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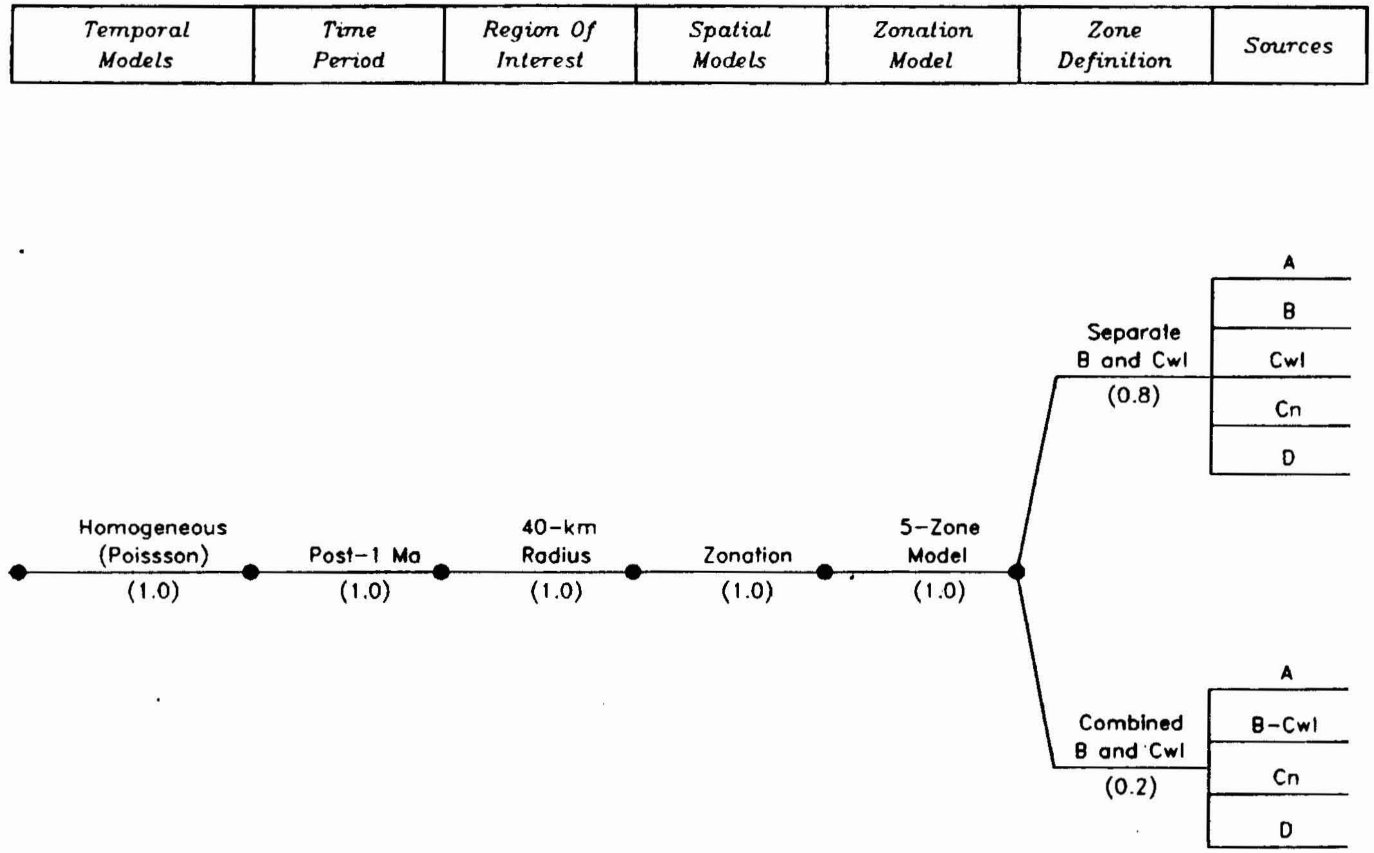
TABLE WD-1
WENDELL A. DUFFIELD - EVENT COUNTS

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 I-IV 2 I, II-IV	(0.90) (0.10)	BC: Black Cone C-G: Aeromagnetic anomalies of V. Langenheim, USGS HC: Hidden Cone LBP: Little Black Peak LC: Little Cones 2LC: 2 separate Little Cones M: Makani Cone RC: Red Cone I-IV: Chronostratigraphic units of Crowe et al. (1995)
Sleeping Butte	1 (LBP+HC) 2 (LBP, HC)	(0.05) (0.95)	
1.0 Ma Crater Flat	1 (all) 2 (LC, RC+BC, M) 3 (LC, RC+BC, M) 4 (LC, RC, BC, M) 5 (2LC, RC, BC, M)	(0.07) (0.14) (0.26) (0.34) (0.19)	
Armagosa Valley	0 1 (D) 2 (C,D) 3 (C,D,E) 4 (C,D,E,F) 5 (C,D,E,F,G)	(0.95) (0.03) (0.01) (0.005) (0.003) (0.002)	

TABLE WD-2
WENDELL A. DUFFIELD - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR SUBZONES	NOTES
Post 1 Ma (1.0)	Subzone A: (NCF+LW) Subzone B: (AV) Subzone Cn: 1 event/1 Ma (0.01) 0 events/1 Ma (0.99) Subzone Cwl: 10 x Cn rate Subzone D: (SB)	AV: Amargosa Valley LW: Lathrop Wells NCF: Northern (1.0 Ma) Crater Flat SB: Sleeping Butte



A: Subzone A

B: Subzone B

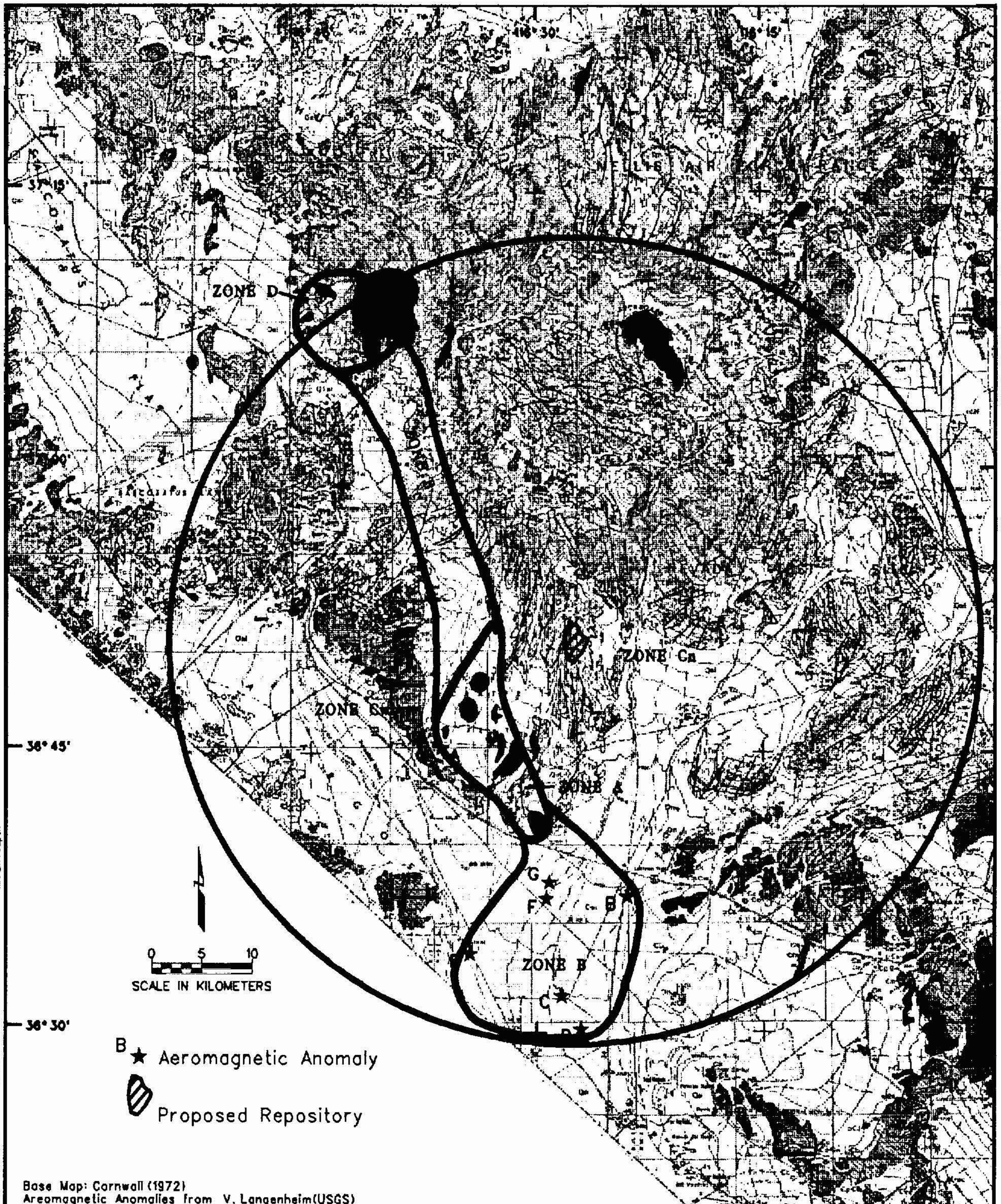
D: Subzone D

Cwl: Subzone C within Walker Lane Belt

Cn: Subzone C outside Walker Lane Belt

B-Cwl: Subzone B and subzone Cwl combined

Figure WD-1 PVHA model logic tree developed by Wendell A. Duffield.



GEOMATRIX	WENDELL A. DUFFIELD REGIONAL BACKGROUND AND LOCAL ZONES	Figure WD-2 PVHA Project

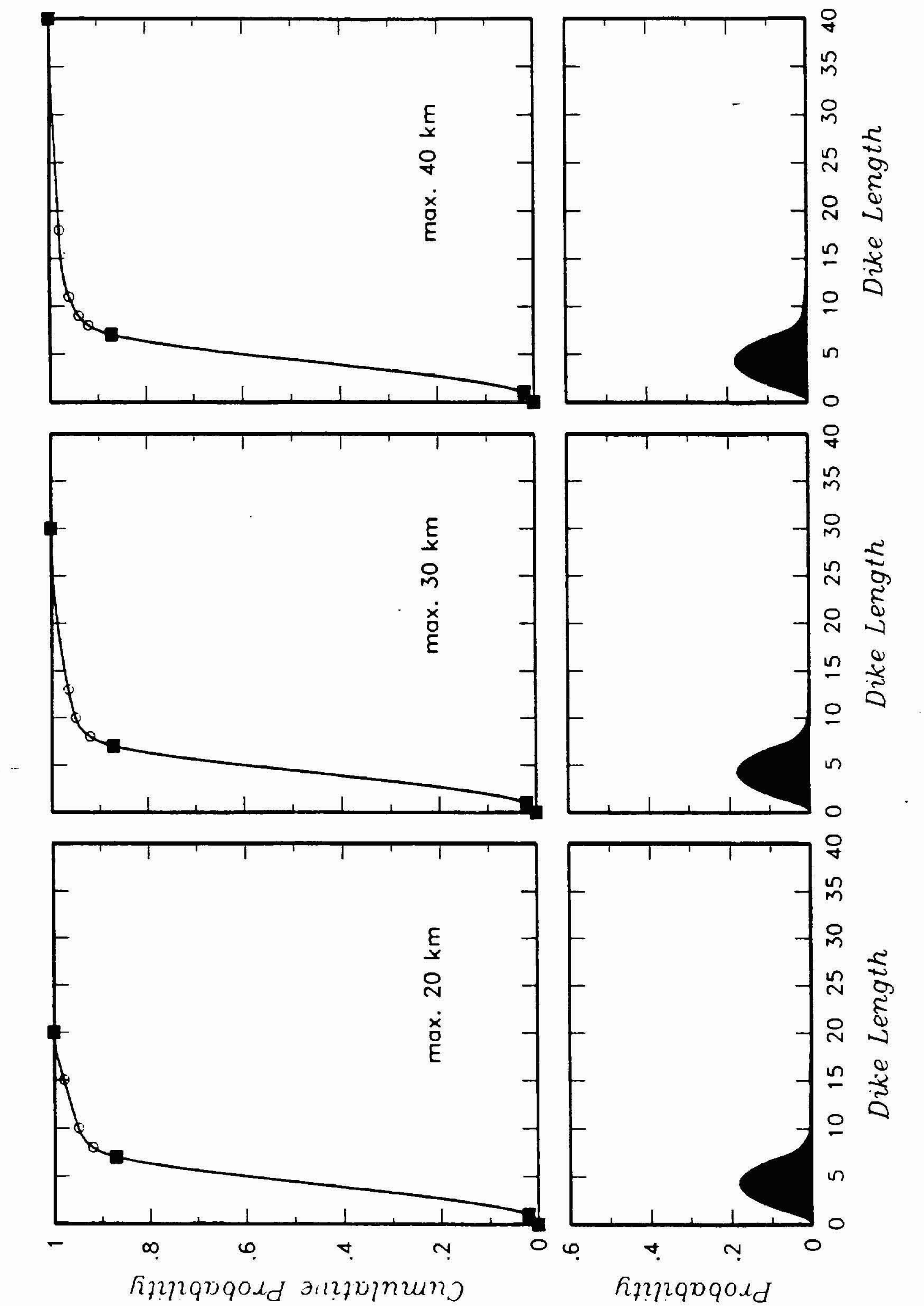


Figure WD-3 Dike length distribution developed by Wendell A. Duffield.

RICHARD V. FISHER
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

Voluminous silicic volcanism occurred in the Yucca Mountain Region (YMR, defined as the region within a 100-km radius of Yucca Mountain) as part of an extensive pulse of mid-Cenozoic volcanism within the southwestern United States. Yucca Mountain is in the south-central part of a major Cenozoic volcanic field that covered 11,000 square kilometers. In the YMR, silicic volcanism was most active between 15 to 11 Ma, and silicic volcanism ceased at about 8.5 Ma with eruptions of the Black Mountain caldera complex. Significant cessation of subduction coincided with the change from silicic to low-volume basaltic cinder cone and lava flow fields. The tectonic regime is not subduction-driven at the present time. Basaltic volcanism in the YMR is caused by regional extension (Crowe et al., 1995).

Crater Flat is an extensional basin within which basaltic volcanism has taken place over the last 4 my (from 3.7 Ma to less than 1 Ma) (Crowe et al., 1995). Yucca Mountain lies to the east, adjacent to Crater Flat. Crater Flat therefore plays a significant role in probability hazard assessments of the proposed repository, which is discussed more fully under Spatial Models, below. The volcanic events within Crater Flat and the Amargosa Valley are assumed to lie within a volcanic field that I term for this analysis the Crater Flat field (CFF). The recent volcanism in the Sleeping Butte field (SBF) is also considered for the hazard assessment.

EVENT DEFINITION

A volcanic event is any incident that occurs during the propagation of magma upward through the crust and onto the earth's surface, such as earthquakes, gas emission, lava flows, volcanic cone production, etc. Pragmatically, a volcanic event can only be recorded (counted) by noting the deposits or the effects of the event. If only gases are expelled, a past volcanic event is difficult to determine. Volcanic cones, domes, dikes, lava flows, and volcanic ash or other tephra layers result from volcanism and can be called volcanic events.

Temporal Aspects

In low-volume basaltic eruptions, an "event" is the release of energy due to the ascent of magma, commonly as a dike, along which cinder cones or lava flows may develop. More than one cone or eruptive feature is likely to form from a dike, but if it can be inferred that the cones or other eruptive features came from the same dike, they are counted as one event. Low-volume basaltic processes are commonly short-lived, generally less than 100 years, because heat dissipation of small volumes is rapid and the magma cools quickly.

Spatial Aspects

Small-volume basaltic events are commonly generated along dikes, such as at the Lunar Crater Volcanic Field. The distance of an event is relatively short, usually less than 3 to 5 km, with an extreme of 20 km, along which more than one lava flow or cinder cone may develop (Scott and Trask, 1971). Therefore, I consider lava flows or cones that are constructed, say, 25 or 30 km apart at essentially the same time to be separate events.

Geochemical Affinity

Within a volcanic field, the deposits usually display a general isotopic affinity that is related to sharing the same magma source. However, distinguishing between individual events based on geochemical differences within a field is difficult and is not used in this analysis. For example, two cones 3 km apart having essentially the same age, but having differences in their geochemistry, would not be distinguished as separate events based solely upon geochemical signature because differences could be caused by local subsurface contamination.

Note: The elements of the PVHA model are summarized in the form of a logic tree in Figure RF-1.

REGION OF INTEREST

Two large regions of interest are identified that serve as background zones to the assessment of volcanic hazard. The first is the area enclosed within a 100-km radius of the site (Figure RF-2). The second is an "eastern zone" that includes several young volcanic fields in the eastern region of late-Cenozoic volcanic centers shown on the Luedke and Smith (1981) map (Figure RF-3). The purpose for selecting the background region is to provide a regional background rate of occurrence of volcanoes in a tectonic province of significance to the site. Because the 100-km radius area includes a large region with no Quaternary volcanic centers other than the Crater Flat field, it is less preferred and is assigned a weight of 0.2. The eastern zone is more representative of the regional rate of volcanism related to the proposed repository site and Crater Flat because the young basaltic volcanic fields (Luedke and Smith, 1981) contain Quaternary age volcanoes (2 Ma or less). The eastern zone is assigned a weight of 0.8.

SPATIAL MODELS

Three alternative spatial models are identified to assess the future occurrence of volcanoes in the YMR (summarized in Figure RF-1). The first approach, termed a field shape approach, follows the method suggested by M. Sheridan (presentation at PVHA Workshop 3), in which the geometry of a volcanic field is assumed to follow a bivariate Gaussian distribution. In using this approach, it is assumed that the boundaries of the CFF and SBF (Figure RF-4) represent between the 90th and 98th percentile of the Gaussian distribution. The percentiles and their relative weights are: 90% (0.8), 95% (0.1), and 98% (0.1). These weights reflect the high uncertainty in the location of the field boundaries.

The second approach is spatial smoothing of the observed events, following the general approach outlined by Connor and Hill (1995). An Epanechnikov smoothing kernel is used. It is assumed that the boundaries to the CFF and SBF contain 90%, 95%, or 98% of the probability density with weights of 0.8, 0.1, and 0.1, respectively. Again, these weights reflect the high uncertainty in the location of the field boundaries. The third approach is the zonation approach, whereby events are assumed to have a uniform probability distribution within either the CFF and SBF or the background zone.

The field shape approach is preferred (weight of 0.7) because it takes advantage of observations made at other basaltic fields in the southwestern U.S., and for reasons described in the section below. The spatial smoothing approach is given a lesser weight (0.2) because there are so few events within the CFF and, therefore, it may provide a weak basis for assessing distribution of future events. The zonation approach is given least weight (0.1) because volcanic fields do not show a uniform spatial distribution of volcanoes.

