observed at one volcano or volcanic system are probably not easily applied to other volcanoes or systems. An important difference which emerges from existing data is that the presence or absence of shallow crustal magma chambers strongly affects eruption patterns. Finally, newly emerging concepts of fractal analysis, and deterministic chaos offer the appeal of explaining the differences in interpretation of eruption patterns using standard statistical approaches. Whether this type of analysis presents new possibilities of establishing deterministically based methods for predicting future volcanic activity remains to be explored by future work.

RECURRENCE MODELS: YUCCA MOUNTAIN REGION

An assessment of the risk of future volcanism for the potential Yucca Mountain site is restricted by the small number of past volcanic events. The limited data make it virtually impossible to either test or discriminate time-distribution models of volcanic events. The options available for assessing volcanic risk are either to revert to traditional methods of hazard assessment which are rooted in subjective judgements of past geologic patterns or to attempt to quantify or bound the problem through probabilistic assessment. We have chosen the option of attempting to quantify risk assessment though use of a simple Poisson model. The advantages of this approach are that it is conceptually simple, assumptions of the method are defined, and the potential errors using this method can be constrained. Stated simply, the justification for the use of a simple (homogeneous) Poisson model for the Yucca Mountain volcanism data is that it represents the most direct approach to probabilistic assessments based on a small data set. The simple Poisson model does not introduce unwarranted complexity. Moreover, because of the small data set, models incorporating other parameters do not generally yield substantially different results. Analogies can be drawn to earthquake occurrence models for seismic hazard analysis. Mathematical representations of earthquake events have evolved as knowledge of the mechanisms driving earthquake events has improved.[40] The trend in seismic risk studies has been to use a stochastic approach when data are limited but to attempt to apply more deterministic models as an increased understanding of seismic mechanisms is obtained. Volcanic recurrence models are in the infancy of development with applications developed primarily for historically active volcanic centers. Even less is known about patterns of small volume, basalt centers typical of the Yucca Mountain area. Here predictions are required for the timing, eruptive behavior and spatial location of future sites of small volume basaltic centers.

Application of a Simple Poisson Model

Four temporal patterns of volcanic activity are possible for the Yucca Mountain region: increasing, steady-state, decreasing, or complex/chaotic. Arguments can be made concerning the magnitude of errors created by assuming a simple Poisson model for each of these four possible patterns. First, if recurrence rates are increasing, a simple Poisson model would tend to underestimate the future recurrence rate.[31] This would not provide an acceptable estimation of volcanic risk. Second, a steady-state system is appropriate to the application of a simple Poisson model. Third, decreasing volcanic recurrence rates would lead to overestimation of recurrence rates which would produce a conservative assessment of volcanic risk. This could prove to be an acceptable method for defining volcanic risk if it can be shown that, even with the conservative approach, the defined risk still meets the regulatory guidelines. Finally, errors associated with complex/chaotic patterns of volcanic activity are more difficult to estimate. However, if the observation period of the record of past volcanic activity exceeds the range of complex/chaotic fluctuations (particularly if the patterns are deterministically chaotic), the range of past changes may be bounded. We argue, for two compelling reasons, that the latter two types of errors are the most likely to be encountered for the Yucca Mountain region and may prove to be acceptable for risk studies. The first reason is that post-Pliocene time-volume-compositional patterns of basaltic volcanism in the Yucca Mountain region are consistent with a waning system.[14] The second reason is that the pattern of formation of small volume, spatially isolated basaltic volcanic centers has persisted in the Yucca Mountain region for almost 10 Ma.[6] This period equals and exceeds the lifetimes of evolution of most basaltic volcanic fields in the southwestern United States. These constraints suggest that the recurrence estimations can be bounded with acceptable assurance.

Revised Calculations of E1

Revised calculations of the recurrence rate of volcanic events (E1) are tabulated in Table I using the most current information from site characterization studies. A simple Poisson model is assumed. The only requirement for including events in the calculations is that the event resulted in the formation of a new volcanic center and the chronology is sufficiently well established to group the centers by age [two groups: 1) Pliocene and 2) Pliocene and Quaternary]. The volume of volcanic events is not used in the calculations and the chronology problems for the younger volcanic centers are not significant in this analysis. Additional calculations using a volume-triggered, simple Poisson model will be described in a separate paper. The following is a summary of field and chronology data used to group the volcanic events:

3.7 Ma Event: 5 volcanic centers clustered on a

	north-trending alignment in Crater Flat.
2.8 Ma Event:	1 volcanic center in the northeast moat zone of the Timber Mountain caldera (basalt of Buckboard Mesa).
1.2 Ma Event:	4 volcanic centers clustered on a north-trending alignment in central Crater Flat.
0.3 Ma Event:	2 volcanic centers clustered on a northeast-trend 45 km northwest of the Yucca Mountain site (basalt of Sleeping Butte).
<0.1 Ma Event:	1 volcanic center located at the south end of Yucca Mountain, 20 km from the potential site (Lathrop Wells center).