Reasons for Favoring the Field Shape Approach

The volcanic events within Crater Flat and the Amargosa Valley are defined here to lie within the CFF. The CFF differs from the CFVZ of Crowe and Perry (1989) because the Sleeping Butte and Thirsty Mesa centers are excluded. They are excluded from the CFF because there is a distinct spatial gap between volcanoes within the two areas that has persisted for over 5 my. The northwest trend parallels the trend of the Walker Lane (Crowe et al., 1995), but I judge the Walker Lane structure to have little significance with respect to local volcanism because it is not an extensional structure. Buckboard Mesa is believed to be related to the moat zone of the Timber Mountain caldera and is not related to the Crater Flat volcanics; hence, it is not included in the CFF. The CFF has an elliptical shape, as is expected for a basaltic volcanic field, based upon reasons given below. The rate of occurrence of volcanic events within the CFF is assessed based on activity over the past 1-2 my, even though the location of the CFF includes older events such as those in the 3.7 Ma area of Crater Flat and Amargosa Valley. Only the past 2 my are used to assess the rate of occurrence of volcanic events because events in the Quaternary are more relevant to modern and future events.

Underlying assumptions pertaining to cone density within small-volume basaltic volcanic fields and shapes of the fields are given as follows. Extension of the lithosphere creates local magma batches at various levels beneath the surface, presumably by decompression melting. The magma source lies beneath the resulting volcanic fields. Small magma batches ascend from the source region to the surface. Each rising magma batch follows a path governed by random physical and possibly chemical inhomogeneities toward the surface. These magma batches therefore intersect the surface at different places above the source region, but the place of intersection cannot be predicted. As a consequence, the rise of many separate batches from the same source can be circumscribed by a "cone of ascent" rather than a vertical pipe. This is indicated by the shape of cinder cone fields. The depth and size of the initial magma batch governs the size of the cinder cone field. Therefore, the area of a cinder cone field cannot exceed the limits of the "cone of ascent" of the magma. The deeper the source, the greater the diameter of the cone of ascent when it intersects the earth's surface.

The general field shape outline (usually elliptical) and the location of the field are directly related to the source region and the stress field within the lower ductile crust, but fractures with a different orientation in the upper brittle part of the crust can localize the final magma ascent. Although Quaternary basaltic volcanoes may not follow shallow structural features, there is occasionally a spatial correlation between basalt centers and deep-seated structural features such as strike-slip faults and ring fracture zones of calderas. Structures in the brittle crust are inferred to be passive features that promote the passage of basaltic magma.

Because the exact mechanism for the formation of magma batches is not known, other than a relationship to regional extension, the reason for localization of a field is not known. It is, therefore, not possible to accurately predict where new fields will occur. Basaltic volcanic fields consist of a few to hundreds of cones. The lifetime of a field is commonly about 5 my.

Studies of fields with large numbers of cones display an elliptical shape and appear to display a Gaussian falloff of the number of cones toward the margins of the field (M. Sheridan presentations at PVHA Workshops 3 and 4). This is consistent with the idea that cone fields lie within a cone of ascent with the magma source below the center of a field. Fields with low numbers of events, such as those in the YMR, may not have sufficient numbers of events to infer a Gaussian falloff, but it is used in the model herein because a Gaussian falloff is justified for fields with hundreds of cones (M. Sheridan presentations at PVHA Workshops 3 and 4).

Small-volume volcanic eruptions come from small-volume magma batches. The smaller the volume, the faster the magma batch will freeze. Therefore, each field of basaltic cones comes from a succession of short-lived magma batches. It is not known whether ascending magma batches break away from a larger, longer-lived magma chamber, or recur as small chambers throughout the history of a basalt field. Recurrence of basaltic volcanism within the same field does not exceed 5 my (M. Sheridan presentation at PVHA Workshop 3). Once a field shuts off, it appears not to start up again.

Although it is highly likely that future volcanic events will fall within existing fields and not outside them (that is, the probability of forming a new field is generally very low), the location of cones within a field is random. There does not appear to be a time-series of eruptions within a particular field. This is consistent with the hypothesis given above for the random paths followed by successive magma batches. The recurrence of an eruption at essentially the same place, as in the case of a polygenetic volcano, would be due to a random hit at the same place.

The alignment of vents within a field may have a different orientation from the general outline of the field itself because the vents may be influenced by shallow structures such as existing faults that are not oriented in the same direction as the basalt field. An example might be the cones in northern Crater Flat, which appear to be aligned in a northeast direction at an angle to the general northwest alignment of the inferred CFF (Faulds et al., 1994).

Boundary of Crater Flat Field

The boundary of the CFF is assumed to represent the 90th to 98th percentile of the Gaussian distribution. This assumption is consistent with the model of magma that rises within a cone of ascent circumscribing the highest density of volcanic events within a field. Volcanic events may occur outside the estimated CFF boundary because of the random paths of magma ascent. Thus, there is a small probability that volcanic activity could occur near the proposed repository. Such near-repository activity would most likely occur along dikes.

EVENT COUNTS

Event counts are assessed for two time periods: the past 1 my and the past 2 my. The counts are identical for the two time periods with the exception of those events in the northern Death Valley area. The number of events, their uncertainties, and the basis for the assessments are given below. Event counts are summarized in Table RF-1.

Lathrop Wells

The minimum and most likely number of events at Lathrop Wells is 1, and the maximum is 4 events. The single-event option is preferred based on the morphology of the cone and the author's observation that there are no unequivocal analog polygenetic cones recognized elsewhere in the world. The single-event alternative is also consistent with the event definition, whereby the age estimates overlap and there is close spatial proximity; geochemical differences do not enter into separating out individual events. I observed chronostratigraphic unit IV several years ago, and at that time I interpreted the associated volcanic units to be primary deposits that were not reworked. Given the significance of this interpretation, however, I would like to re-examine the deposits. Because that locality has now been removed by quarrying, and no other localities containing similar deposits have been identified, it is impossible to verify my original interpretation.

In the 2-event alternative, chronostratigraphic unit I and combined units II and III are separate events. This is based upon age determinations that indicate unit I is a distinctive unit, and the age estimates for units II and III overlap; unit IV is not considered a separate event. The 3-event alternative is similar to the 2-event alternative, except that unit IV is considered to be a separate event. In the 4-event alternative, units I, II, III, and IV are each considered separate events.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.6), 2 (0.3), 3 (0.05), and 4 (0.05).

Sleeping Butte

The minimum and most likely number of events at Sleeping Butte is 1: the maximum is 3 events. A single event is preferred because a NE-trending dike connects Black Cone and Hidden Cone. The NE orientation is consistent with local faults and the regional stress regime. Black Cone and Hidden Cone each represent a separate event in the 2-event choice. The 3-event alternative is based upon paleomagnetic data presented by D. Champion (PVHA Sleeping Butte field trip) that suggest there were 2 events at Hidden Cone.

The event counts and their relative weights for the Sleeping Butte area are the following: 1 (0.7), 2 (0.25), 3 (0.05).

1.0 Ma Crater Flat

The ~1 Ma basalts of northern Crater Flat most likely represent 1 event, although a maximum of 4 events could have occurred. For the single-event option, eruptions formed cones along an en echelon set of dikes during a 100-year or shorter time frame; the overlapping age determinations and the linear arrangement of the 4 cones provide strong evidence for the single-event option. The 12-km length and the slight curvature to the chain of cones argue against all of the cones resulting from a single dike. More likely, a dike set formed as a set of "fingers" that converge at depths of a few to several kilometers below the surface. The option with 2 events would involve combining adjacent cones (for example, Makani and Black cones as 1 event, Red and Little cones as another event). The 3-event option would involve Red and Black cones as a single event, with Makani Cone and Little Cones each defining additional events. The 4-event option, where each of the 4 cones is related to a single event, is the maximum number for the area (the Little Cones are interpreted to have been erupted during a single event due to their small size and close proximity). If there were evidence of separate dikes, or more accurate age data for the individual cones, 4 events would be more likely than 2 or 3 events because the spatial separation of the cones is close to the maximum separation allowed within this definition of event.

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.8), 2 (0.05), 3 (0.05), and 4 (0.1).

Northern Death Valley

Two Quaternary events are identified in the Death Valley area: the 1.7 Ma basalt of Shoreline Butte and the <0.7 Ma basalt of Cinder Hill (also called Split Cone) (B. Crowe informal PVHA memo). In the post-1 Ma period, 1 event is counted; in the post-2 Ma period, 2 events are counted.

Ubehebe Craters

A minimum of 1 and a maximum of 5 post-1 Ma events have occurred in this area; the most likely number is 2. All of the interpretations come from consideration of the data reported in Crowe and Fisher (1973) and my personal observations. All of the features mapped could represent pulses of eruptions during a single eruptive event. Two events can be counted if the

Strombolian eruptions within Ubehebe crater occurred as 1 event followed by the phreatic events. This is the favored alternative. A 4-event alternative would entail the eruption of Ubehebe crater, two clusters, and a Strombolian event. A 5-event alternative would assume that the Little Hebe eruption was a separate event.

The event counts and their relative weights for the Ubehebe Craters area are: 1 (0.3), 2 (0.6), 4 (0.05), and 5 (0.05).

Lunar Crater

The Quaternary Lunar Crater field is an elongate ellipse, about 25 km long, containing 82 vent counts and 28 clusters based upon the work of Crowe et al. (1992). Most of the cinder cones and lava flows are aligned in an en echelon pattern. This suggests that many vents were formed contemporaneously by an en echelon system of dikes that are presently unexposed. It is probable that several vents were simultaneously fed by activity along each assumed dike.

The major clustering pattern suggests the following event counts and their relative weights: 1 (0.05), 2 (0.3), 3 (0.6), and 28 (0.05).

Cima Field

The Cima field has a roughly circular shape, suggesting the presence of multiple events.

The event counts and their relative weights for the Cima field are: 1 (0.01), 7 (0.5), 22 (0.35), and 29 (0.14).

RATES OF OCCURRENCE

The rates of occurrence of volcanic events are calculated from the event counts averaged over two periods: the past 1 my and the past 2 my. The post-1 Ma time period is given higher weight (0.8) because the author believes that the best indicator of the rate of future small-volume basaltic volcanism is the more recent volcanic activity. The 2 Ma period is given lesser weight (0.2), but is included because this includes all of the Quaternary period.

Because the time periods over which the rates are calculated are relatively short compared to the life of a volcanic field, it is judged that the rates should be treated as homogeneous over these periods.

Undetected Events

In addition to events identified and interpreted at the surface, there is the potential for undetected subsurface events that might exist at depths of less than 300 m beneath the present-day topographic surface and not be represented at the surface. Most of the topographic surface of the CFF within which volcanism has occurred is at an elevation below the repository. Therefore, undetected events in CFF would be about 300 m or more below the repository.

I speculate that there are 10 times as many dikes at depths of 2.5 to 5 km than are at the surface. This would mean that the ratio of the number of dikes at depth to the number at the surface is 10:1 at 2.5 to 5 km depth and is 1:1 at the surface. Then, by extrapolating arithmetically the relationship between the ratio and depth to a depth of 300 m, a ratio of 1.5 to 2.0 is determined. As a first estimate, I suggest that the number of events at the surface within a volcanic field could be multiplied by 1.5 to 2.0 to obtain the total number of events that could be present at a depth of 300 m. A logarithmic extrapolation results in ratios of 1.15 and 1.32. I believe that the arithmetic and logarithmic extrapolations should be given equal weight (0.5).

EVENT GEOMETRIES

Individual dike lengths range from 0.5 to 5 km, although an event may consist of a set of dikes longer than 5 km. An event is most likely to be associated with a single dike having a length that is less than 5 km near the surface. En echelon sets of dikes have maximum lengths that are based on the dimension of the volcanic field in the orientation parallel to the direction of regional maximum horizontal compressive stress. In the YMR, this dimension is about 20 km for the CFF along a strike of N30E (Figure RF-5). The following cumulative distribution is assessed for the length of an event:

0.5 km	0.0
1 km	(0.5)
5 km	(0.8)
10 km	(0.97)
20-25 km	(1.0)

Equal weight is given to the maximum lengths of 20 and 25 km.

Note: At the request of Dr. Fisher, the cumulative density was assumed to be linear between the discrete points given. The resulting cumulative distributions and density functions are shown on Figure RF-5.

Dikes should be oriented parallel to the direction of regional maximum horizontal compression, N30E (G. Thompson presentation at PVHA Workshop 2), with an uncertainty of plus or minus 20 degrees representing the 95% confidence interval. Dikes are more likely to be centered on an event than to extend unilaterally. Therefore, a triangular distribution is used to define the event location.

HYDROMAGMATIC ACTIVITY

A large hydromagmatic explosion is very unlikely and has an estimated probability of occurrence of about 1 in 1,000. This type of event would require a significant amount of water and permeable rocks in the subsurface below a depth of about 0.5 km. Hydromagmatic activity generally occurs at depths of about 100 m, and more rarely at a depth of 200 m because of pressures that subdue the ability of steam explosions to occur. There is a higher probability that a hydromagmatic event would occur in a valley where abundant water could be located within alluvium. The groundwater table is about 620 m beneath Yucca Mountain and about 320 m beneath the proposed repository.

TYPE OF ERUPTION

Basaltic eruptions characterized as Strombolian with lava flows and dikes of small volume have occurred in the YMR during the past 1 my, so a continuation of this pattern is most likely. Phreatoplinian eruptions are rare in basaltic fields and are considered unlikely. Although some water was involved in eruptions at Lathrop Wells, it had little effect upon the geometry of the cinder cone.

Silicic volcanism died out in the YMR about 8.5 Ma, and the probability of large-volume silicic volcanism is insignificant within the YMR.

Approved and signed
Richard V Fisher
april 18, 1996

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TABLE RF-1
RICHARD V. FISHER - EVENT COUNTS

Location	Counts (Cones)	Weight	Notes
Lathrop Wells	1 I-IV 2 I, II+III 3 I, II, III 4 I, II, III, IV	(0.6) (0.3) (0.05) (0.05)	BC: Black Cone HC: Hidden Cone 2HC: 2 events at Hidden Cone LBP: Little Black Peak LC: Little Cone M: Makani Cone RC: Red Cone SB: Shoreline Butte SC: Split Cone I-IV: Chronostratigraphic units of Crowe et al. (1995)
Sleeping Butte	1 (LBP+HC) 2 (LBP, HC) 3 (LBP, 2HC)	(0.7) (0.25) (0.05)	
1.0 Ma Crater Flat	1 (all) 2 (LC+RC, BC+M) 3 (LC, RC+BC, M) 4 (LC, RC, BC, M)	(0.8) (0.05) (0.05) (0.1)	
N. Death Valley (1 MA)	1 (SC)	(1.0)	
N. Death Valley (2 Ma)	2 (SC, SB)	(1.0)	
Lunar Crater	1 2 3 28	(0.05) (0.30) (0.60) (0.05)	
Cima	1 7 22 29	(0.1) (0.05) (0.35) (0.14)	

TABLE RF-2
RICHARD V. FISHER - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Post 1 Ma (0.8)	CFF: (NCF+ LW) SBF: (SB) BK100: (DV1, UH) BKEZ: (DV1, UH, LC, C)	CFF: Crater Flat Field BK100: 100 km radius Background Zone BKEZ: Eastern Background Zone NCF: Northern Crater Flat LW: Lathrop Wells SB: Sleeping Butte SBF: Sleeping Butte Field DV1: Death Valley (1 Ma) DV2: Death Valley (2 Ma) UH: Ubehebe LC: Lunar Crater C: Cima
Post 2 Ma (0.2)	CFF: (NCF+ LW) SBF: (SB) BK100: (DV2, UH) BKEZ: (DV2, UH, LC, C)	

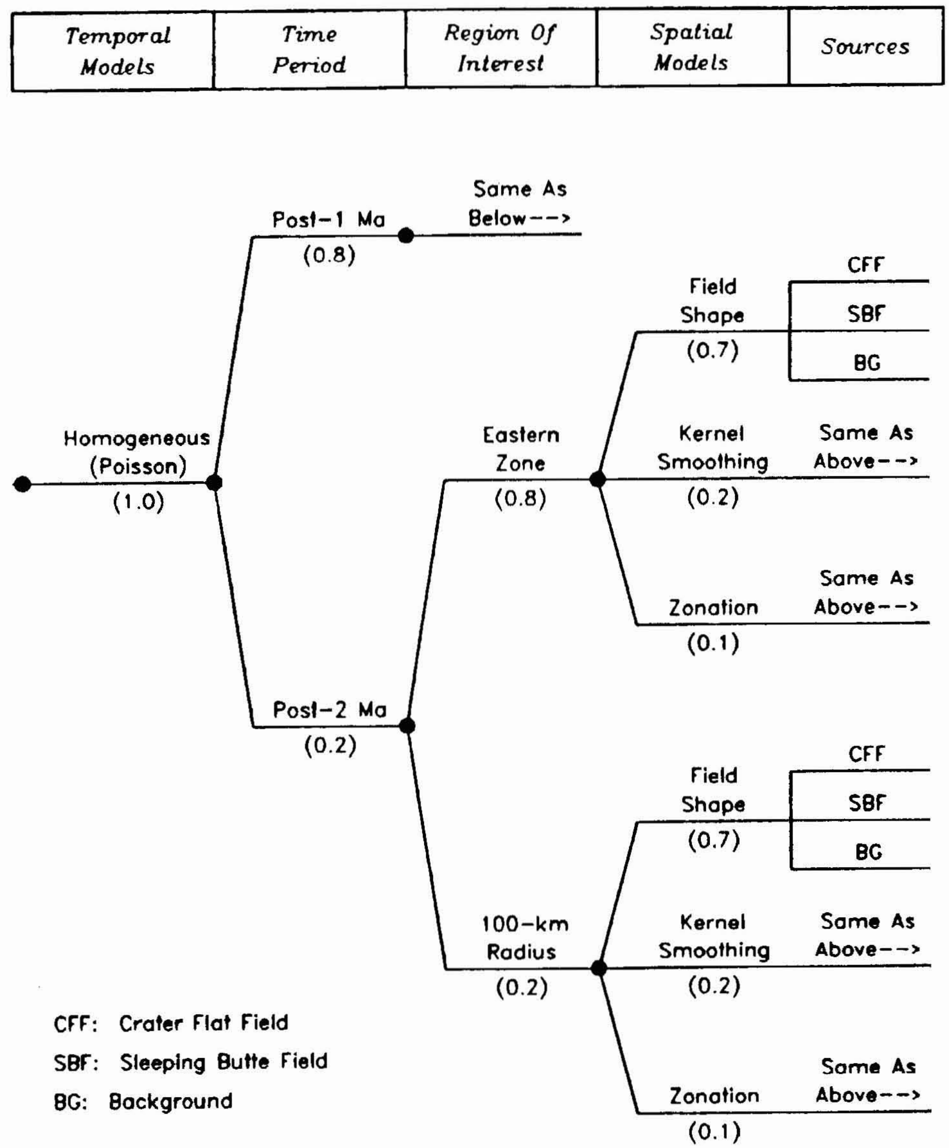
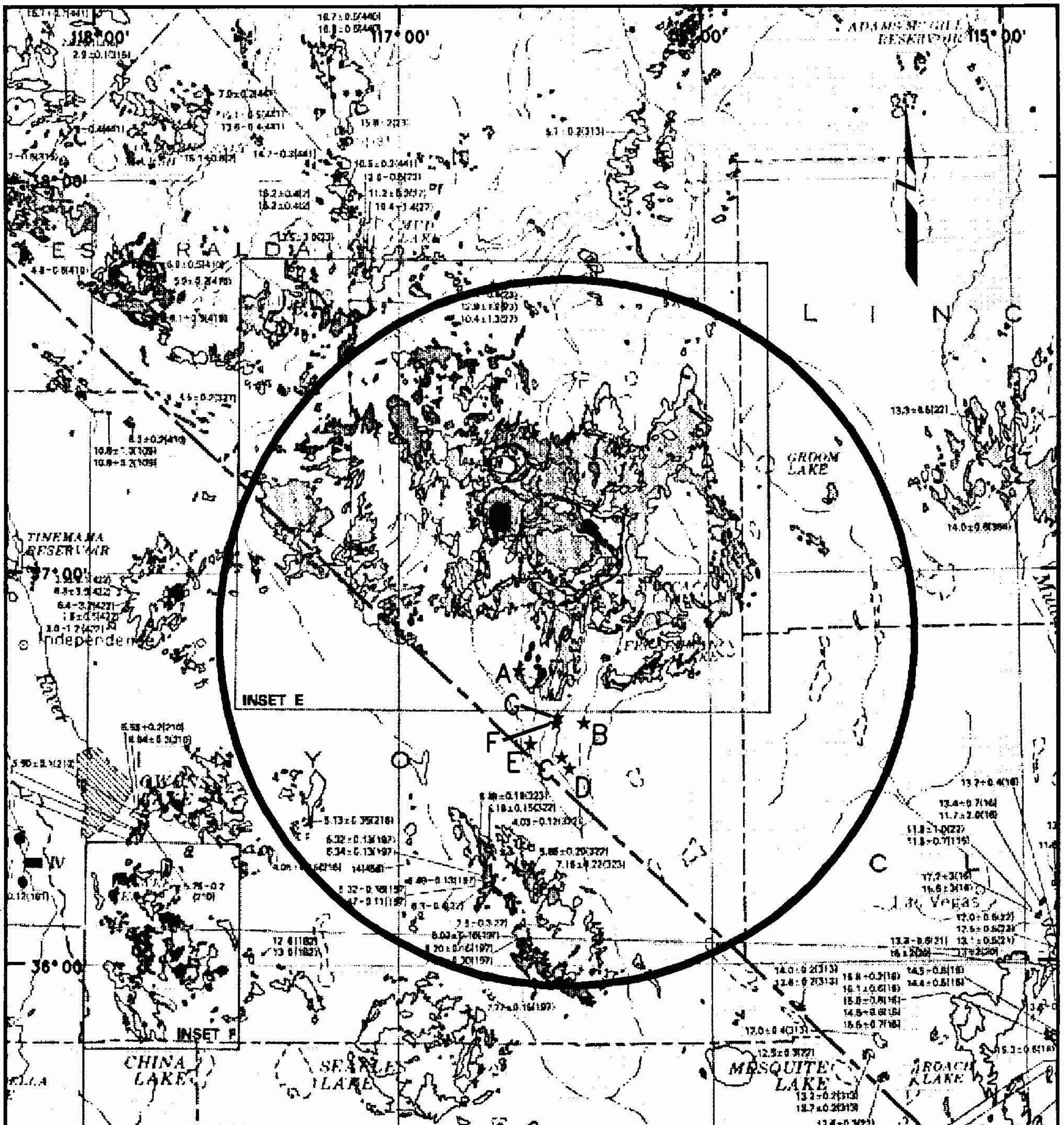


Figure RF-1 PVHA model logic tree developed by Richard V. Fisher.



B★ Aeromagnetic Anomaly

Proposed Repository

0 25 50
SCALE IN KILOMETERS

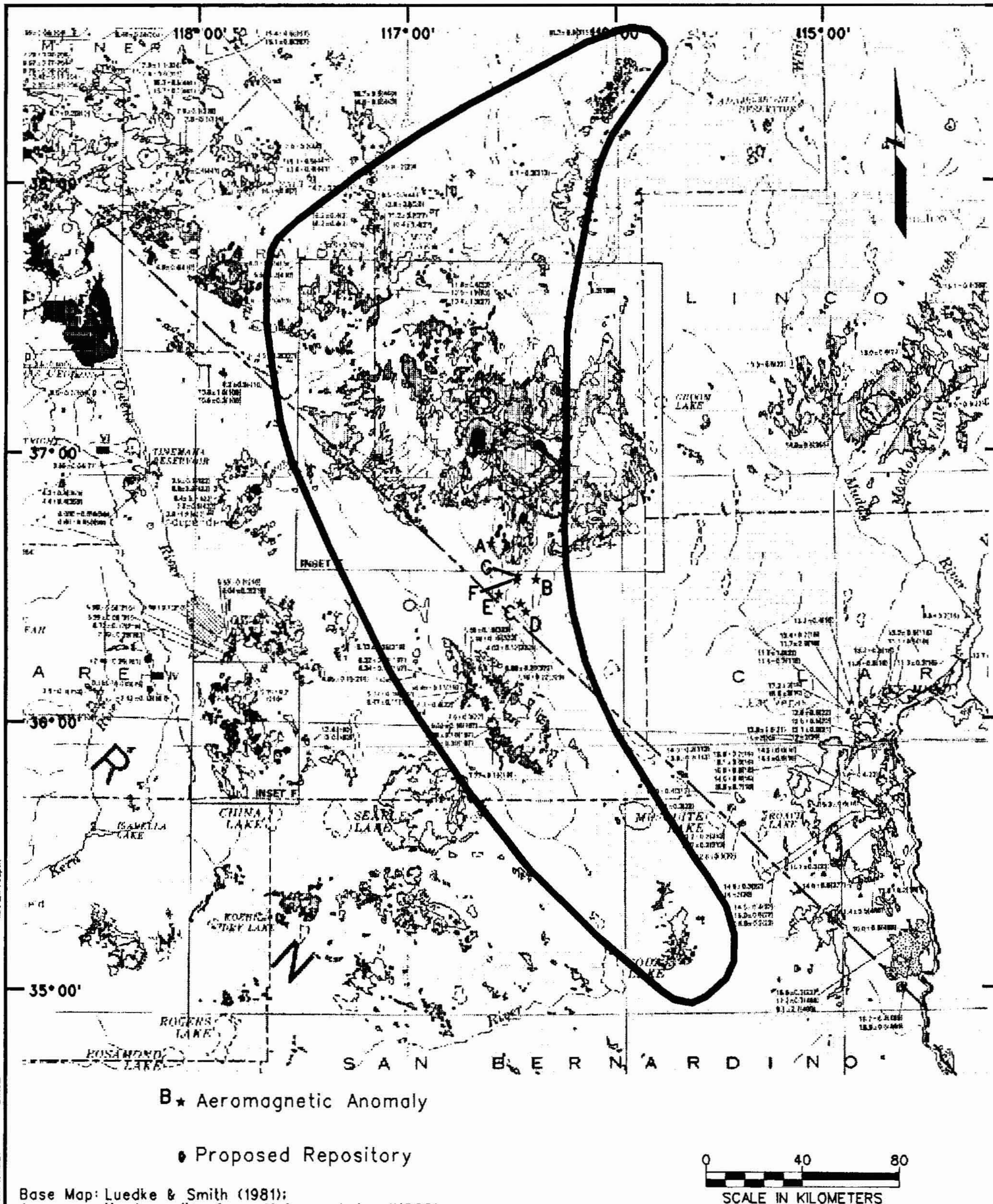
Base Map: Luedke & Smith (1981);
Aeromagnetic Anomalies from V Langenheim (USGS)

GEOMATRIX

RICHARD V. FISHER
REGIONAL BACKGROUND ZONE:
100 KM RADIUS

Figure RF-2

PVHA Project

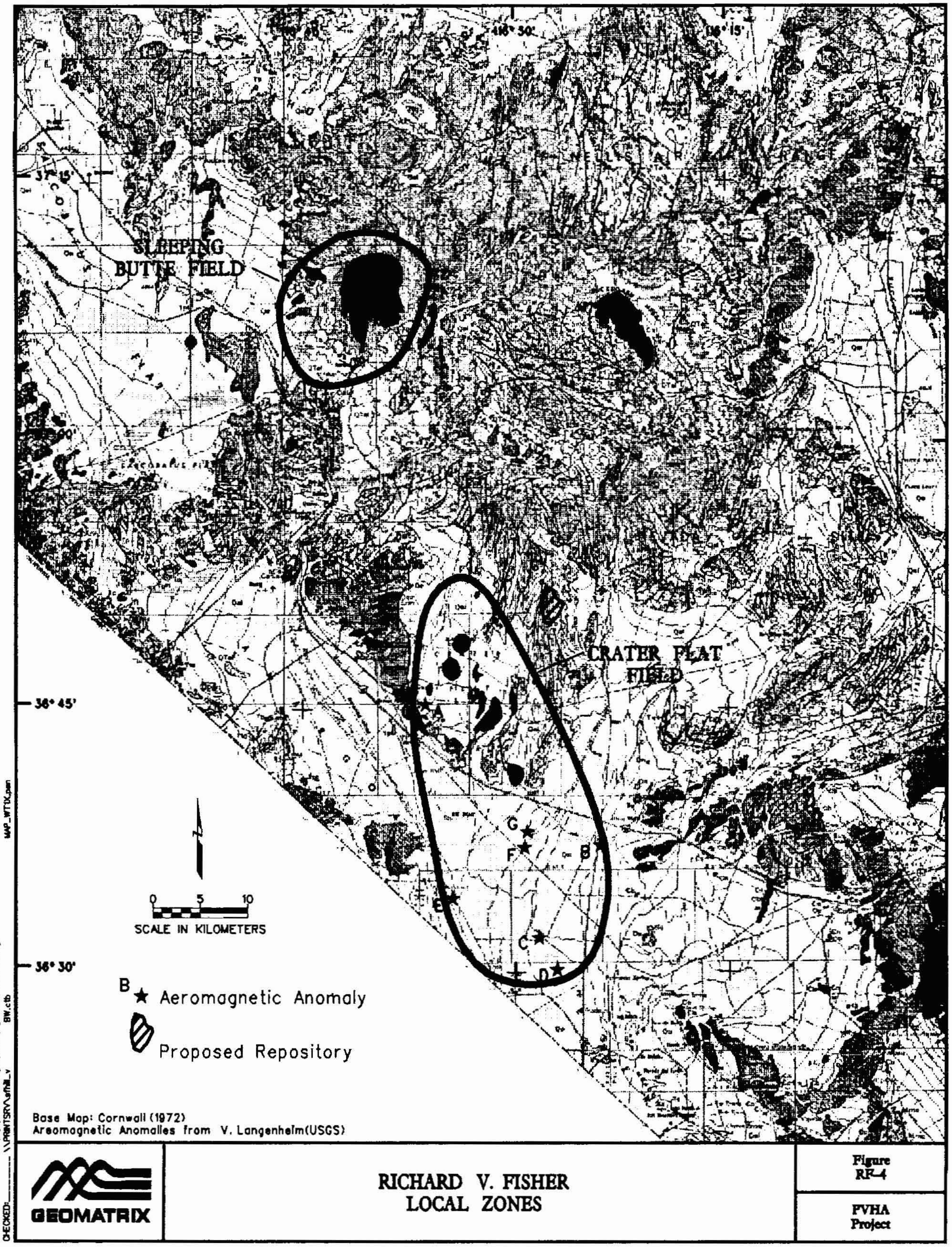


GEOMATRIX

RICHARD V. FISHER
REGIONAL BACKGROUND ZONE:
EASTERN ZONE

Figure RF-3

PVHA Project


116° 30'
116° 15'
37° 15'
SLEEPING BUTTE FIELD
CRATER FLAT FIELD
36° 45'
36° 30'
A
B
C
D
E
F
G
0 5 10
SCALE IN KILOMETERS
B ★ Aeromagnetic Anomaly
Proposed Repository
Base Map: Cornwall (1972)
Areomagnetic Anomalies from V. Langenheim(USGS)
GEOMATRIX
RICHARD V. FISHER
LOCAL ZONES
Figure RF-4
PVHA Project

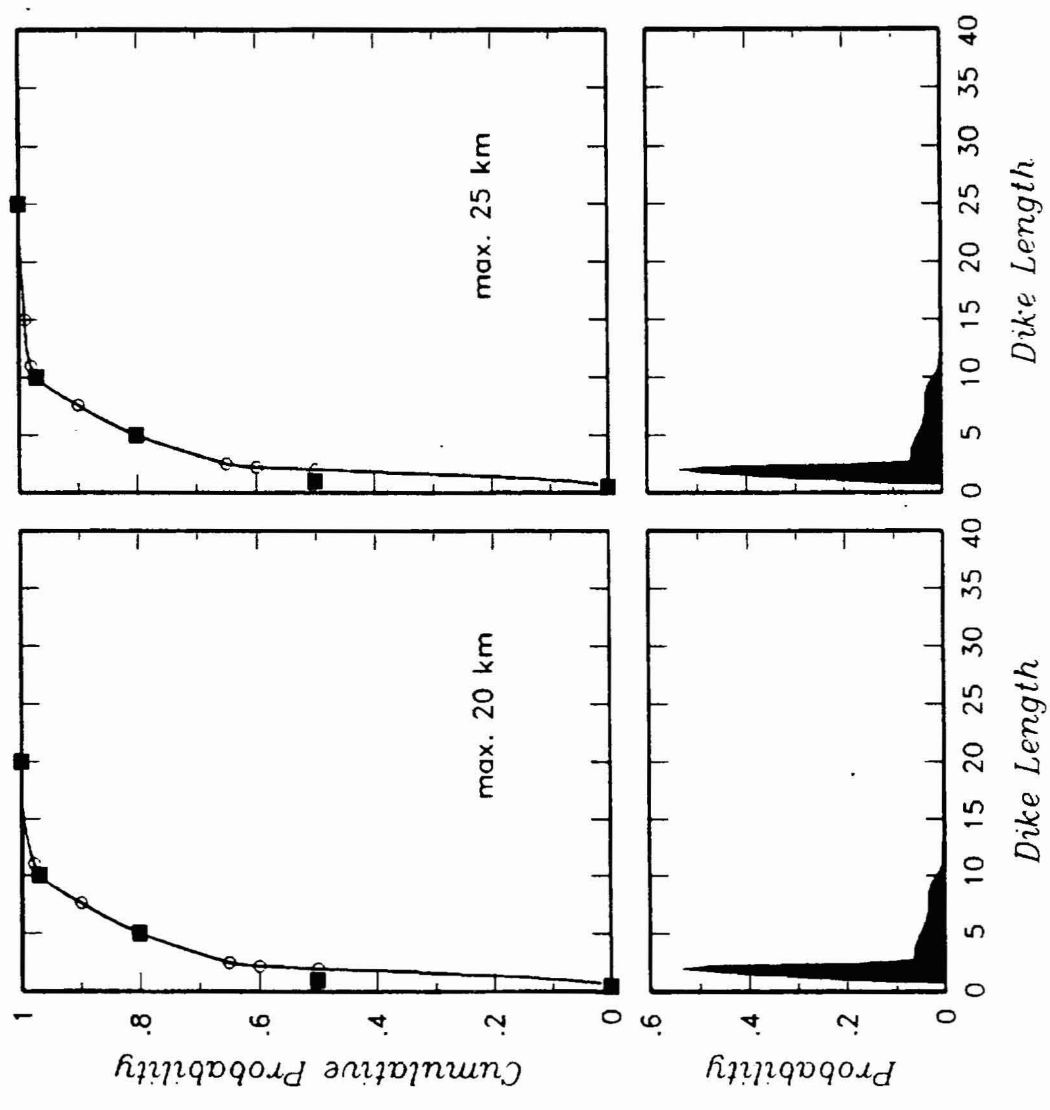


Figure RF-5 Dike length distribution developed by Richard V. Fisher.

WILLIAM R. HACKETT
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

The Yucca Mountain region (YMR) is the area within a radius of about 100 km centered on the proposed repository site. The YMR lies within the southern Great Basin, on the boundary between the Basin and Range Province, where regional extension is accommodated by a combination of normal faulting and dike intrusion, and the Walker Lane belt, which is characterized by strike-slip movement. The presence of diffuse partial melt at upper-mantle depths beneath the YMR, as may be inferred from geophysical data, does not help to quantify a probabilistic volcanic hazard analysis (PVHA) because this observation may generally apply across the Basin and Range Province. Of greater importance to the PVHA is geologic and geophysical evidence for patterns of past volcanism in the YMR, including vent locations and the nature of volcano clustering, the chronology of volcanism, and the extent to which ascending magma is influenced by the YMR stress field or upper-crustal geologic features.

In the YMR, a key distinction exists between the earlier Miocene, caldera-related eruptions, which were characterized by explosive silicic volcanism, as opposed to post-caldera basaltic volcanism younger than about 10 Ma. Locations of post-caldera basaltic volcanoes have been influenced by regional extension and the development of north-trending, fault-bounded structural depressions. This contrasts with the more localized calderas and other volcanic structures that developed during the earlier period of silicic volcanism.

The probability of a return to silicic volcanism is extremely low. More than 10 my have elapsed since the last silicic volcanism, and this hiatus is substantially longer than the less-than-five-million-year lifetime of typical silicic-caldera volcanic systems worldwide. Large-scale ascent of basaltic magma into the crust would probably be necessary to induce crustal melting and future silicic volcanism. Such a change to silicic volcanism in the YMR is not geologically imminent for several reasons. The small volumes of basalt erupted during the past 10 my suggest a correspondingly small supply of basaltic magma into the crust. In addition, there is no contemporary geophysical evidence, such as anomalous heat flow or hydrothermal activity, to suggest the presence of silicic magma at depth. During the past 8-10 my, silicic volcanism has migrated outside the YMR, to the western margin of the Great Basin.

The Amargosa Valley Isotopic Province (AVIP; G. Yogodzinski presentation at PVHA Workshop 3) encompasses the YMR and is an area in which basaltic volcanoes younger than about 10 Ma have distinctive neodymium-isotopic compositions, suggesting generation of magma from a common source of old lithospheric mantle. The similarity of the isotopic composition of basaltic magma erupted within the AVIP, as distinguished from the surrounding region, allows us to focus our investigation from the entire southern Great Basin to a more local region with common magma properties and with greater significance to the PVHA.