Recent reconnaissance field studies have shown that a lava mesa located 5 kilometers east of the basalt of Sleeping Butte, which was thought to underlie the Thirsty Canyon tuff (8.5 Ma), overlies the tuff. Examination of the mesa shows that it consists of multiple lava flows erupted from a cluster of north-trending scoria cones marking the high-standing topography of the lava mesa. The geomorphic preservation of the lava flows and coalesced-scoria cones is suggestive of a possible Pliocene age (4-5 Ma). We have submitted the samples for K-Ar and $^{40}Ar/^{39}Ar$ age determinations. Because the lava mesa is located on the CFVZ, we have included it in one set of the recurrence rate calculations. There are an estimated three centers associated with this volcanic feature.

The calculations summarized in Table I were completed over a span of more than eleven years. They use different distribution models of volcanic events (simple Poisson, volume-triggered/Poisson, Weibull process). The recurrence rate calculations range from 10^{-5} to 10^{-7} events yr^{-1}. The mean value (geometric mean) of the recurrence rates of Table I is 4.0×10^{-6} events yr^{-1}. This is equivalent to the formation of a new volcanic center every 250 ka. The column titled Quaternary Events on Table I is the

TABLE I: VOLCANIC RECURRENCE RATE (E1)

PUBLICATION	EVENTS (yr^{-1})	QUATERNARY EVENTS*	RATE MODEL	TIME (Ma)
Crowe and Carr, 1980	4.0E-6	7.2	Poisson: Cone Count	1.8 2.8
Crowe, Johnson, and	6.0E-7 to 1.1E-6	1.1 to 19.8	Magma Output (210 m3 yr-1)	1.8-3.7
Beckman, 1982	9.4E-6	17.1	Poisson: Cone Count	1.8
	6.4E-6	11.5	Poisson: Cone Count	2.8
	8.0E-6	14.4	Poisson: Cone Count	3.7
Crowe et al., 1989	2.8E-5	73	Magma Output (133 m3 yr-1) (Lathrop=130 ka)	3.7
	7.0E-6	12.6	Magma Output (133 m3 yr-1) (Lathrop=20 ka)	3.7
	5.0E-6	9.0	Magma Output (66 m3 yr-1) (Lathrop=130 ka)	1.8
	3.2E-6	5.8	Magma Output (66 m3 yr-1) (Lathrop=20 ka)	1.8
Crowe and Perry, 1990	1.9E-6	3.4	Magma Output (33 m3 yr-1) (Lathrop=130 ka)	1.8
	1.6E-6	2.9	Magma Output (33 m3 yr-1) (Lathrop=20 ka)	1.8
Ho, 1991	2.3E-6	3.7	Weilbull: Episode	1.2
	5.0E-6	8.0	Weilbull: Cycle	3.7
	6.2E-6	9.9	Weilbull: Cone Count	6.0
	5.5E-6	8.8	Weilbull: Cone Count	1.6
This Report	3.9E-6	7.2	Poisson Cone Count	1.8
	1.7E-6	3.6	Poisson Cluster Count	1.8
	3.5E-6	5.4	Poisson Cone Count	3.7
	1.3E-6	2.3	Poisson Cluster Count	3.7
	3.2E-6	5.0	Poisson Cone Count	5.0
	1.2E-6	2.2	Poisson Cluster Count	5.0

* Calculated number of volcanic events projecting the recurrence rate for the Quaternary Period. There were 3 to 7 volcanic events in the Yucca Mountain region in the Quaternary.

extrapolated number of volcanic centers formed in 1.8 Ma (Quaternary period) using individual recurrence rates. Recurrence rates that give more than double or less than one-half the number of events in the Yucca Mountain region are judged to be unrealistic geologically. If these rates are removed from Table I, the values cluster in the range of 1-6 x 10^{-6} events yr^{-1}. The numbers in this range are considered, because of the nature of the calculations, to be not different when judged in the perspective of the underlying uncertainties. We note that after over a decade of consideration, there have been no significant changes in the recurrence rate calculations for volcanic events in the Yucca Mountain region. Moreover, calculations by other workers using different approaches[31] are consistent with our results.

The uncertainty of the recurrence rate calculations cannot be quantified accurately because the data are too limited to attempt uncertainty analysis. However, bounds on conservative rates of activity can be established by examination of the recurrence rates of volcanic activity in other basaltic volcanic fields. Here, there have been a sufficient number of volcanic events to attempt statistical analysis of recurrence rates. However, the major limitations of this type of analysis are twofold: 1) choice of time-distribution models and 2) inadequate chronology data. Because of these limitations, we again assume that the distribution of volcanic events in time in these fields are Poisson-distributed.

The volcanic centers of the Yucca Mountain region form a very small volcanic field in comparison with basaltic volcanic fields in the southwestern United States. The CFVZ is toward the end, if not an end member, of the smallest fields developed in the western United States.[41] The cumulative volume of magma erupted during the Quaternary in the field is less than 0.5 km^3 (dense rock equivalent; DRE). By contrast, major basaltic volcanic fields have erupted magma volumes in the Quaternary that exceed several tens of km^3 (DRE). We are in the process of determining the volume, number of vents, and number of vent clusters formed during the Quaternary in basalt fields of the Great Basin, southern basin-range and the adjoining areas of the plateau transition zone. To date, we have initial data only for the Cima volcanic field in California (Mojave desert), and the Lunar Crater field (central Nevada).

Figure 1 is a plot of the location of Quaternary volcanic vents in the Lunar Crater volcanic field collated from published studies.[42,43] The latitude and longitude of each vent have been converted to an x,y coordinate for this plot for convenience of data analysis. The line through the data is a distance-weighted least-squares fit and is used to assess the linearity (structural control) of the vent distributions. Figure 2 is a similar plot for the Cima volcanic field using locations of Quaternary vents from Dohrenwend et al[44,45]. The Cima vent locations are more dispersed than the Lunar Crater vents, implying less structural control of vent locations for the former field. The number of identified Quaternary vents for each field is somewhat arbitrary. If there was uncertainty in Quaternary age assignments, we skewed the data toward higher vent counts. The vents counts can be regarded as maximum. There are 82 vents defining 28 clusters of Quaternary age in the Lunar Crater volcanic field, and 29 vents in 22 clusters in the Cima volcanic field. A cluster includes closely spaced groups of vents that probably shared a common feeder dike system.

Recurrence rates of volcanic activity for both volcanic fields can be estimated using a simple Poisson model. Rates for the Lunar Crater field must fall between 4 x 10^{-5} events yr^{-1} (vent count) and 1 x 10^{-5} yr^{-1} (cluster count). This is equivalent to the formation of a new volcanic center or cluster every 22,000 to 100,000 years. Rates for the Cima volcanic field are between 2 x 10^{-5} yr^{-1} (vent count) and 1 x 10^{-5} yr^{-1} (cluster count). This is equivalent to the formation of a new volcanic center or cluster every 50,000 to 100,000 years. The vent density of the Lunar Crater volcanic field (number of vents per km^2) approaches values for the highest known vent densities of basaltic volcanic fields in the world[46]. We make two arguments concerning the significance of the data for the Lunar Crater and Cima volcanic fields. First, the recurrence of volcanic events in these active fields are relatively long compared with the isolation period of radioactive waste (10,000 years). Second, the recurrence rates for these fields provide reasonable bounds on maximum rates of volcanic activity for the Yucca Mountain region.

Data from Table I constrain the recurrence of volcanic events for the Yucca Mountain region in the general range of an event every few hundred thousand years. It is physically implausible to assign recurrence rates for volcanic events in the Yucca Mountain region that approach or equal estimated rates for the Lunar Crater or Cima volcanic fields. An event rate of 10^{-5} yr^{-1} must, therefore, be regarded as a very robust **upper** bound to rates of volcanic activity for the Yucca Mountain region.