Volcanic fields elsewhere in the Great Basin also offer insights on volcanic processes and event magnitude, but are relatively unimportant for evaluating event frequency in the YMR. As an example, the writer has extensive knowledge of Snake River Plain volcanism. This region is a good analog for understanding basaltic volcanism, dike intrusion, and associated structural disruption, but is not a close analog in terms of volcano clustering, event frequency (recurrence rate), or age of basaltic volcanism in the YMR.

The most probable sites of future volcanism in the YMR should be those areas where young volcanoes have erupted in the past. Thus, the spatial and temporal distribution of past volcanoes in the YMR is the basis for quantifying the probability of future volcanic disruption at the proposed repository.

EVENT DEFINITION

Temporal Aspects

An event is defined as a cogenetic set of intrusives and extrusives that are products of a single magma batch. An event occurs within the geologically brief time it takes to inject magma into the crust and to solidify—decades to hundreds of years. Lithostratigraphic data and isotope geochronology are the principal tools available to determine the age and frequency of volcanism, and usually there is considerable uncertainty.

Spatial Aspects

The spatial dimensions of an event are best constrained by the length of a basaltic dike that has ascended to a kilometer or less beneath the earth's surface. This length is taken to be approximately 2 km, but multiple dikes may have an aggregate length exceeding 10 km, and the maximum length of a dike is estimated to be on the order of 30-40 km (see discussion of Event Geometry below).

Geochemical Affinity

Because the intrusives and extrusives associated with an event are cogenetic, this implies that they result from a single magma batch. However, recent geochemical data from the YMR and other regions suggest that individual magma batches may not be compositionally uniform. Geochemical data are therefore best interpreted in light of lithostratigraphic and geochronologic data, using an integrated approach.

Note: *The elements of the PVHA model are summarized in the form of a logic tree in Figure WH-1.*

REGION OF INTEREST

The region of interest is an area of detailed analysis that has been chosen to include volcanic centers that are significant to the PVHA in light of the temporal and physical aspects of volcanism in the YMR. The region of interest also defines a background zone of regional volcanism.

The region of interest includes Yucca Mountain, together with major portions of the adjacent structural blocks. Its area is approximately that of a circle with a 40-km radius about the repository site, and 40 km is also about equal to the maximum basaltic-dike length used in this assessment (Figure WH-2).

The region of interest includes the area of most recent volcanism (AMRV; Smith et al., 1990), but expanded to the north and east to include the volcanic centers at Pahute Mesa, Paiute Ridge, and Nye Canyon. The region of interest is thus the northern part of the AVIP. The southern AVIP is not included because of its distance from the repository and because of the predominantly pre-Quaternary age of volcanism (Luedke and Smith, 1984).

As discussed below, the region of interest is called the "10 Ma zone" because it encloses events with ages less than approximately 10 Ma. Volcanic centers younger than about 10 Ma have the greatest significance to the PVHA because this is the period of post-caldera basaltic volcanism that has continued into the Quaternary and is therefore most likely to represent future volcanism. In addition, the writer believes that the 10-11 Ma basalt within the Solitario Canyon fault must be included in the PVHA due to its proximity to the repository site. Internal consistency therefore requires that all other basalts younger than about 10 Ma also must be considered within the region of interest.

SPATIAL MODELS

Homogeneous Source Zones

Two basic approaches are taken to assess the future spatial distribution of volcanic events. The first approach is a "zonation" of the region into several source zones representing different time periods that may have different rates. It is assumed that the probabilistic distribution of events within each zone is uniform in space. Three alternative representations of homogeneous source zones in the region of interest are made. In the first, the region of interest (defined above) is identified and called the 10 Ma zone because it encloses post-10 Ma centers (Figure WH-2). In this zonation, there is no subdivision of the 10 Ma zone. In the second homogeneous source zone, a region is identified—called the 5 Ma zone—that encloses the post-5 Ma centers and is identical to the AMRV of Smith et al. (1990) (Figure WH-3). The 10 Ma zone is also included as a background zone. In the third homogeneous source zone, a smaller region is identified—termed the 1 Ma zone—that encloses the post-1 Ma volcanics in Crater Flat, Lathrop Wells, and Sleeping Butte (Figure WH-4). The 1 Ma zone also follows the northwesterly trend of the Walker Lane. Again, in this zonation the 10 Ma zone serves as the background zone.

Thus, the three alternative source zones are linked to the ages of the volcanic centers in the region of interest. The relative weights assigned to the zones reflect the degree to which the time periods provide useful information about the future spatial distribution of volcanism. The weights assigned are:

1 Ma zone	(0.6)
5 Ma zone	(0.3)
10 Ma zone	(0.1)

The post-1 Ma time period is most important because of its recent geologic age and the proximity of young volcanic centers to the proposed repository. The post-5 Ma time period is also significant because it includes most of the post-caldera basalts of the YMR, and because it is not too old to reflect geologically recent changes in the tectonic regime. The post-10 Ma time period, while it provides a background zone for the other more local zones, probably captures events that are too old to be representative of contemporary or future processes.

Spatial Smoothing

The fact that volcanoes are clustered in the region of interest (Connor and Hill, 1995) is a strong indication that future volcanism will occur in the vicinity of past volcanoes. A second approach therefore assesses the spatial probability of volcanism by using a kernel method that treats volcanism as a point process within a defined spatial and temporal bandwidth. Connor and Hill (1995) use an Epanechnikov kernel as the smoothing operator, but this gives zero probability of a new volcano forming beyond the smoothing distance "h" from all mapped volcanoes. To allow a finite probability of a new volcano beyond the selected smoothing distances "h" (discussed below), an equivalent Gaussian kernel is used here instead, with the further implication that the Gaussian smoothing distances "h" will be a factor of 2.5 times smaller than equivalent Epanechnikov "h" values (Silverman, 1986).

To assist reviewers in comparing with the results of Connor and Hill (1995), if an Epanechnikov kernel were used here as the smoothing operator, the three smoothing distances and corresponding weights would be: 8 km (0.5), 16 km (0.4), and 24 km (0.1). These distances span the range of possible vent clusters that are observed in the region of interest. The equivalent Gaussian smoothing distances used here are 3.2 km (0.5), 6.4 km (0.4), and 9.6 km (0.1).

The relative weights given to the two approaches for modeling the spatial occurrence of volcanism are: zonation approach (0.4) and spatial smoothing approach (0.6). The spatial smoothing approach is preferred because it takes full advantage of observed volcano locations in the YMR. The fact that volcanoes are clustered in the region of interest is a strong indication that future volcanism will occur in the vicinity of past volcanoes. The selected smoothing distances and weights are chosen to reflect the scales of volcano clustering in the region of interest, specifically based on Figure 2 of Connor and Hill (1995). Greatest weight is assigned to the 8-km smoothing distance because this is the scale at which the Crater Flat and other Quaternary volcanoes of the region of interest are spatially clustered. Greater smoothing distances of 16 and 24 km also are included in the analysis to capture the distances at which volcano clusters begin to group in the YMR. The spatial smoothing approach produces a nonuniform spatial probability distribution with "soft" boundaries. It differs from the homogeneous source zone approach, which assumes a homogenous distribution of past and future events within its source zones, each of which has a "hard" boundary.

EVENT COUNTS

Based on the definition of volcanic "events" given earlier, the number of events—and their uncertainties—are assessed for each of the centers in the region of interest. The number of events is assessed for the past 1, 5, and 10 my, which is the basis for identifying the three different source zones. For the post-1 Ma period, event counts are made for northern Crater Flat, Lathrop Wells, and Sleeping Butte. For the post-5 Ma period, these counts are supplemented with counts from the 3.7 Ma vents of Crater Flat, Amargosa Valley, Buckboard Mesa, and Thirsty Mesa. For the post-10 Ma period, additional counts are made at Rocket Wash, Pahute Mesa, Paiute Ridge, Nye Canyon, Yucca Flat, and Solitario Canyon. Event counts are summarized on Table WH-1.

In all cases, the potential for undetected events is evaluated at each site and is included in the maximum estimate of counts at each location. At young volcanic centers, older events may be undetected as a result of coverage by the younger deposits. At older (Pliocene and Miocene) volcanic centers, events may be undetected as a result of removal by erosion or coverage by surficial deposits. Another type of undetected event is dike intrusion without an accompanying volcanic eruption. The geologic record of volcanism in the region of interest is considered to be a close approximation to the dike-intrusion record. Basaltic magma that has ascended to less than 1 km of the surface will have a high probability of erupting because magma pressure and volatile expansion will generally overcome the low tensile strength of fractured, near-surface country rocks. However, there exists *a priori* a finite probability that some dikes might not erupt. Undetected events are added to the event counts in specific areas.

Lathrop Wells

One to 5 events (including 1 undetected event) are interpreted, with 3 events and 1 event having the highest probabilities. The 1-event interpretation requires a monogenetic cone, consistent with the paleomagnetic data of Champion (1991). The preferred scenario of 3 events is based on geomorphic data cited by S. Wells and L. McFadden (presentations at PVHA Lathrop Wells field trip). Available age dates have major uncertainties, and the best evidence for multiple events is provided by the geomorphic and soils data. The 4-event scenario would include all 4 chronostratigraphic units of Crowe et al. (1995), and the 5-event scenario includes an undetected event.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.4), 2 (0.1), 3 (0.4), 4 (0.05), and 5 (0.05).

Sleeping Butte

One to 3 events are interpreted in the Sleeping Butte area, with 2 events most likely. In the 1-event interpretation, Little Black Peak and Hidden Cone are assumed to represent a single event; in the 2-event interpretation, they are assumed to be separate events. The 3-event interpretation allows for 2 events at Hidden Cone, which was suggested by preliminary geomorphic and paleomagnetic data discussed on the PVHA field trip. Three events also allows for the possibility of an undetected event.

The event counts and their relative weights for the Sleeping Butte area are: 1 (0.4), 2 (0.5), and 3 (0.1).

1.0 Ma Crater Flat

One to 6 events (including 1 undetected event) are assessed, with 3 events most likely. In the interpretation that is best supported by the data, Red and Black cones are combined to form 1 event (based on their similar geochemistry), with the additional 2 events represented by Makani Cone and Little Cones. The 1-event interpretation is not given much weight because of the long dimensions for the event (12 km, which would imply a dike set or very long dike), and the different geochemistry of Little Cones from Red Cone and Black Cone. In the 2-event interpretation, the Little Cones represent 1 event (based on their different geochemistry) and Makani, Red, and Black cones are considered 1 event. In the 4- and 5-event interpretations, the 2 Little Cones are considered either 1 event or 2 events, respectively. The 6-event interpretation includes an undetected event.

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.1), 2 (0.3), 3 (0.4), 4 (0.1), 5 (0.05), and 6 (0.05).

Buckboard Mesa

The Buckboard Mesa geologic observations (Crowe et al., 1995) indicate a fissure system and 2 vents. The preferred interpretation is that these features represent a single event, but they could have resulted from 2 events.

The number of events and their associated weights are: 1 (0.8), and 2 (0.2).

3.7 Ma Crater Flat

Geologic field observations (Crowe et al., 1995; author's independent observations) of the 3.7 Ma basalts of Crater Flat allow 1 to 8 events (including 2 hidden), with 3 the preferred interpretation. Numerous dikes and scoriaceous outcrops are located in the area, and the centers are eroded, faulted, and dissected, leading to uncertainties in the number of events. Geologic data in Crowe et al. (1995, p. 3-71) provide evidence for 6 events; an additional 2 undetected events may be present. The highest weight is placed on 3 events based on the distribution of vent areas.

The event counts and their relative weights for the 3.7 Ma area are: 1 (0.05), 2 (0.1), 3 (0.3), 4 (0.2), 5 (0.2), 6 (0.1), 7 (0.025), and 8 (0.025).

Amargosa Valley

The aeromagnetic anomalies in Amargosa Valley (V. Langenheim presentation at PVHA Workshop 1) represent a minimum of one event and a maximum of 7, with a most likely number of 3. A direct assessment of the probability that each anomaly represents a volcanic event is:

anomaly A=0.1, B=1.0, C=0.8, D=0.8, E=0.2, F=0.2, and G=0.2. This assessment takes into account the available geologic data (e.g., anomaly B has been drilled and age-dated, anomaly D has been drilled but not dated; the depth of anomalies B, C, and D is known or inferred to be about 200 m below a sequence of Quaternary alluvial deposits).

From this assessment, the following cumulative distribution of the number of events is assessed at: 1 (1.0), 2 (0.8), 3 (0.64), 4 (0.13), 5 (0.03), 6 (0.005), and 7 (0.0005).

Thirsty Mesa

One to 3 events are interpreted, with a preferred estimate of 1 event. The geologic relationships (Crowe et al., 1995) suggest that this is a monogenetic shield volcano that resulted from numerous outpourings over decades, but all are genetically related.

The event counts and their relative weights for the Thirsty Mesa area are: 1 (0.7), 2 (0.2), and 3 (0.1).

Nye Canyon

Geologic field descriptions of the available exposures (Crowe et al., 1995) suggest a minimum of 1 event and a maximum of 6 events (including an undetected event). The preferred interpretation of 4 events is based on the observation that the unit consists of four separate volcanic centers.

The event counts and their relative weights for the Nye Canyon area are: 1 (0.05), 2 (0.1), 3 (0.2), 4 (0.5), 5 (0.1), and 6 (0.05).

Rocket Wash

The Rocket Wash exposure, although highly eroded, appears to have a single vent area (Crowe et al., 1995) and is interpreted to have formed from a single event. The possibility of an undetected event is also allowed in the 2-event scenario.

The event counts and their relative weights for the Rocket Wash are: 1 (0.8), and 2 (0.2).

Yucca Flat

Basalt was identified in a drillhole (Crowe et al., 1995), and the preferred interpretation is that it represents a single lava flow. The preferred count is therefore 1, and, allowing for an undetected event, 2 events are considered.

The event counts and their relative weights for the Yucca Flat area are: 1 (0.9), and 2 (0.1).

Paiute Ridge

The geologic relationships at Paiute Ridge (Crowe et al., 1995) allow interpretations ranging from a minimum of 1 event to a maximum of 6 events (including an undetected event). The preferred count of 2 events, is based on strong paleomagnetic evidence for basalts exposed along Paiute Ridge to be cogenetic (1 event), with the basaltic dike of Scarp Canyon representing a second event.

The event counts and their relative weights for the Paiute Ridge area are: 1 (0.05), 2 (0.4), 3 (0.3), 4 (0.1), 5 (0.1), and 6 (0.05).

Pahute Mesa

Geologic field descriptions from the Pahute Mesa area (Crowe et al., 1995) allow interpretations ranging from a minimum of 1 event to a maximum of 4 events. The preferred count is 2 because of the petrographic contrast of the central group of units, versus two other petrographically similar units to the east and west. If all 3 groups are separate events, the count is 3; the 4-event scenario allows for an undetected event.

The event counts and their relative weights for the Pahute Mesa area are: 1 (0.1), 2 (0.6), 3 (0.2), and 4 (0.1).

Solitario Canyon

A basaltic dike apparently intruded and was subsequently brecciated along the Solitario Canyon fault (Crowe et al., 1995; author's independent observations). Although geochronologic data suggest this basalt may have an age of 11 Ma, it is included with the other post-10 Ma volcanoes because of its proximity to the proposed repository.

The event count for the Solitario Canyon fault area is 1.

RATES OF OCCURRENCE

Using the event counts discussed above, the rates of occurrence are established for use in the PVHA. These rates are calculated over various time periods and for particular source zones (see summary in Table WH-2).

Three alternative time periods are considered for estimating the future rate of occurrence of volcanic events:

Post-1 Ma (0.6)
Post-5 Ma (0.3)
Post-10 Ma (0.1)

Each time period is, in turn, related to particular zones (shown in Figure WH-2 and discussed previously under Spatial Models).

For the post-1 Ma time period, the rate for the 1 Ma zone is derived from the counts at northern Crater Flat, Lathrop Wells, and Sleeping Butte. The background zone rate comes from an equally weighted average of the counts from the entire post-10 Ma period, the period from 10 Ma to 1 Ma, and the period from 10 Ma to 5 Ma.

For the post-5 Ma period, the rate for the 5 Ma zone is derived from the counts at northern Crater Flat, Lathrop Wells, Sleeping Butte, the 3.7 Ma area of Crater Flat, Thirsty Mesa, Buckboard Mesa, and Amargosa Valley. The rate for the background zone is derived in the same way as for the post-1 Ma period.

For the post-10 Ma period, the rate for the 10 Ma zone is derived from the counts at all of the areas used for the post-5 Ma period, plus Rocket Wash, Pahute Mesa, Paiute Ridge, Nye Canyon, Yucca Flat, and Solitario Canyon. The 10 Ma zone is identical to the background zone for this time period.

Undetected Events

Undetected events are included in the event counts at each individual location in the estimate of the maximum number of events.

TEMPORAL MODELS

A homogenous Poisson model is used because the available data satisfy this model, and such a model has the important attribute of simplicity.

The different time frames used in establishing each homogenous source zone (10-, 5-, and 1-Ma zones) have been adopted and weighted in an effort to capture uncertainty about the time period that best represents temporally homogenous (and representative) magmatic events and what these events might imply for the future. The post-10 Ma period captures postcaldera volcanism in the region of interest; permits incorporation of the 10-11 Ma Solitario Canyon basalt near the repository; provides a background zone for the other, more localized zones; and is assigned the lowest weight because the long time frame is believed to be least representative of future volcanism. The post-5 Ma period does not mark a change of volcanic pattern within the region of interest, but is selected to provide an intermediate time frame for calculating a Pliocene-and-younger volcanic rate; it is given an intermediate weight. The post-1 Ma volcanoes occur in the Crater Flat volcanic field near the proposed repository, and this time period is therefore heavily weighted. Any time-dependent differences in volcanic rates are believed to be captured in the analysis by adopting these three time periods and assigning relative weights to them.

EVENT GEOMETRY AND MAGNITUDE

When an event is defined by two or more features (e.g., cones), the center of mass of the features considering their volumes is used as the point location of the event. These points have been assessed for several centers by the author.

Event dimensions are constrained by the length of a dike or a set of dikes related to a single magmatic event. The following distribution of event lengths is used:

<1 km	(0.2)
1-2 km	(0.3)
2-5 km	(0.3)
5-10 km	(0.1)
10-15 km	(0.05)
>15 km	(0.05)

Dike (event) length is an important parameter in this PVHA because the distribution of dike lengths strongly influences the probability of magma to intrude beyond its volcanic-source zones. The small magma volumes erupted at individual basaltic centers and the low magma-generation rate in the region of interest (Crowe et al., 1995) suggest that feeder dikes are small, and the observed outcrop lengths of exposed dikes and aligned vents in the region of interest indicate that dike lengths are most commonly less than 5 km. The 12-km length of the 1 Ma Crater Flat cones, if fed by a single dike, gives a maximum observed length for an event in the region of interest, but dikes can intrude farther than the aligned vents they produce. A maximum length for dikes in the region of interest is difficult to establish with certainty, but might be on the order of twice the observed maximum length. A value of 30 ± 10 km is adopted here; such a dike would be capable of intruding several structural blocks in the YMR, but might erupt only in topographically low, alluvial valleys. The weights assessed for the maximum dike lengths are 20 km (0.3), 30 km (0.4), and 40 km (0.3), reflecting the large uncertainty and no strong preference for any of the three values. Events are more likely to be centered on the dikes, and a triangular distribution is used to model event location.

Note: *At the request of Dr. Hackett, a smooth interpolation function was fit to his discrete cumulative density estimates for dike length. The resulting cumulative distributions and density functions are shown on Figure WH-5.*

Dike orientation is an important parameter in this PVHA because potential intersection of the proposed repository by a dike is dependent on dike trajectory as well as length. Abundant empirical, theoretical, and numerical treatments of the dike-intrusion process have shown that dike orientation is strongly controlled by a regional stress field (Parsons and Thompson, 1991). Dikes intrude parallel to sigma-2 and perpendicular to sigma-3. Stock et al. (1985) provide the only published measurements of the in situ stress state at Yucca Mountain. At depths of 1 to 1.3 km, their measurements indicate that sigma-2 is approximately N25E. The orientation of future dikes in the region of interest is therefore taken as N25E±30 degrees, where N25E is the median value of a Gaussian distribution with a two-sigma range of 60 degrees. Twenty degrees of the 30-degree total uncertainty is due to uncertainty in the measurement of in situ stress, and the remaining 10 degrees is due to uncertainty in the dike following a path perpendicular to sigma-3.

The average width of a dike is on the order of 1 m, with a range of 0.5 to 2 m, based on outcrop observations in the YMR and analog regions. The zone of magma-induced faulting and fissuring above a dike is expected to be less than 0.5 km in width (Mastin and Pollard, 1988). The point location for an event is taken to be the center of a dike trace; i.e., dikes are as likely to propagate southwest as northeast. Other geologic controls may operate, such as the easier propagation of dikes through low-density, low-strength alluvium (beneath Crater Flat), relative to welded tuffs and carbonate rocks (comprising Yucca Mountain). This factor was considered, but deemed insignificant, specifically as a discrete boundary condition that would inhibit northeastward dike propagation beyond the eastern boundary of the Quaternary Crater Flat volcanic field. The thickness of alluvium beneath Crater Flat is generally less than a few hundred meters, whereas dikes are fanlike bodies that penetrate several kilometers to tens of kilometers of the crust. Thin alluvial deposits of eastern Crater Flat are therefore considered incapable of significantly influencing the propagation of dikes in the shallow subsurface. That is, the major bedrock units (welded tuffs) through which shallow dikes must propagate are the dominant geologic materials beneath Crater Flat as well as Yucca Mountain. No special condition is warranted to inhibit northeastward dike propagation from future Crater Flat volcanoes toward the proposed repository.

Because the proposed repository is several hundred meters higher in elevation than Crater Flat, buoyancy considerations would argue that future basaltic dikes from Crater Flat might not intersect the repository. However, it should be noted that the zone of magma-induced normal faulting, tensile fissuring, and gas emission will extend upward from the dike top, and may intersect the repository.

Event "magnitude" is indicated by the area of structural disruption, or the zone of tensile disruption of rocks above an ascending dike. Cogenetic volcanic materials are also most likely to be emplaced within this zone. For this analysis, the most likely dimensions of a future magmatic event are a shallow dike length of 2 km and a zone of structural disruption of about 0.5 km, resulting in a 1 km^2 area of disruption, with or without accompanying volcanism.

HYDROMAGMATIC ACTIVITY

In order to have a significant hydromagmatic explosion, the water table needs to be within about 100 m of the surface for steam pressure to overcome the lithostatic pressure, and porous rocks must be present to allow flux of external water to the magma-water interface (Fisher and Schmincke, 1984). This type of explosion is rarely seen in the YMR and is therefore considered to be extremely unlikely in the site area, given the groundwater conditions.

There is some evidence of small-volume hydrovolcanism at two localities: Lathrop Wells and Nye Canyon (Crowe et al., 1995). Given 2 examples out of about 30 total events, the probability of this type of hydrovolcanism is 2 in 30, or 0.067.

TYPES OF ERUPTION

The types of volcanic features that could occur in the region of interest in the future, based on the record of volcanism during the past 10 my, are monogenetic basaltic features (Crowe et al., 1995): (1) a group of cogenetic scoria cones and small-volume lava flows (<0.1 km^3) from a common dike-fed fissure eruption (e.g., Buckboard Mesa); (2) a smaller, single scoria cone and small-volume lava flow that covers only a few km^2 (e.g., Red Cone and Black Cone); (3) a hydrovolcanic tuff cone or mixed Strombolian/hydrovolcanic tuff cone (explosive volcanism is not a characteristic of the region of interest; however, there is some evidence of hydrovolcanism at Nye Canyon and Lathrop Wells); and (4) a small shield volcano formed by many small-volume lava flows (e.g., Thirsty Mesa). The probability that a future volcanic event will be one of these monogenetic types is: group of scoria cones and lava flows (0.60, or 18 of about 30 total events in the region of interest), single scoria cone (0.30, or 9 of 30 events), hydrovolcanic tuff cone (0.067, or 2 of 30 events), and small shield (0.033, or 1 of 30 events).

A polygenetic tephra cone with a small lava flow, similar to the polygenetic model proposed by Crowe et al. (1995) for the Lathrop Wells volcano, has a probability of less than or equal to 0.033 (less than or equal to 1 in 30 total events). Another type of volcanic event that could occur is a silicic Plinian eruption. This would require a large volume of a type of magma that has been unavailable within the region of interest during about the past 8-10 my. Miocene silicic calderas to the north of the repository show no geologic or geophysical evidence (such as ongoing hydrothermal activity) to suggest that they may be reactivated to produce future silicic Plinian eruptions. Given that there have been no silicic eruptions in the region of interest during the past 8 my, the probability of a return to silicic volcanism is about 1 in 8 million, or 1.2×10^{-7} per year. Silicic volcanism has not only ceased in the region of interest during the past 8-10 my, but has also migrated beyond the region of interest to the western edge of the southern Great Basin (e.g., the Quaternary silicic volcanism of the Coso field, Long Valley caldera, and Mono-Inyo craters). This regional spatial-temporal pattern suggests that the probability estimate of a return to silicic volcanism in the region of interest can be decreased by several orders of magnitude, perhaps to less than 10^{-9} per year.

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April 9, 1996

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TABLE WH-1
WILLIAM R. HACKETT - EVENT COUNTS

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1	(0.4)	AM: Aeromagnetic anomalies of V. Langenheim, USGS BC: Black Cone HC: Hidden Cone 2HC: 2 events at Hidden Cone LBP: Little Black Peak LC: Little Cone 2LC: 2 separate Little Cones M: Makani Cone RC: Red Cone u: undetected events
	2	(0.1)	
	3	(0.4)	
	4	(0.05)	
	5 (u)	(0.05)	
Sleeping Butte	1 (LBP+HC)	(0.4)	
	2 (LBP, HC)	(0.5)	
	3 (LBP, 2HC)	(0.1)	
1.0 Ma Crater Flat	1 (all)	(0.1)	
	2 (LC, RC+BC+M)	(0.3)	
	3 (LC, RC+BC, M)	(0.4)	
	4 (LC, RC, BC, M)	(0.1)	
	5 (2LC, RC, BC, M)	(0.05)	
	6 (u, 2LC, RC, BC, M)	(0.05)	
Buckboard Mesa	1	(0.8)	
	2	(0.2)	
3.7 Ma Crater Flat	1	(0.05)	
	2	(0.1)	
	3	(0.3)	
	4	(0.2)	
	5	(0.2)	
	6	(0.1)	
	7 (u)	(0.025)	
	8 (2u)	(0.025)	
Amargosa Valley	1 (B)	(0.0184)	
	2 (B+C) or	0.0817	
	(B+D)	(0.0816)	
	3 (B+C+D) or	(0.2949)	
	(B+C+G) or	(0.0660)	
	(B+D+E)	(0.0660)	
	4 (B+C+D+E) or	(0.1473)	
	(B+C+D+G)	(0.1473)	
	5 (B+C+D+B+G)	(0.0853)	
	6 (B+C+D+B+F+G)	(0.0110)	
	7 (A-G)	(0.0005)	
Thirsty Mesa	1	(0.7)	
	2 (u)	(0.2)	
	3 (2u)	(0.1)	
Rocket Wash	1	(0.8)	
	2 (u)	(0.2)	

TABLE WH-1 (Cont'd)
WILLIAM R. HACKETT - EVENT COUNTS

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Pahute Mesa	1	(0.1)	
	2	(0.6)	
	3	(0.2)	
	4 (u)	(0.1)	
Paiute Ridge	1	(0.05)	
	2	(0.4)	
	3	(0.3)	
	4	(0.1)	
	5	(0.1)	
	6 (u)	(0.05)	
Nye Canyon	1	(0.05)	
	2	(0.1)	
	3	(0.2)	
	4	(0.5)	
	5	(0.1)	
	6 (u)	(0.05)	
Yucca Flat	1	(0.9)	
	2 (u)	(0.1)	
Solitario Canyon	1	(1.0)	

TABLE WH-2
WILLIAM R. HACKETT - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Post 1 Ma (0.6)	- 1 Ma Zone: (NCF+ LW+SB) - Background (10 Ma Zone): Post 10 Ma rate (0.33) (3.7+TM+BM+RW+PR+PM+NC+YF+SC) 10 - 1 Ma rate (0.33) (3.7+TM+BM+RW+PR+PM+NC+YF+SC) 10 - 5 Ma rate (0.33) (RW+PR+PM+NC+YF+SC)	AV: Amargosa Valley BM: Buckboard Mesa LW: Lathrop Wells NC: Nye Canyon NCF: Northern Crater Flat PM: Pahute Mesa PR: Paiute Ridge RW: Rocket Wash SB: Sleeping Butte SC: Solitario Canyon TM: Thirsty Mesa YF: Yucca Flat 3.7: 3.7 Ma Crater Flat
Post 5 Ma (0.3)	- 5 Ma Zone: (NCF+LW+SB+TM+BM+AV) - Background (10 Ma Zone): Post 10 Ma rate (0.33) (PR+PM+NC+YF+ 3.7) 10 - 1 Ma rate (0.33) (PR+PM+NC+YF+3.7) 10 - 5 Ma rate (0.33) (PR+PM+NC+YF)	
Post 10 Ma (0.1)	- 10 Ma Zone: (NCF+LW+SB+TM+BM+AV +RW+PM+PR+NC+YF+SC+ 3.7)	

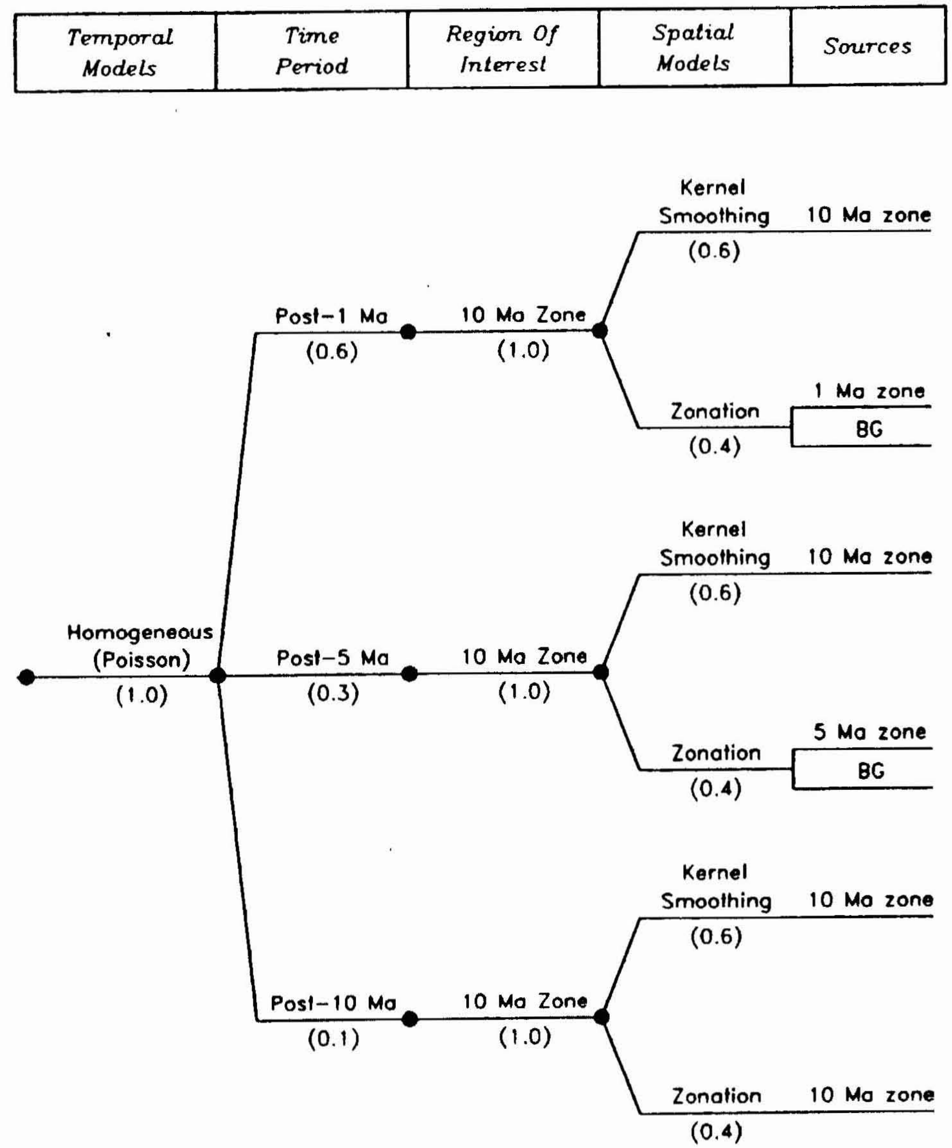
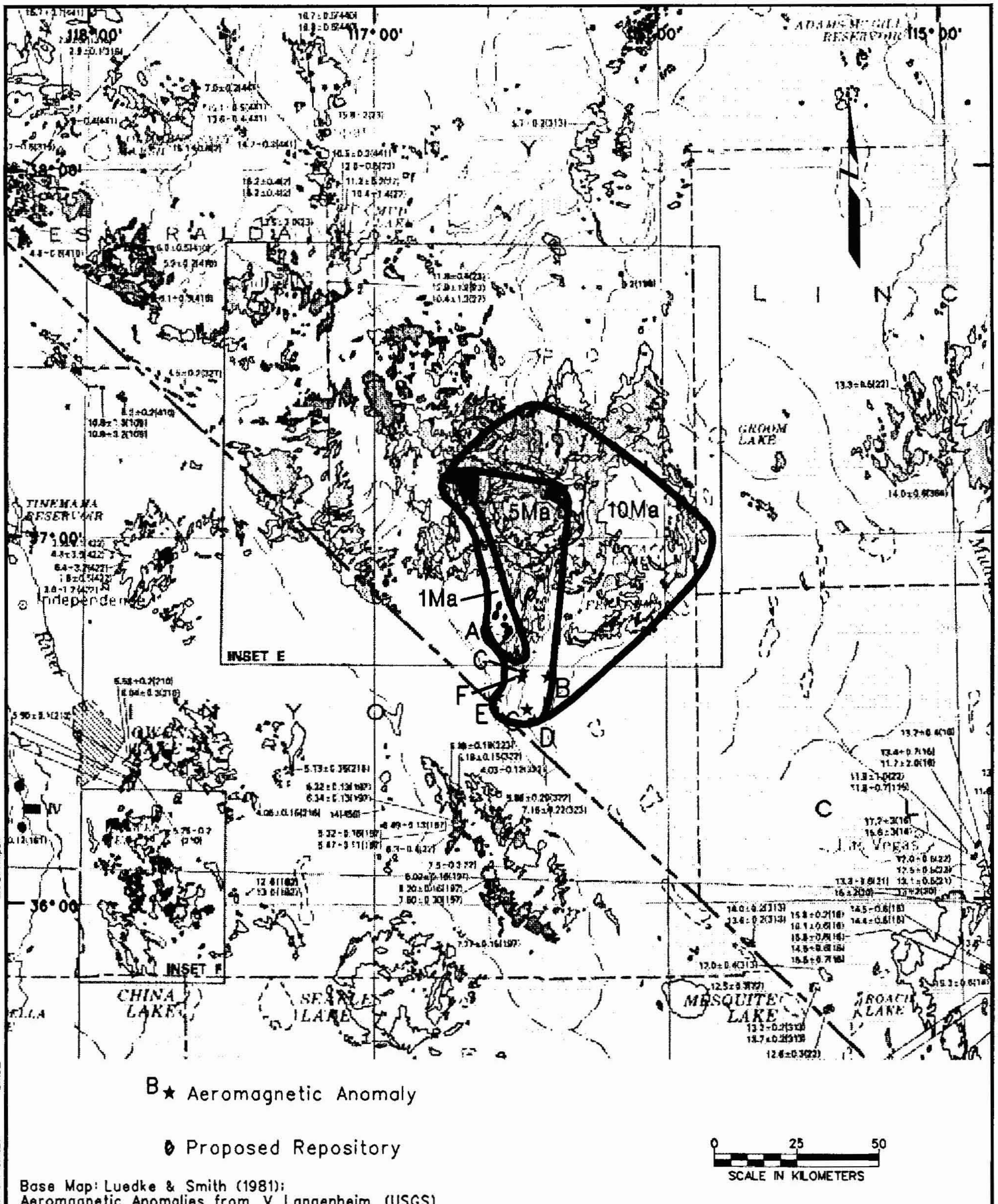


Figure WH-1 PVHA model logic tree developed by William R. Hackett.