FUTURE DIRECTIONS

Work will continue on refinement of probability calculations and determination of values using a volume-triggered, simple Poisson model. However, the physical bounds from other fields make it unlikely that

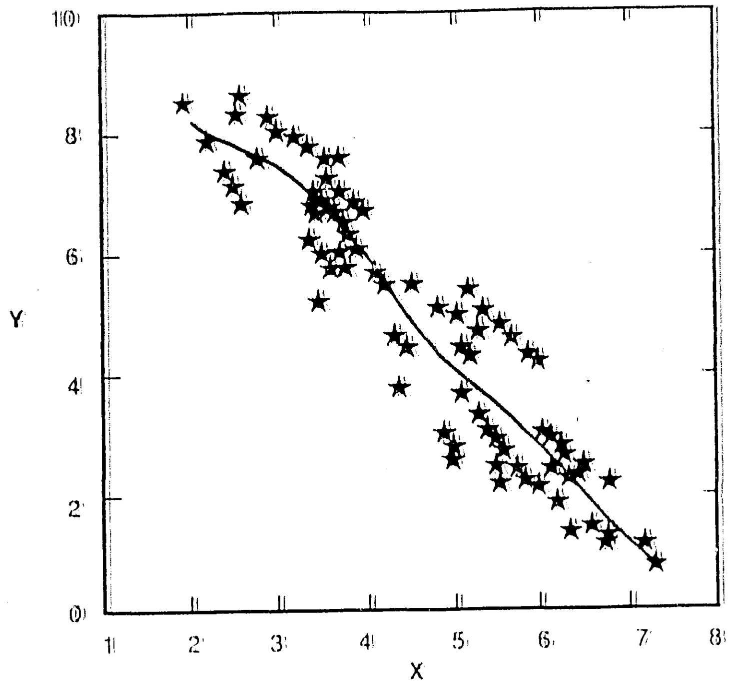

Figure 1: Plot of vent locations (latitude and longitude converted to x,y coordinates) for the Lunar Crater volcanic field of central Nevada. The line through the data is a distance-weighted least squares fit using a weighted quadratic multiple regression on every data point. Vent locations in the Lunar Crater are strongly structurally controlled. Individual vent and vent clusters follow northeast trends which define several probable age distinct, fissure systems in the volcanic field.[43] There are 82 identified vents which form 29 clusters of probable Quaternary age in the volcanic field.

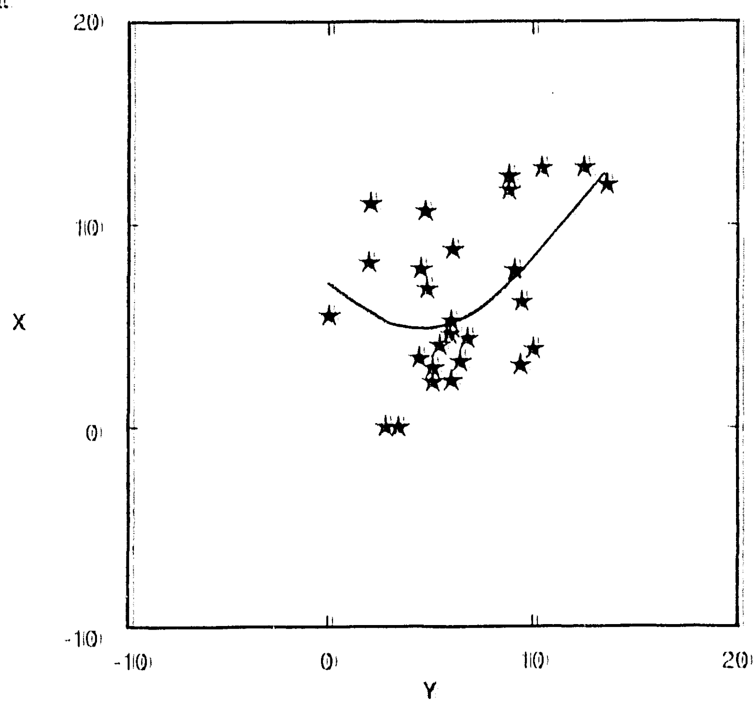

Figure 2: Plot of vent locations (latitude and longitude converted to x,y coordinates) for the Cima volcanic field. The line fitted to the data is the same type as described in Figure 2. There are 29 vents forming 22 clusters, all of probable Quaternary age in the Cima volcanic field.

calculated values will fall outside of the data ranges established in Table I. We will continue to follow developments in the volcanological literature of time-distribution models for eruptive events of volcanic centers. An important corollary area of research we are pursuing is development of time-space-volume patterns of basaltic volcanic events in active volcanic fields of the southwestern United States. Currently little detailed work has been completed on eruptive patterns of basaltic volcanic fields in a continental setting. However, the only physically credible mechanism that could lead to higher estimated recurrence rates of volcanic activity in the Yucca Mountain region would be a cycle of increased rates of activity. We currently see no basis for predicting such a style of activity using the volcanic record of the region. In subsequent papers we will present a similar assessment for the probability of magmatic disruption of the potential Yucca Mountain site (Pr(E2 given E1)).

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