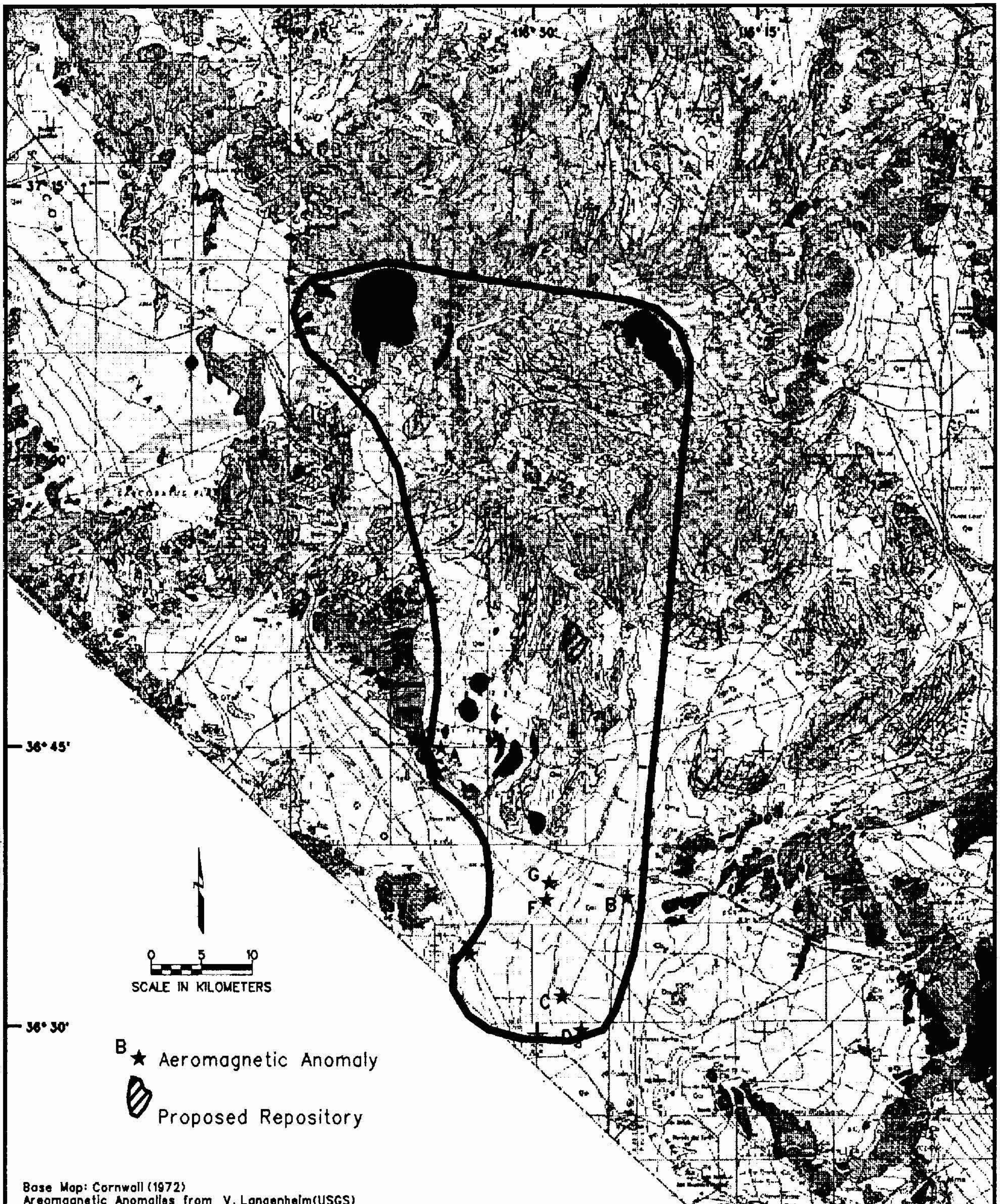


GEOMATRIX

WILLIAM R. HACKETT
10 Ma BACKGROUND ZONE
WITH 5 Ma AND 1 Ma ZONES

Figure WH-2

PVHA Project

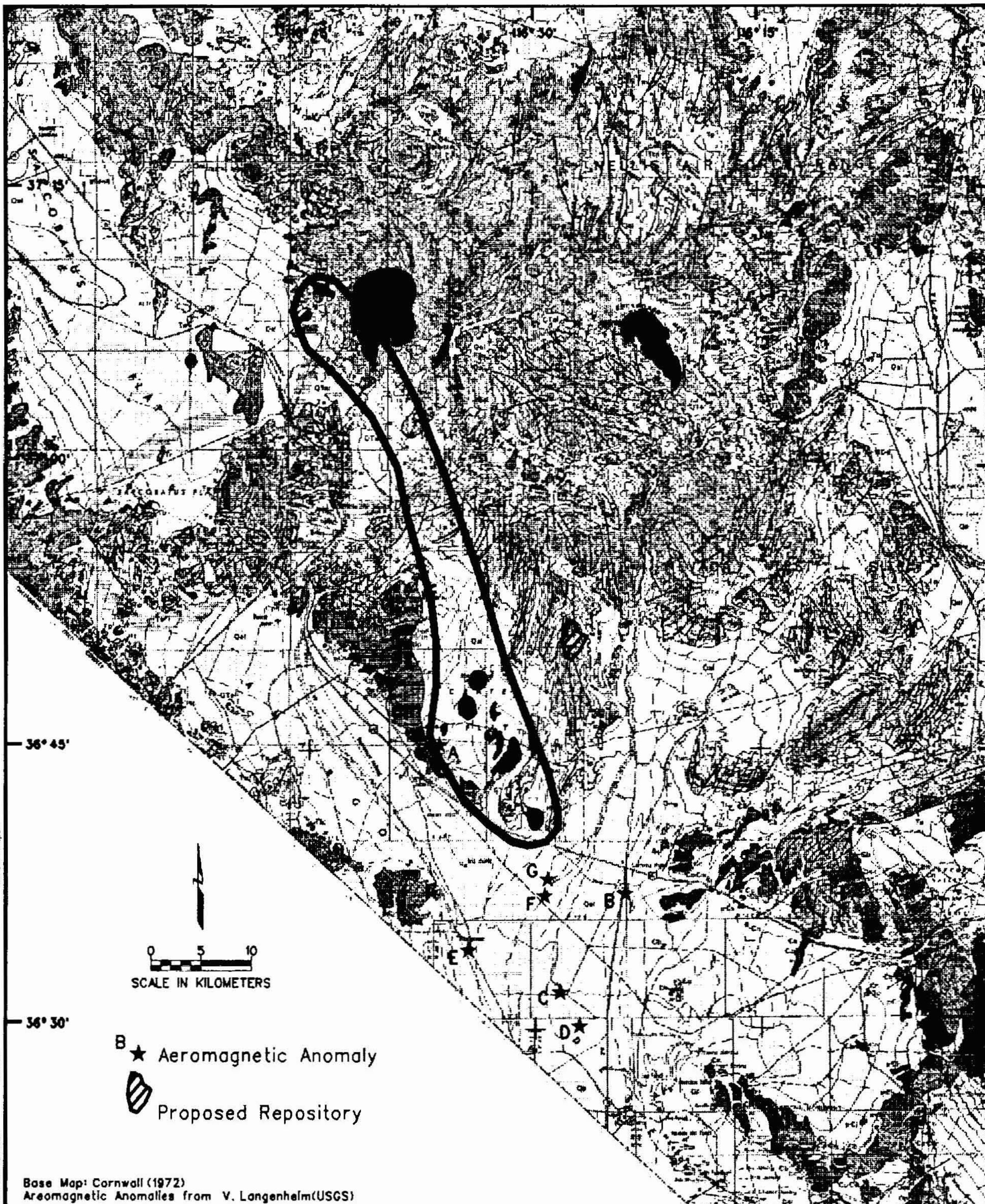


GEOMATRIX

WILLIAM R. HACKETT
5 Ma ZONE

Figure WH-3

PVHA Project



WILLIAM R. HACKETT
1 Ma ZONE

Figure WH-4

PVHA Project

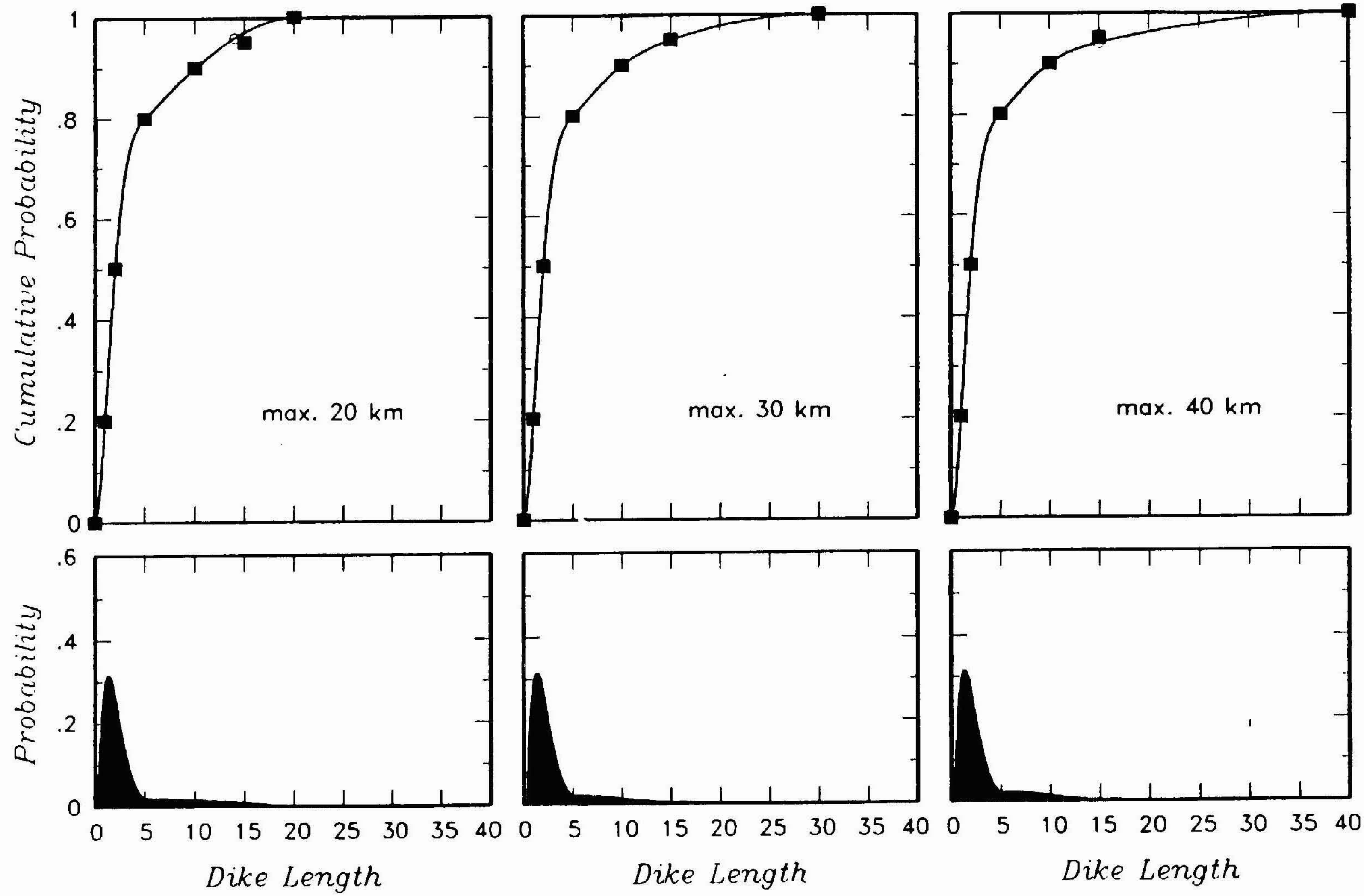


Figure WH-5 Dike length distribution developed by William R. Hackett.

MEL A. KUNTZ
ELICITATION INTERVIEW FOR PVHA PROJECT

VOLCANIC/TECTONIC SETTING

Regional Perspective and Factors Related to Magma Production

The term Yucca Mountain region (YMR) is used herein in a general sense to refer to the area within a radius of 100 km from the proposed high-level nuclear waste repository at Yucca Mountain. The YMR lies near the boundary of the Basin and Range Province, characterized by east-west extension, and the Sierra Nevada belt, characterized mostly by north-south translational movement. The Walker Lane structural belt is the accommodation zone between these provinces, and the YMR lies near the northeastern border of the Walker Lane, but within the Basin and Range Province. Rates of extension were high in the YMR region prior to 10 Ma, but in the post-10 Ma period, extension rates have decreased significantly. Large-volume rhyolitic volcanism has continued over the past several million years in areas of maximum extension at the periphery of the Basin and Range, such as at Long Valley, the Coso Range, and Yellowstone, where a mantle plume may also play a role. In these areas, high rates of extension in the lithosphere may lead to decompression melting in the upper asthenosphere, resulting in large volumes of basaltic magma that produce extensive lithospheric melting and production of large volumes of rhyolitic magma, resulting in classic bimodal volcanism. There has been a change in the style of volcanism in the YMR concurrent with the change in extension rate. Large-volume caldera eruptions, characteristic of the earlier, rapid-extension period, have ceased and have been replaced by small-volume basaltic eruptions over the past 10 my that are widely dispersed in both time and space [1](Typical sources: Crowe et al., 1995; presentations by B. Crowe, J. Stewart, and G. Thompson at PVHA Workshop 3).

The geothermal gradient in the YMR, when projected to the Moho, suggests that the upper asthenosphere is close to its incipient melting temperature (G. Thompson presentation at PVHA Workshop 4). Mechanisms suggested for tipping the balance in favor of localized melting to produce basaltic magma include injection of hot mantle (a plume); lowering of confining pressure,

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1

An immense amount of data and ideas were reviewed for this study, and judgments made for this elicitation were formulated from these sources. Specific references are given whenever possible, otherwise general references for ideas that have been formulated from many sources are given at the end of the paragraph where that type of idea is presented.

perhaps causing decompression melting; or lowering the melting point of the melting region by adding water (R. Carlson presentation at PVHA Workshop 4). Whether these mechanisms are related to regional tectonics or are essentially haphazard is not known. The low volumes of recent basaltic eruptions and the lack of recent rhyolitic volcanism may be due largely to the fact that both the upper asthenosphere and the entire lithosphere in the YMR region have been drained of their low-temperature, partial-melting fractions by previous melting events, resulting in an asthenosphere and a lithosphere that are essentially non-fertile with respect to future melting events. Geophysical data suggest that there is no extensive basaltic magma body beneath the YMR, which implies that basaltic magma production is local and episodic in much of the interior of the Basin and Range (Crowe et al., 1995).

The isotopic studies of G. Yogodzinski (presentation at PVHA Workshop 3) show that basalts in the YMR are part of a regional geochemical province termed the Amargosa Valley Isotopic Province (AVIP), which is the surface expression of a unique mantle region that has been isolated from convecting mantle for about 1 billion years and has not been affected by Basin and Range extension (R. Carlson presentation at PVHA Workshop 4). The significance of the AVIP for my elicitation is that it helps to define the region of interest or background zone for the purpose of evaluating the volcanic hazard for the repository site. As pointed out by G. Walker (presentation at PVHA Workshop 4), the relatively narrow, roughly north-south-oriented distribution of basaltic volcanic vents within the AVIP may represent the plan shape of the zone of mantle melting, which may be roughly akin to a N-S-oriented dike at depth.

Local Perspective and Factors Related to Magma Delivery to the Surface

The relationships between magma generation and magma delivery to the surface involve a complex set of conditions including, but not confined to, extension rate, magma volume, magma supply rate, deep and shallow structural control of dikes by regional stress orientations, presence or absence of favorably oriented near-surface structures, and the integrated density contrast over the entire column of lithosphere and upper asthenosphere above the site of magma generation and below the potential site of eruption. The interrelationships between these processes are poorly understood. A general feeling emerged among some, if not most, members of the expert panel that magma delivery to the surface in the YMR is probably controlled at depth by a roughly north-south-oriented structure, perhaps a deep transverse (?) fault. On the other hand, the orientation of this structure may simply reflect the north-south orientation of the melting anomaly represented by the AVIP, and deep structural control may be lacking or not very influential. It seems clear that near-surface structures affect the orientation of feeder dikes and cinder cones in the Crater Flat volcanic field (CFVF). For example, the alignment of cones in northern Crater Flat appears to be related to a northeast-trending structure. The ring-fracture zone of the Timber Mountain caldera probably provided conduits to the surface that localized eruptions and ponded basalt flows for the Thirsty Mesa and Buckboard Mesa basalts. In summary, magma may have followed N-S or NNW-SSE-oriented structures at depth, but was largely controlled by NE-trending structures that are parallel to the regional direction of maximum horizontal compressional stress or by local, caldera-related structures in the near surface. (Typical sources: Crowe et al., 1995; presentations by J. Stewart, G. Thompson, G. Walker, J. Faulds, and C. Fridrich at PVHA workshops and field trips).

In several presentations to the expert panel at PVHA workshops, G. Thompson stressed that regional extension in the YMR can be expressed in two ways; normal faulting and/or dike injection. It appears that normal faulting has been the major (only?) process within the Yucca Mountain block in the past 5 my and that faulting and dike injection (volcanism) have both operated within the Crater Flat region within the same time period. Unfortunately, models that adequately explain why one process dominated the other in the two respective areas are not available. If such an explanation were available, it might help to explain why there appears to be such a sharp boundary at the eastern edge of the CFVF, just west of the proposed repository site. It is clear to the author that the eastern boundary of the CFVF is sharp in terms of distribution of volcanic vents; basaltic eruptions have not occurred beyond this boundary eastward into Yucca Mountain in Pleistocene and Pliocene time. Recent field studies of the Yucca Mountain-Crater Flat area by C. Fridrich (in press), and newly acquired seismic reflection data for the same area interpreted for the expert panel by G. Thompson (presentation at PVHA Workshop 4) indicate that the boundary is not a significant structural break such as a major fault. Rather, "the faults that cut Yucca Mountain and that have facilitated extension are minor, and the magnitude of extension is small to moderate; no major bounding faults that define the mountain structurally are known to exist; therefore, Yucca Mountain is not a discrete tectonic block, or at least has not functioned as one in post-Paleocene time" (O'Leary and Weissenberg, in press). Fridrich (in press) states that "Yucca Mountain is an arcuate, multiple-fault-block ridge that wraps around the north, east, and south flanks of the Crater Flat alluvial basin. This ridge and the flat that it nearly encloses are structurally inseparable; together, they constitute a single domain in terms of their structural style and tectonic history, and they are distinct in these features from adjacent areas." Thus, factors that govern the eastern boundary of the CFVF appear not to be of a structural nature, and they remain largely unexplained and unknown at this time. Uncertainty about the character of the boundary is reflected in and incorporated in my hazard analysis models. (Typical sources: Fridrich, in press; O'Leary and Weissenberg, in press; Ferrill et al., 1995; and presentations by G. Thompson, C. Fridrich, and G. Walker at PVHA workshops and field trips.)

A factor that may be important in localizing volcanism within Crater Flat, but not in Yucca Mountain, involves subtle differences in the integrated density contrast over the entire column of lithosphere and upper asthenosphere above a site of magma generation and below a potential site of eruption and its effect on magma-driving pressures. This factor may be related to the general observation (there are obvious exceptions) that volcanic vents in the YMR generally occur in low topographic areas (e.g., Crater Flat, Amargosa Valley) and that high topographic areas (e.g., Yucca Mountain, Bare Mountain) have fewer or no vents. An explanation for this relationship may lie in the fact that an extra few hundred meters of low-density rocks in the higher topographic areas may provide a density barrier to emplacement of basalt dikes. I suggested that subtle density differences in the upper crust affected magma-driving pressures and produced areas of no eruptions in an otherwise widespread region of volcanic vents in the eastern Snake River Plain, Idaho (Kuntz, 1992). There are insufficient density data available for the Crater Flat-Yucca Mountain region to make basic calculations to evaluate this factor as it relates to volcanic hazard for the repository site. However, this factor may be important in localizing basaltic vents in Crater Flat with respect to Yucca Mountain.

EVENT DEFINITION

Temporal Aspects

A *volcanic event* in the context of the basaltic volcanism expected in the YMR is defined as a set of eruptive and noneruptive fissures and associated cones and flows that form during a single diking episode. An event may consist of a dike set, such as en echelon dikes, and multiple separate vents. Based on my knowledge of the timing of volcanism in Hawaii and the eastern Snake River Plain, I view a volcanic event as occurring within a few months to no more than a few years or, possibly, a few tens of years. The crystallization time of an ascending dike in the crust is the principal control on the time frame; dikes a few meters thick and 1 to 10 km long cannot remain fluid for long periods (months or years) in the middle to shallow crust in the YMR.

Spatial Aspects

A volcanic event may have different features (e.g., eruptive fissures, cones, flows) because of the range of processes that operate. These features are generally close to one another (typically 1-10 km) and generally aligned, which helps group the features into a single event. Typically, the maximum distance between eruptive features in a single event is a few kilometers, with maximum distances of perhaps 15 km (the 12-km end-to-end distance of vents in northern Crater Flat is close to the largest distance imaginable). Once an event has occurred, it is not expected that another event would recur in the same exact location, because stress has been released and the dike system has cooled and sealed.

Geochemical Affinity

The significance of geochemical differences in distinguishing between events is unclear. The Lathrop Wells cone is the best-studied cone in the world from a geochemical perspective. It is not known whether the subtle geochemical differences associated with this cone are significant because there are no similar studies elsewhere that can be used to determine the chemical variability or "noise" level in single eruptive episodes. A geochemical perspective is needed from multiple geochemical analyses in analog areas, particularly historical examples, where it is known with certainty that the deposits occurred within a single event. Because of these uncertainties, I do not use geochemical affinities or differences to define volcanic events.

Note: *The elements of the PVHA model are summarized in the form of a logic tree in Figure MK-1.*

REGION OF INTEREST

As stated by R.V. Fisher (presentation at PVHA Workshop 4), choosing a region of interest or background zone provides a regional assessment of occurrence rate of basaltic volcanoes in a tectonic province that is of immediate significance for the repository site. The principal factors that I used to identify the region of interest are age of volcanic deposits and the isotopic composition of the flows. The age range chosen (Quaternary and Pliocene, 0-5 Ma) encompasses tectonic and structural regimes that governed the basaltic volcanism in the YMR; those factors are not likely to change in the next 10,000 to 100,000 years, the time-frame for the hazard analysis. The second factor is defined by the AVIP, which contains Quaternary and Pliocene volcanic fields near the repository and provides information regarding the magma source region and recurrence rates.

The AVIP region extends from the Buckboard Mesa-Sleeping Butte on the north, through the volcanoes that constitute the Crater Flat field, and south to include the Amargosa Valley aeromagnetic anomalies. I exclude the Death Valley region from my background zone because of large uncertainties in data relating to the age and number of volcanic events in that region. Additional factors favoring exclusion are that much of the basaltic volcanism of the southern Death Valley region is older than 5 Ma and Death Valley is affected by a tectonic regime that is different than the regime affecting the YMR. (Sources: G. Yogodzinski presentation at PVHA Workshop 3, and B. Crowe informal PVHA memo)

The background zone is subdivided into 5 zones assessed to have different recurrence rates for future volcanism (Figure MK-2). Zone A is coincident with the background zone. The boundaries of Zone A were selected to include Bare Mountain on the west, Thirsty Mountain and Buckboard Mesa on the north, and the Amargosa Valley aeromagnetic anomalies on the south. The boundaries essentially follow those given by G. Yogodzinski for the northern two-thirds of the AVIP. Zones B and C are coincident with the northern and southern sections, respectively, of the Crater Flat volcanic zone (CFVZ) identified by Crowe and Perry (1989). Zone D contains a block of relatively deep basement rock brought up along and to the west of the Bare Mountain fault. Zone E contains the Yucca Mountain structural block, and Zone F contains the Timber Mountain caldera.

SPATIAL MODELS

Four alternative models are used to assess the future locations of volcanic activity in the YMR:

(1) **Uniform Zone:** In this model, the future distribution of volcanic events is assumed to have a uniform probability of occurrence anywhere within Zone A. The model consists of post-5 Ma volcanoes that have a geochemical affinity suggestive of the same asthenospheric source (i.e., within AVIP).

(2) **Zonation:** In this model, volcanism within Zone A is not randomly distributed; rather, the volcanism is confined to certain areas within the zone. I believe there are geologically reasonable explanations for the clustering of some of the post-5 Ma vents within the background zone and for the lack of vents within other parts of the background zone, as described above in the section on local perspective and factors related to magma delivery to the surface. For that reason, I subdivide the background zone into subzones B to F that have different vent distributions and, therefore, different likelihoods for future eruptions. Within each zone, there is an assumed uniform probability of occurrence. Zone C has the highest frequency of young volcanoes in the area of interest, and Zone B has the next highest frequency. Zone D does not contain evidence of Quaternary faulting nor post-Miocene volcanism. Zone E contains the Yucca Mountain structural block, which is highly faulted but contains no young volcanic features. The boundary between Zone C and Zone E separates 2 areas with very distinct differences in the rate of volcanic occurrence. Low-density rhyolite outflow facies on the edge of the Timber Mountain caldera within Zone E may have

created a density barrier to post-11.5 my basaltic eruptions. Zone F includes the Timber Mountain caldera and the 2.8 Ma Buckboard Mesa basalts.

(3) **Spatial Smoothing:** Observed locations of volcanic events in Zone C (the Crater Flat-Amargosa Valley area) are smoothed using a smoothing operator, following the general approach suggested by Connor and Hill (1995). The smoothing kernel is Gaussian in order to avoid the sharp edges of the Epanechnikov kernel and the associated sharp truncations in the probability surface. Smoothing is done only for those events within Zone C because there are no observed events within adjacent zones, and the events in the northern and southern parts of the background zone do not contribute to the hazard at the site. In order to reflect my uncertainty in the nature and location of the boundary between subzones C and E (which contains the proposed repository site), I assumed that the boundary contains, alternatively, 90 or 95 percent of the probability density, with the remaining probability allowed to occur in the regions outside of Zone C. The weightings for these two options are 0.6 and 0.4, respectively. This reflects my judgment that future volcanic events have a high likelihood of occurring within Zone C and not in adjacent regions.

(4) **Field Shape:** Following the method of Sheridan (1992), the observed locations of volcanic events within Zone C are assumed to represent realizations of a parametric shape for a volcanic field. A bivariate Gaussian shape is assumed and the distribution of observed vents is used to define the orientation of axes, aspect ratio, and absolute dimensions.

The relative weights assigned to the four alternative spatial models are: uniform zone (0.2), zonation (0.35), spatial smoothing (0.3), and field shape (0.15).

An important aspect in dealing with the four alternative spatial models is that they should reflect my uncertainty in the nature and location of the boundary between subzones C and E. My uncertainty regarding the boundary is dealt with in two ways. First, I have given higher weights to those models that better account for a diffuse boundary (uniform background model, spatial smoothing, and field shape) and lower weight to the subzone model that emphasizes hard boundaries. Second, within the subzone model, I have chosen to make the western boundary hard to reflect the fact that I believe the Bare Mountain fault is a sharp limit to the distribution of vents in the Crater Flat volcanic field, i.e., I believe that vents will not occur to the west of that boundary and dikes located within the field will not extend beyond that boundary. The eastern edge of the Crater Flat source zone, however, is not considered to be an absolute boundary to the events occurring within the zone. The rate density decays linearly from the rate within the zone to the background rate over a distance L. The value of L ranges from 0 (an absolute boundary) to 5 km.

There are very few geologic indicators that one can use to select L. I have chosen to base L on the eastern edge of the Crater Flat basin as determined by seismic and gravity evidence (V. Langenheim presentation at PVHA Workshop 1; G. Thompson presentation at PVHA Workshop 4). The eastern edge of the basin lies about 5 km east of the eastern topographic (hard) boundary of Crater Flat, thus the maximum value of L is 5 km. I judge that L values of 0 and 5 are equally likely.

EVENT COUNTS

Based on the definition of a volcanic event given above, the number of events and their uncertainties are assessed for each of the centers in the YMR. Sources of information used for these assessments included many presentations made at PVHA workshops and field trips (particularly those by B. Crowe, S. Minor, R. Fleck, and D. Champion) as well as my own interpretations of map and field data. Event counts are summarized in Table MK-1.

Lathrop Wells

The Lathrop Wells center represents 1 to 4 events, with 1 event most likely. The volcanic units are in close spatial proximity and, given the considerable uncertainty in dates, all could be related to a single event that occurred over a few years at about 125 ka. The scatter in available age dates is a function of the various analytical techniques, and if a perfect technique were developed, units Q1, Q2, and Q3 (after Crowe et al., 1995) could yield the same age. More weight is given to the paleomagnetic data of D. Champion and J. Geissman (presentations at PVHA Workshop 3) than to the other techniques, and the paleomagnetic data do not suggest more than 2 events. In the 2-event interpretation, based mainly on paleomagnetic data, units Q1 and Q2 are combined to represent 1 event and Q3 represents a separate event. In the 3-event interpretation, Q1, Q2, and Q3 are considered to be separate events. There is no evidence of an ash blanket associated with Q4, and this unit is considered unlikely to represent a separate eruptive event; Q4 is considered a separate event only in the 4-event scenario.

The following event counts and their relative weights are assigned for the Lathrop Wells center: 1 (0.95), 2 (0.03), 3 (0.019), and 4 (0.001).

Sleeping Butte

The geologic relationships in the Sleeping Butte area suggest 1 to 3 events, with 2 events most likely. Hidden Cone (HC) and Little Black Peak (LBP) have similar ages, but paleomagnetic data suggest they represent 2 separate events with a close spatial relationship. A possible separate event is postulated for an older flow associated with Hidden Cone (OHC). This postulated basalt forms an arm that extends to the NW from the main cone and has been dated by R. Fleck at 0.37 ±0.042 Ma (handout with sample locality 913-8B, PVHA Sleeping Butte field trip). Four scenarios are considered, as follows: 1 event—LBP and HC are 1 event; 2 events—LBP and HC are 1 event and OHC is 1 event (interpretation 2a) or OHC is not an event and LBP and HC form separate events (interpretation 2b); 3 events—OHC, HC, and LBP each form separate events.

The event counts and their relative weights for the Sleeping Butte area are: 1 (0.6), 2 (0.3), and 3 (0.1).

1.0 Ma Crater Flat

The 1.0 Ma basalts represent 1 to 4 events. One event is judged most likely on the basis of the available dates, including paleomagnetic data, the close spatial relationship of the cones, and the cones' orientation. In this interpretation, the cones would likely be related to a dike set, rather than a single dike, because the 12-km length is probably too long to be a single dike. Red and Black cones represent a single event in the 3-event interpretation, and Red, Black, and Little Cones are considered 1 event (based on their spatial relationship) in the 2-event interpretation. The maximum number of events is 4, because the 2 cones exposed at Little Cones are considered to be related to the same event.

The following event counts and their relative weights are assigned for northern Crater Flat: 1 (0.6), 2 (0.3), 3 (0.05), and 4 (0.05).

Buckboard Mesa

The basalts of Buckboard Mesa are interpreted to be associated with a single eruptive event. There is a single vent feature, and the basalts appear to be ponded in the moat zone of the caldera complex. The location of the deposits is likely related to the ring fracture zone, where a significant amount of collapse has occurred, thus providing ready access of basaltic magmas to the surface and a depression for ponding of flows.

Event counts and probabilities are as follows: 1 (0.95), 2 (0.05).

3.7 Ma Crater Flat

The 3.7 Ma basalts represent 1 to 6 events, with 1 event most likely. The single-event interpretation is preferred because of the proximity of the vent areas (within 4-5 km), similarities in age estimates, and similarities in flow types (i.e., low-density, fissure eruptions). Larger numbers of events are considered possible based on considering each of the vent features interpreted by Crowe et al. (1995) to be either individual events or in various combinations.

The following event counts and their relative weights are assigned for the 3.7 Ma area of Crater Flat: 1 (0.75), 2 (0.05), 3 (0.15), 4 (0.02), 5 (0.02), and 6 (0.01).

Amargosa Valley

The designation of aeromagnetic anomalies A to G is that given by V. Langenheim (presentation at PVHA Workshop 1). Anomaly A is not easily distinguishable from the large anomaly associated with the Timber Mountain caldera complex and is not considered further here. Anomaly B has been drilled and dated; its age is 3.8-4.3 Ma and it is covered by 105 m of Quaternary alluvial deposits. Anomaly D has been drilled for a water well and lies at a depth of 183 m. Unlike anomaly B, which has reversed magnetic polarization, D has normal magnetic polarization. Anomaly C has reverse magnetic polarization and is modeled to occur at a depth of about 200 m, but has not been drilled. Based on depth of Quaternary burial where known and interpreted, available dates, and magnetic polarities, it is judged that all of the anomalies are relatively close in age and span the age range of 3 Ma to 4.3 Ma. This time period includes an older period of reversed magnetic polarity, a period of normal polarity, and a younger period of reversed magnetic polarity. In interpreting numbers of events, uncertainties in these age estimates are considered.

One to 6 events are considered based on interpretation of aeromagnetic anomalies; the 3-event interpretation is judged most likely (see Table MK-1 for the various combinations). Anomalies B, C, and D are the most likely anomalies to represent buried basalt centers, and most of the weight is given to interpretations that include them as separate events. The minimum of 1 event is based on anomaly D being older than 5 Ma and anomaly C not representing a buried basalt body. The 2-event interpretation is based on anomalies B and D representing separate events; the 3-event interpretation includes anomaly C as an event.

The following event counts and their relative weights are assigned to the Amargosa Valley area: 1 (0.02), 2 (0.1), 3 (0.6), 4 (0.15), 5 (0.1), and 6 (0.03).

Thirsty Mesa

The 4.8 Ma lava and scoria deposits comprising Thirsty Mesa appear to have occurred during a single eruptive event (some field data provided via pers. comm. with S. Minor, USGS).

The event counts and their weights are as follows: 1 (0.95), 2 (0.04) and 3 (0.01).

Rocket Wash

At Rocket Wash, a single event is interpreted with an approximate age of 8 Ma.

Solitario Canyon

A basalt dike identified in the Solitario Canyon fault represents the only known post-caldera volcanic event to have affected the Yucca Mountain block. An age of approximately 11 Ma has been reported for this dike (PVHA Background Report 3). The limited exposures suggest a single event.

RATES OF OCCURRENCE

Using the event counts discussed above, the rates of occurrence of future volcanic events are established for use in the PVHA. These rates are calculated over various time periods and for particular source zones (see summary in Table MK-2).

Three alternative time periods are considered for estimating the future rate of occurrence of volcanic events. These alternatives, and the volcanic event counts included, are as follows:

Post-2 Ma	Northern Crater Flat, Sleeping Butte, Lathrop Wells
Post-5 Ma	Post-2 Ma events plus Buckboard Mesa, 3.7 Ma Crater Flat, Amargosa Valley, Thirsty Mesa
Post-11 Ma	Post-5 Ma events plus Rocket Wash and Solitario Canyon

The weights for the alternative time periods are: Post-2 Ma (0.5), Post-5 Ma (0.45), and Post-11 Ma (0.05).

The post-2 Ma period is given the highest weight because it is a period during which tectonic processes and rates of extension similar to those expected in the future have been operative. Due to the low rates of activity and low number of volcanic events in the YMR, however, the post-2 Ma period may not include enough events to provide a realistic picture of rates. Thus, in order to increase the number of events to evaluate rates, the post-5 Ma period is given a relatively high weighting. The post-11 Ma period is least preferred because it spans a period that includes the immediate post-caldera tectonic activity, as well as the more recent tectonic regime defined by lower rates of extension. This period is included as part of the analysis because it includes the dike in the Solitario Canyon area of the Yucca Mountain block, which is the only identified basaltic volcanic event known to have affected the Yucca Mountain block.

Estimated Rates

The primary basis for estimating the rates of occurrence within Zones A through F is the event counts over the three alternative time periods. Some of the zones, however, contain no events so their rates have been estimated relative to those zones containing events. Zone A is the large regional zone and contains sufficient numbers of events to estimate rates. Zone C has the highest rates, followed by Zone B to the north. Zone F has the next highest rate, as represented by the event at Buckboard Mesa. The rate in Zone E should be very low, as indicated by a lack of events over the past 5 my and only one interpreted event (Solitario Canyon) in the past 11 my. Zone D should have the lowest rate, as no events have been recognized in the past 11 my. Further support for the relative differences between Zones B and C and Zones D, E, and F lies in the observation that B and C lie in structural basins and D, E, and F lie in uplifted structural blocks. The geologic record indicates that basaltic eruptions are more likely to occur in valleys than uplifted structural blocks.

The estimated rates for the various zones and time periods are shown in Table MK-2. In most cases these are related to the counts at locations within the zones. For example, for the post-5 Ma time period, the rate within Zone C is assessed based on the sum of the counts at northern Crater Flat, the 3.7 Ma area of Crater Flat, Lathrop Wells, and Amargosa Valley. For all time periods, the rates within Zones D and E are assessed, first, relative to each other and, second, relative to zones containing events. These assessments are consistent with the relative rates discussed previously. Note that these estimates have considerable uncertainty, which is included in the logic tree.

Undetected Events

In addition to those events identified and interpreted at the surface, there is the potential for undetected, or subsurface, events that might exist at depths below 300 m (depth of the proposed repository) but not be represented at the surface. In general, dikes ascending through the crust that extend to as shallow as 300 m would be expected to vent at the surface. At deep crustal levels, magma pressure drives the ascent of the dike. But at shallow depths (upper 1-2 km) gas exsolution is also an additional driving factor and probably ensures an eruption at the surface. If such shallow subsurface dikes exist in the YMR, they would likely have been identified, although they may not be detectable in all cases.

The following factors should be multiplied by the rates for all time periods to account for undetected events: 1.0 (0.25), 1.1 (0.5), 1.5 (0.2), and 2.0 (0.05).

TEMPORAL MODELS

Two temporal models are considered: a homogeneous model (see Connor and Hill, 1995) that assumes that the rate of occurrence of volcanic events is uniform through time; and a nonhomogeneous model that accounts for a waxing or waning of occurrence rates through time (e.g., the model described by Ho et al., 1991). These alternative models are assigned weights as follows: homogeneous (0.8) and nonhomogeneous (0.2).

For both models, start times of 2, 5, and 11 Ma (and their associated weights of 0.5, 0.45, and 0.05, respectively) are used. Because there may be too few events within any given source zone to exercise the nonhomogeneous model, the ratio of the rates using the homogeneous and nonhomogeneous models should be determined for Zone A (for the three start times), and the same ratios should be used for Zones B to F.

EVENT GEOMETRIES

When an event is defined by two or more features (e.g., cones), the mid-point of the features should be used as the point location of the event.

The length of a future individual dike would likely be 1 to 3 km; however, the length of a dike set could be more than 12 km on the basis of the 12-km dike or dike set that is postulated to link the 1 Ma eruptive centers in Crater Flat. The *cumulative* distribution of individual dike lengths and dike-set lengths has the following form:

1 km	(0.1)
3 km	(0.5)
8 km	(0.75)
10 km	(0.90)
10-18 km	(1.0)

The above specifies the distribution for dike (or dike-set) lengths in an individual eruptive episode. The value of 10 km represents a limiting dike-set length. This value is the preferred estimate for the maximum dike-set length because studies of well-exposed dike swarms emplaced at depths of about 2 km or less in Utah have shown that dike-set lengths do not exceed 10 km (Delaney and Gartner, 1995), and this value is only slightly less than the 12-km dike or dike set postulated to link the 1 Ma eruptive centers in Crater Flat. The value however is uncertain and is assessed to range from 10 to 18 km with weights of 10 (0.4), 12 (0.3) 15 (0.2) and 18 km (0.1).

Note: *At the request of Dr. Kuntz, a smooth interpolation function was fit to his discrete cumulative density estimates for dike length. The resulting cumulative distributions and density functions are shown on Figure MK-3.*

Dike orientations for future events are judged to have two possible orientations. The main orientation would have a central tendency at N30°E, parallel to the maximum horizontal compressional stress direction for the region, based on earthquake focal mechanisms and borehole breakouts. There is a 90% probability that the orientation lies between north-south and N60°E (i.e., N30E ±30). Based on the inferred orientation for feeder dikes at the Lathrop Wells volcanic center and for inferred dikes at several cones in the 1 Ma volcanic centers in northern Crater Flat, a second possible dike orientation is N15°W±15°. There is a 90% probability that the dike orientation lies within this range for the second orientation. The relative frequencies for the two dike orientations are as follows: N30°E (0.7), N15°W (0.3). Expected dike widths are 1 to 2 m.

In assessing the geometry of events relative to a point location for the event, the most likely location for the point is the center of the dike, with a decreasing probability that it would be at either end of the dike. The probability distribution has a semicircular shape.

HYDROMAGMATIC ACTIVITY

The likelihood of a significant, hydromagmatic explosion in the YMR is very small. There is very little evidence for hydromagmatic eruptions at the volcanic centers in the region. The evidence for basal surge deposits at Lathrop Wells is equivocal. In the repository site area, the groundwater table is about 2000 ft below the land surface. In the eastern Snake River Plain, less than 5% of volcanic vents show evidence for hydromagmatic activity. About half of the maar volcanoes in the Snake River Plain were erupted through water-bearing alluvial sediments (e.g., Menan Buttes) and the remainder were erupted through at least 600 feet of overlying basalt flows. At the proposed repository site, the water table is at a depth of about 2,000 feet below the land surface and the water table is about 600 feet below the land surface in Crater Flat. Based on the comparison between the eastern Snake River Plain and the YMR, I suggest that 2 to 4 out of every 100 volcanic events in the YMR could be expected to be associated with significant hydromagmatic activity.

TYPE OF ERUPTION

The expected type of eruption in the YMR over at least the next 10,000 years is basaltic fissure eruptions forming cinder cones. Some eruptions will approach Strombolian activity with associated significant deposits of ash. Lava flows will be thick and extend less than a few kilometers, volumes will be low, and ash blankets could extend as far as 12 to 15 km away from the vent. Zones of deformation will likely form above an ascending dike, as described by Hackett and Smith (1994) for the eastern Snake River Plain. The chances for silicic volcanism are negligible because there is no evidence for such in the YMR in the past 11 my.

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5/22/96

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TABLE MK-1
MEL A. KUNTZ - EVENT COUNTS

LOCATION	COUNTS (CONES)	WEIGHT	NOTES
Lathrop Wells	1 (Q1-4)	(0.95)	BC: Black Cone
	2 (Q1+2, 3)	(0.03)	B-G: Aeromagnetic anomalies of V. Langenheim, USGS
	3 (Q1, 2, 3)	(0.019)	HC: Hidden Cone
	4 (Q1, 2, 3, 4)	(0.001)	2HC: 2 events at Hidden Cone
Sleeping Butte	1 (LBP+HC)	(0. 6)	LBP: Little Black Peak
	2 (LBP, HC)	(0.3)	LC: Little Cones
	3 (LBP, 2HC)	(0.1)	M: Makani Cone
1.0 Ma Crater Flat	1 (all)	(0.6)	Q1-4: Quaternary map units of Crowe et al. (1995)
	2 (LC+RC+BC, M)	(0.3)	RC: Red Cone
	3 (RC+BC, LC, M)	(0.05)	
	4 (RC, BC, LC, M)	(0.05)	
Buckboard Mesa	1	(0.95)	
	2	(0.05)	
3.7 Ma Crater Flat	1	(0.75)	
	2	(0.05)	
	3	(0.15)	
	4	(0.02)	
	5	(0.02)	
	6	(0.01)	
Amargosa Valley	1 (B)	(0.02)	
	2 (B, D)	(0.1)	
	3 (B. C. D)	(0.6)	
	4 (B, C, D, E) or	(0.075)	
	(B, C, D, F+G)	(0.075)	
	5 (B, C, D, F, G) or	(0.033)	
	(B, C, D, E, F) or	(0.034)	
	(B, C, D, E, G)	(0.033)	
	6 (B, C, D, E, F, G)	(0.03)	
Thirsty Mesa	1	(0.95)	
	2	(0.04)	
	3	(0.01)	
Rocket Wash	1 event	(1.0)	
Solitario Canyon	1	(1.0)	

TABLE MK-2
MEL A. KUNTZ - RATES OF OCCURRENCE

TIME PERIOD	COUNT METHOD FOR ZONES	NOTES
Post 2 Ma (0.5)	A: (NCF+LW+SB)	AV: Amargosa Valley BM: Buckboard Mesa LW: Lathrop Wells NCF: Northern (1.0 Ma) Crater Flat RW: Rocket Wash SB: Sleeping Butte SC: Solitario Canyon TM: Thirsty Mesa 3.7: 3.7 Ma Crater Flat
	B: (SB)	
	C: (NCF+LW)	
	D: 1.0 of E (0.1) 0.5 of E (0.5) 0.1 of E (0.4)	
	E: 1.0 of F (0.01) 0.5 of F (0.25) 0.1 of F (0.55) 0.01 of F (0.19)	
	F: 1/3 of B (0.7) 1/6 of C (0.3)	
Post 5 Ma (0.45)	A: (NCF+3.7+LW+TM+SB+AV+BM)	
	B: (TM+SB)	
	C: (NCF+3.7+LW+AV)	
	D: 1.0 of E (0.1) 0.1 of E (0.5) 0.1 of E (0.2)	
	E: 0.5 of F (0.25) 0.1 of F (0.55) 0.01 of F (0.19)	
	F: (BM)	
Post 11 Ma (0.05)	A: (NCF+3.7+LW+TM+SB+AV+BM+RW +SC)	
	B: (TM+SB+RW)	
	C: (NCF+3.7+LW+AV)	
	D: 1.0 of E (0.1) 0.1 of E (0.5) 0.1 of E (0.2)	
	E: (SC)	
	F: (BM)	

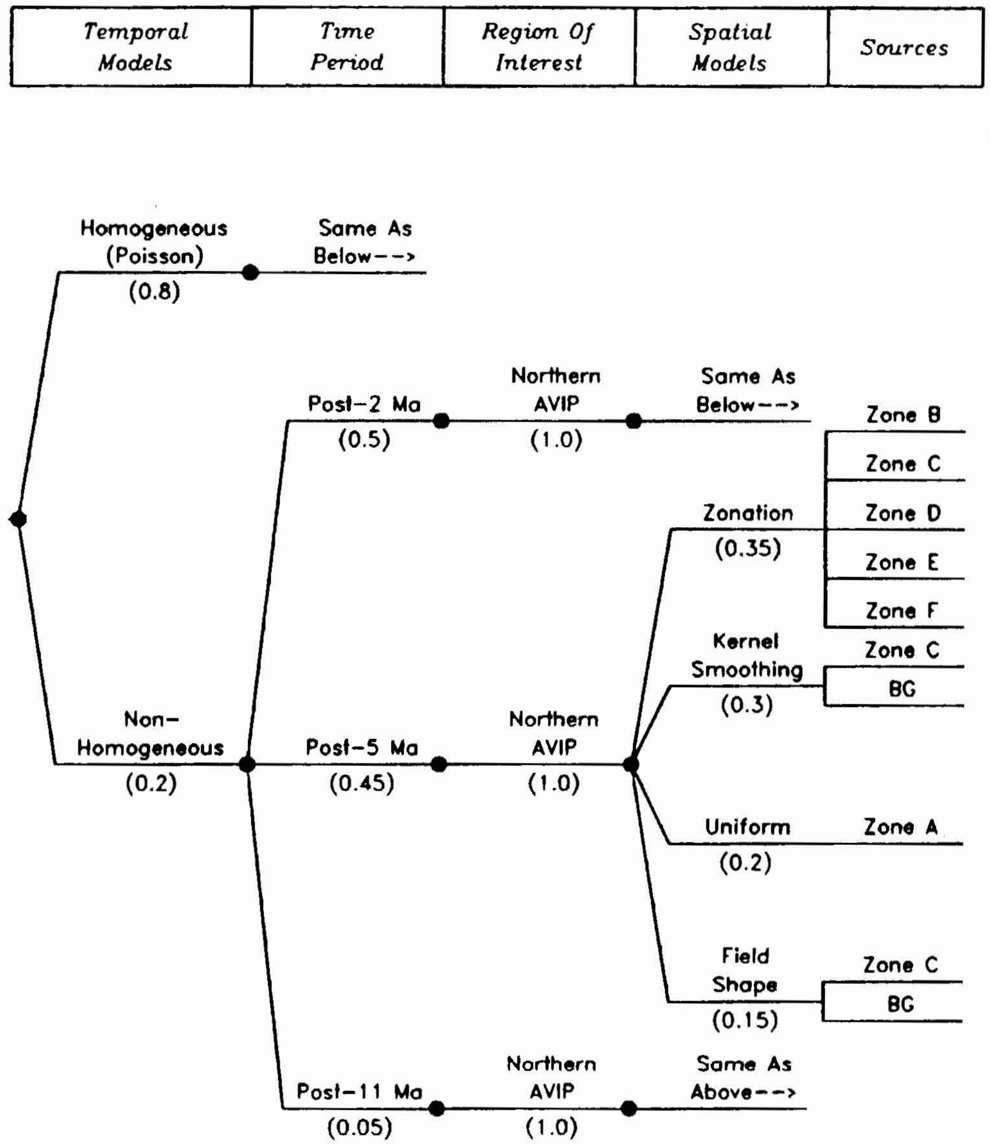
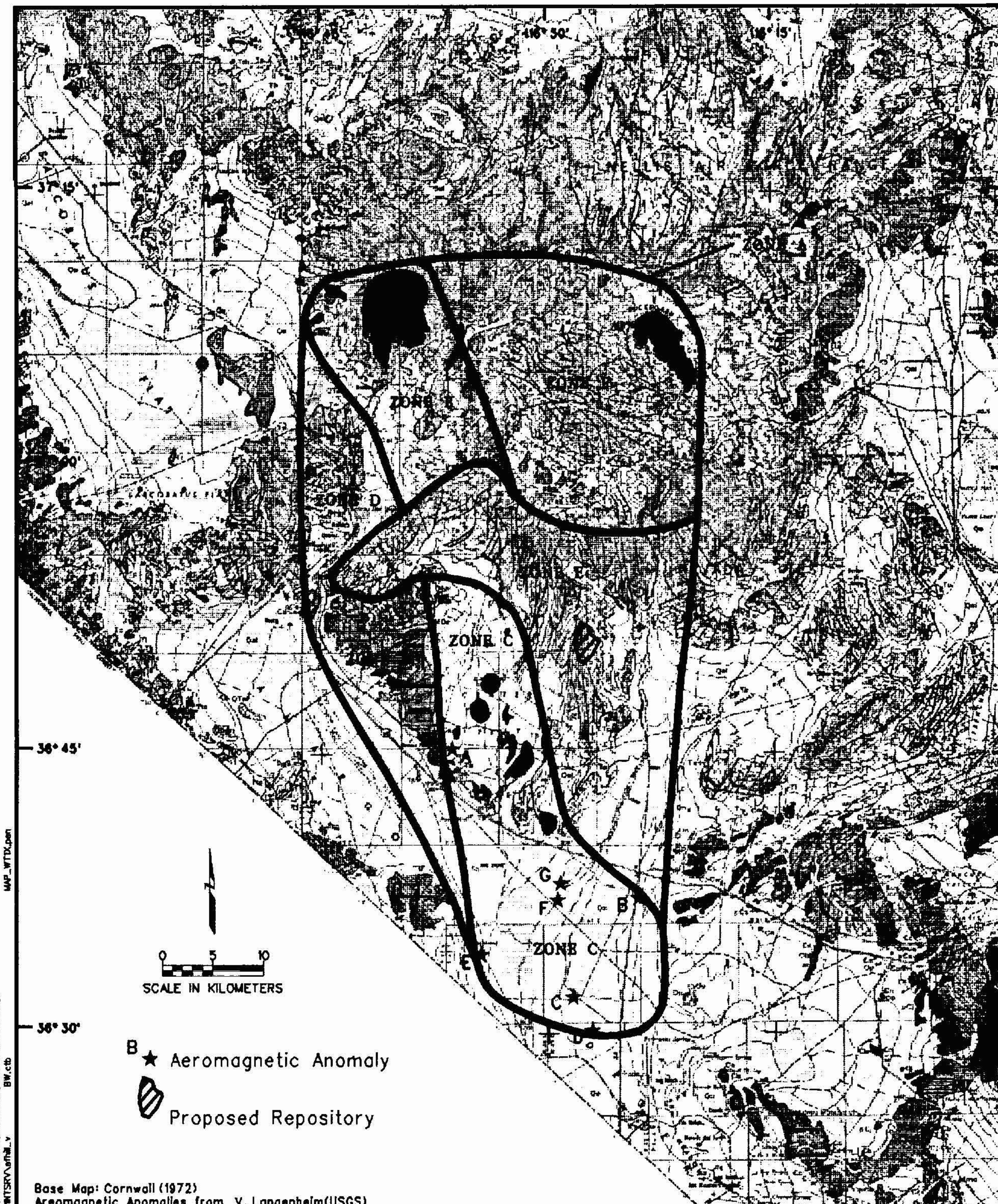


Figure MK-1 PVHA model logic tree developed by Mel A. Kuntz.



GEOMATRIX

MEL A. KUNTZ
LOCAL ZONES

Figure MK-2

PVHA Project

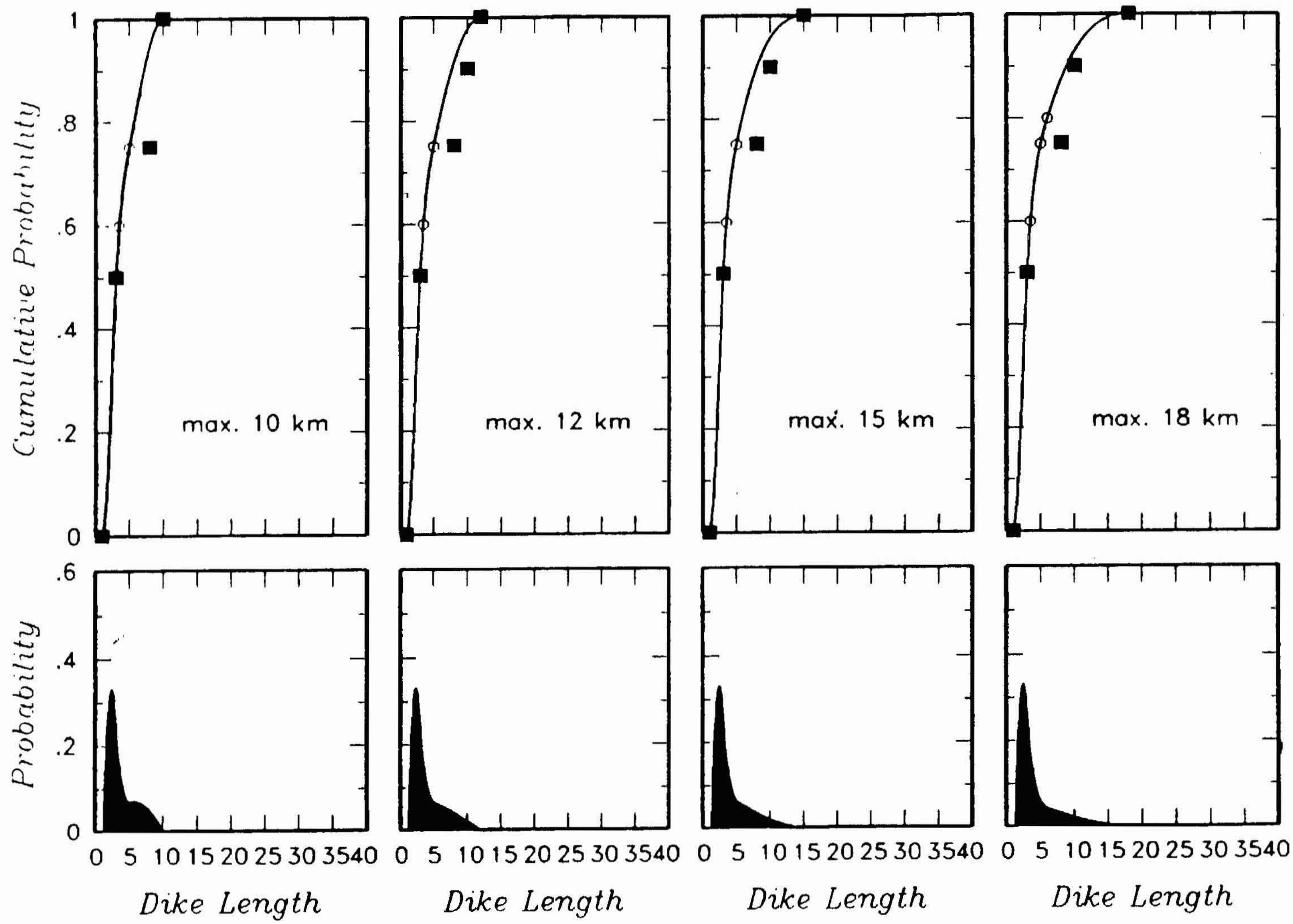


Figure MK-3 Dike length distribution developed by Mel A. Kuntz.